Design and Installation of Mounting Systems for an Electric Personal Watercraft

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Abstract

As part of the Renewable Energy Vehicle project, the REVski is a personal watercraft which is being converted to electric drive. The unique nature of the project and unusual layout of the internal surfaces and hard points, makes mounting and protecting the key electrical components of the drive system difficult.

The design requirements of the mounting system were identified using the applicable Guidelines and Standards for electric vehicles and watercraft, as well as the corrosion resistance, fatigue life, cost and functional requirements agreed upon by the project team.

After several iterations of design, the final mounting system was selected based upon maximising mounting space and minimising electric cable length. The strength of the design and likely fatigue characteristics were estimated through computer simulations and found to meet the design requirements. Mounting structural parts and installing components was planned and executed successfully and the system is currently performing above expectations. The REVski is now operational and undergoing testing.

Acknowledgements

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Finally, I would like to thank the REVski team, past and present, for their dedication and effort. I have greatly enjoyed working together and have learnt so much from.

Contents

REVski Background

The personal watercraft (PWC) has been a common sight on waterways for over 40 years, with Kawasaki motors introducing the original Jetski in 1972 (Josephson 2007). A PWC is a small watercraft designed mainly for leisure activities, with some practical use, such as surf lifesaving. PWCs are now produced by a wide range of manufacturers and for a wide range of markets, from small nimble craft to extremely high performance craft for competition.

Currently all PWCs employ much the same drive system, a light, high power petrol engine married to an axial jet pump. These powertrains are generally highly inefficient with a typical fuel consumption of 20l per hour of use at cruise speed, increasing to 40l per hour at top speeds (Wenz 2008). PWCs also produce harmful environmental pollution as well as excessive noise pollution (Mosisch & Arthington 1998). This has resulted in restrictions in the areas which PWCs can operate, particularly in America and Europe, where large areas of lakes and waterways are restricted.

Therefore, an electric PWC would be a benefit to the environment and community, as well as opening up new areas for the use of PWCs. The unique performance characteristics of electric motors also hold interesting possibilities, with potential performance over and above similarly rated internal combustion PWCs (Toliyat & Kliman 2010).

To explore these possibilities, the Renewable Energy Vehicle (REV) Project has undertaken a project to retrofit a conventional PWC with an electric power train. The REV Projects overall goal is to design and build zero emission vehicles viable for the both the performance and commercial markets (UWA REV 2015). The project, dubbed REVski, started in 2013 and is based upon a 2008 Sea Doo GTI130. This craft was originally fitted with a 1'498cc three cylinder petrol engine producing 130hp (Beckley 2013).

The major components of the REVski consist of a battery pack, motor controller and motor. The battery pack is a 7.6 kWh waterproof pack fitted in the front half of the craft. This consists of 240 3.2V Headway Lithium Iron Phosphate batteries (Hildebrand 2014). These are arranged inside PVC tubes, wired together to produce 96V and made watertight (Hildebrand 2014, Gribble 2014). The battery pack powers a Curtis 1238E controller. This will be installed inside an easily accessible waterproof box, along with other key components. The controller converts the 96V DC into 96V AC over a frequency range of 1-150Hz. This supplies a 3-phase, 2-pole, fully submersible motor with a continuous rating of 50kW, which directly drives the original jet pump, propelling the REVski.

Mounting Requirement of REVski

In the ski, all electrical systems must be fastened securely to the hull of the watercraft and be protected from solid and water ingress, to prevent short circuit or injury. There are several restricting factors limiting the options available for mounting the components securely.

- No modification can be made to the hull; this maintains its certification
- No options exist for securing large components in the front of the ski as the battery pack takes up most of the room.
- The electric motor is utilising the original engine mounts in the centre of the ski
- All other pre-existing hard points fibre glassed into the hull are inaccessible for large components
- Key components, such as the motor controller and DC-DC voltage converter must be easily accessible when installed in the ski.

Due to these restrictions, a novel solution must be found, designed and installed; this is the focus of this final year project. To accomplish this, a literature review was conducted, design requirements identified and defined, designs made and assessed to meet the requirements, the system installed, evaluated and future work identified.

Literature Review

Statutory Requirements

The standards and guidelines which are applicable to personal watercraft must be reviewed to ensure that the mounting system designed by this project meet the requirements. The standards will be reviewed for anything pertaining to minimum load requirement, component or machinery restraint or minimum crash requirements. The standards reviewed were:

- AS 1799.1 – 2009 Small craft - General Requirements for Power Boats
- AS 4132.1 - 1993 Boat and Ship Design and Construction – Part 1: Design Loadings
- The National Standard for Commercial Vessels
- ISO 13590:2003 Small craft - Personal watercraft - Construction and System Installation Requirements
- National Code of Practice for the Construction and Modification of Light Vehicles, Guidelines for the Installation of Electric Drives in Road Vehicles

Moving through the standards first, AS 1799.1 – 2009 Small craft - General requirements for power boats simply states;

> "*Be of sufficient strength to withstand the maximum loads likely to be applied in normal or emergency service.*" (AS 1799.1 – 2009 pg. 22)

AS 4132.1 - 1993 Boat and Ship Design and Construction – Part 1: Design Loadings makes no mention of impact or crash loadings and no mention of any restraining requirements.

The National Standard for Commercial Vessels published by the Australian Maritime Safety Authority states that, "Each item of machinery must be secured to the vessel's structure to prevent injury to persons, damage to components and excessive vibration." (Australian Maritime Safety Authority 2011, Part C Section 5 pg. 14)

ISO 13590:2003 Small craft - Personal watercraft - Construction and System Installation Requirements, is the international standard on the design and construction of PWCs. While the standard makes no mention of restraint requirements, for certification of the hull a fully laden drop test from 2.5m onto water is required. From this height the craft will impact the water at 7m/s, conservatively assuming the deceleration takes 0.2sec, this gives a 3.5g deceleration on impact.

Of the guidelines, the National Code of Practice for the Construction and Modification of Light Vehicles, Guidelines for the Installation of Electric Drives in Road Vehicles (NCOP14) (Department of Infrastructure and Regional Development 2011) is the most applicable, as the ski is a converted electric craft and will travel at high speeds. This states that the battery restraints must adequately withstand at least the crash accelerations in Table 1 (NCOP14) (Department of Infrastructure and Regional Development 2011).

Impact direction	Acceleration
Front impact	20 g
Side impact	15 g
Rear impact	10 g
Vertical (rollover) impact	10 g

Table 1 Impact Requirements for Battery Restraining System (NCOP14 2011)

For the safety of the user and to have the highest possibility of meeting all statutory requirements, the mounts will be designed to be able to withstand the accelerations outlined in the NCOP14, without total failure. At these forces the fiberglass hull will likely fracture, so there is no reason for the mountings to be rated for more than a single instance of these accelerations. As such, the design will only need to ensure that nothing fractures or becomes dislodged during the extreme accelerations recommended by the National Guidelines.

IP Rating

The IP Code is an International Protection Marking originally developed by the International Electrotechnical Commission, the Australian Standard based on this is AS 60529 – 2004 (AS 60529 2004). This standard sets out the rating of ingress protected enclosures for electrical equipment below 72.5kV and the testing to achieve these ratings. The IP designation is made up of two numbers, e.g. IP35. The first number in the designation is the solid particle protection; ranging from 0 - no protection to 6- dust tight. The second number is the liquid ingress protection; this is the important aspect for the REVski. This ranges from 0 – not protected to 8 – submersed between 1-3m for an indefinite time (AS 60529 2004). The selection of an appropriate rating for the controller enclosure is dependent on the situation inside the ski. The full list of designations is available in appendix 1.

The inside of the REVski cannot be completely sealed during operation; particularly the seal around the impellor shaft. This means that all electrical equipment must be protected from water, particularly the 96V systems as these present a serious danger to the operator. During normal operation or use, any enclosure in the ski must be splash proof as water may enter the hull and splash onto the electrical enclosure, this requires a minimum of an IPX4 rating. In the extreme event of a flooded hull, the ski is designed to remain neutrally buoyant (ISO 13590:2003). The electrical enclosures should never be more than just submerged and as such, an extreme situation rating of IPX7 is advised for the REVski.

Material Suitability

Given the saline water which the REVski will be used in, all of the components within the REVski must be highly corrosion resistant. Given the strength which will be required in the mounting structure the options are effectively limited to Stainless Steel, Aluminium alloys and high strength plastics. Wood products could also be used, however their low and inhomogeneous material strength make them less suitable. High strength plastics generally have excellent formability and workability and are lightweight as well as being electrically insulating, but can be expensive at the high load ratings and dimensions required (Dotmar Engineering Plastic Products n.d). Aluminium also has excellent workability and is lightweight compared to steel; it's also cheap and will likely be strong enough to bear the loads imposed by the enclosure (Onesteel Metalcentre 2015a). However, it will form a galvanic couple with stainless steel, corroding when in electrical contact with large surface areas of stainless steel (AS 1799.5 1991). Otherwise it is very resistant to corrosion in sea water. Finally stainless steel, it is very strong and durable, potentially making the structure thin and light. However, it is very difficult to work with, almost impossible with the hand tools available to the team and is expensive to purchase (Onesteel Metalcentre 2015b). The minimum properties of common aluminium alloys and stainless steel grades are given by AS 1866 -1997 (extrusions) / AS 1734- 1997 (plate and sheet) and AS 4673 – 2001 respectively.

Previous Work

R. Clark presented several options for the design of the mounting system at the beginning of the project (Clark 2013). The final design he recommended is shown below.

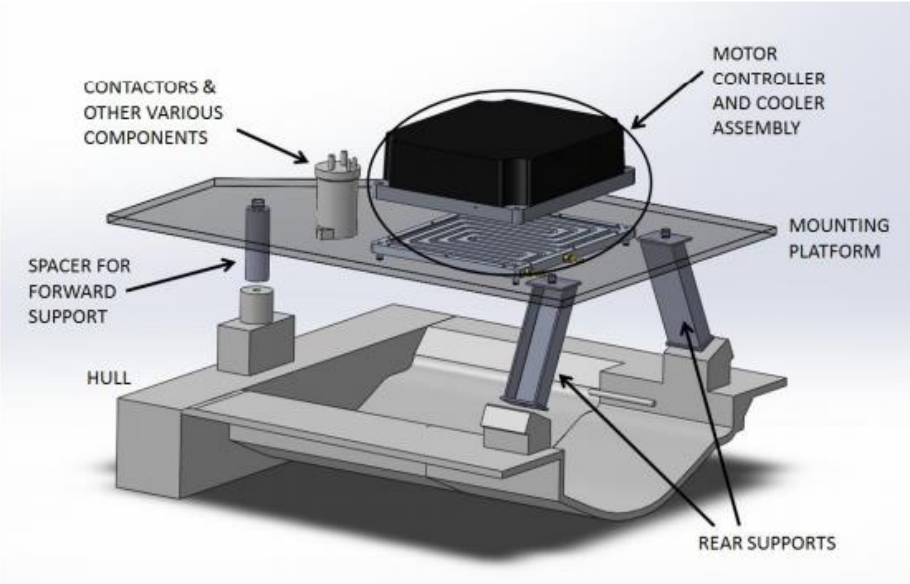

Figure 1: Design proposed by R. Clark 2013

However, due to changes in the designs of the surrounding structures, specifically the battery pack and changes to the motor mounting, this design is no longer valid as is. The ability for the structure to withstand the forward acceleration required by the NCOP14 is also a concern, as the design was only tested in the vertical direction (Clark 2013).

Another piece of work done previously, was estimating the typical load conditions during operation. This was conducted by R. Jayamanna in 2013 and estimated the g-load by fixing an accelerometer to a hire PWC and recording data during operation (Jayamanna 2013). The maximum accelerations experienced in this data set are tabulated below.

Direction of acceleration	G-force
Vertically Downwards (ie external force applied downwards)	1.44g
Vertically Upwards	4.18g
Aft (Force applied towards rear of ski)	2g
Bow (Towards front of ski)	1.83g
Port Side	2.63g
Starboard Side	2.21g

Table 2: Acceleration results from Jayamanna 2013

Having used power craft and PWCs for many years, the author views this results with some reservation as the forces seem extremely high. However, lacking any other solid data on typical accelerations during operation, these results will be used. Any estimations and conclusions made using these loads will be conservative; resulting in higher weight and cost, but will not compromise safety.

Design Requirements

From the literature review and team consultation, the following design requirements were identified.

- The National Guideline for Installation of Electric Drive, extreme accelerations or some combination of accelerations, must be survived without fracture or dislodgement at least once
- An extreme acceleration of 15g from below must also be survived at least once, in addition to the Guideline requirements. This is to simulate an impact with an underwater object at speed or a substantial drop

- Restrain and support the motor controller and major heavy components, other mounting options exist for the other required components
- Minimum IP65 rating for component protection, IP67 rating preferable
- No modification to hull
- Minimal modification to existing components
- Fatigue life of >1000hrs of normal operation
- High corrosion resistance in seawater environment
- Must fit into ski

Interfaces

A major issues in the design process were the very limited options for securing the components to the hull, interference with other components and the odd shape of the cavity. The only accessible mounts fibre-glassed into the hull are the motor mounts highlighted in the image below by the long arrows in red. On the motor itself, the endcaps are held in place with the cap screws indicated by the short blue arrows. As the hull cannot be modified, the available alternatives were to use adhesives directly onto the hull or to fibreglass additional mounting points onto the hull. Adhesives were eliminated due to the potential for the fibreglass to pull away from the hull or for the adhesive joint to fracture due to impacting. Fibre-glassing is a viable option, but an unattractive one due to the difficulty of the work in the confined space and the potential for a weak bond to the existing material. As such, utilising the motor mounts in some way was identified as the best option. This meant either attaching to the mounts directly or fastening to the motor.

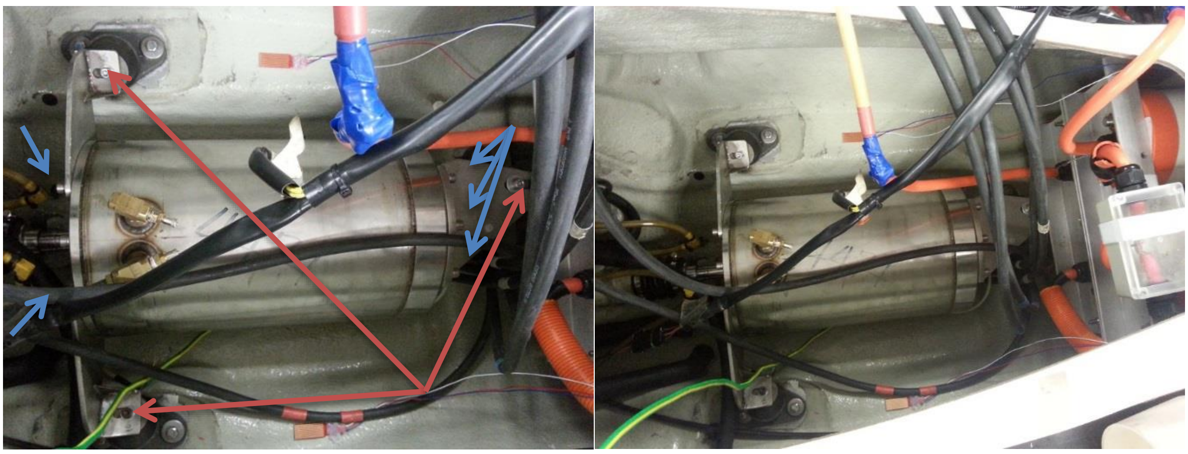

Figure 2: Available mounting points and interior of hull. Mounts to hull highlighted in red and mounts to motor in blue.

A secondary issue was interference with the coolant fittings on the motor, these can be seen above. To ensure clearance, the base of the mounting system was required to be a minimum of 80mm above the top of the motor. This would provide adequate clearance for any required fittings.

Additionally, the top of the waterproof enclosure could not interfere with the underside of the seat. This would prevent the seat from being properly secured and prevent the sealing of the engine access opening. To prevent this, a maximum height of 400mm above the motor was specified for the entire system and the height checked before final installation.

Components

The mass of the components which require mounting inside the ski will be the load applied to the mounts during acceleration events. These masses are given below, along with other information integral to the design.

Integra Waterproof Enclosure

The key electrical components for the ski will be mounted into an enclosure manufactured by Integra. This waterproof box was already purchased for the REVski in the previous year. It is IP68 rated and large enough for the key electrical components given in the table below, but still able to fit into the ski through the access hatch. The components are mounted to an internal mounting plate which is then fastened into the enclosure. The lid is clear to allow inspection and designed to hinge, the lid can be rotated 180˚, disabling the hinge if need be, as it may be difficult to open inside the ski. The key components which will be mounted into the Integra enclosure are the motor controller and the DC-DC converter. Their weights and critical information are outlined below, along with the enclosures' measurements.

Component	Weight	No. of Fastening Points	Size of Fastening Points	Dimensions (mm)
Integra Waterproof Enclosure	3kg	4	1/4in.	476x449x292
Motor Controller	6.82kg	4	7mm	275x232x85
Cooling Plate for Controller	2kg	4*	7mm	275x232x25
DC-DC Converter	2.5kg	4	5mm	180x140x70
Allowance for connecting items (cables, cooling hoses ect.)	2kg	N/A	N/A	N/A
Total Weight	16.32kg (17kg)			

Table 3: Enclosure components and details. *Cooling plate uses same mounting points and bolts as motor controller.

Mounting the Integra enclosure is relatively simple, with the feet shown below extending 5mm from the underside. Flange mountings and feet are also available for purchase.

Figure 3: Integra waterproof enclosure, internal of enclosure on left and base to the right. Note, the feet of the enclosure sitting proud of base in the second image.

Other components

Due to the size restriction of the access hatch, the purchased Integra enclosure is the largest possible size. Unfortunately, there is not sufficient room for all components which require waterproofing inside this box. These components will be installed in additional waterproof boxes and mounted in the ski.

The additional components are a part of the drive circuit. On the positive potential side from the battery to the controller are the main isolator, 600A high rupture current fuse and contactor one; on the negative side are contactor two and battery monitoring shunt. Details on these components are given below.

Component	Weight	No. of Fastening Points	Size of Fastening Points
Isolator	0.3kg	2	8mm
Main Fuse	0.5kg	2	5mm
Contactor x2	0.3kg(each)	2	5mm
Battery monitoring shunt	0.1kg	2	5mm
Allowance for connecting items (cables, cooling hoses ect.)	0.5kg	N/A	N/A
Total Weight	2kg		

Table 4: Additional drive circuit components

The majority of these components can be mounted anywhere in the ski with the exception of the isolator, which must be mounted in an accessible hatch close to the drivers position. Ideally they would be located in positions which minimise the cable length.

Material Review and Selection

Material Properties

As mentioned in the literature review, there are three main material options for the mounting bracket. These are aluminium alloys, stainless steel and high strength plastics. Plastic was eliminated due to poor facture toughness and relatively high cost for the strength required. The material options selected for use in the support structure were 6060 –T5 extruded sections / 5083-H321 sheet or 316 stainless steel. These materials are recommended for use in corrosive environments, are readily available and workable (AS 1799.1 – 2009, AS 1799.5 -1991 & AS 1734 - 1997). The Integra waterproof enclosure which was already purchased is made from polycarbonate. The material properties of these materials are outlined below.

Material	Ultimate Strength MPa	Yield Strength MPa	Density g/cm^3	Elastic Modulus GPa
6060 – T5 temper aluminium (extruded sections)	150	110	2.7	69.5
5083 - H321 temper aluminium (sheet)	305	215	2.66	71
316 stainless steel	520	205	8	193
316 A4-70 stainless steel bolts	700	450	8	193
Polycarbonate	62	N/A	1.2	2.35

Table 5: Basic material properties of potential materials. (AS 1866, AS 1734, AS 4673, ASM International 1995 & Schaefer-Peters 2009)

Due to an earlier failed design for the battery box, large amounts for aluminium I-beams and 3mm sheets were available for use, with the sheets being 5083 grade and the extruded I-beams being 6060-T5 grade (Hildebrand 2014 & Jayamanna 2013). However, the use of aluminium raised the issue of galvanic corrosion. Aluminium being higher on the galvanic series than stainless steels would act as the anode in a galvanic couple and corrode quicker than otherwise might be expected due to the large surface area of stainless steel in the motor and motor mounts (Kaufman 2005). This is easily resolved by isolating the stainless steel from the aluminium by separating them with an insulating material.

Fatigue Properties

To ensure that the design is able to meet the >1000hr design life specified in the design requirements the fatigue strengths for the materials must be identified. The values identified in this section are for laboratory tests and conditions; as such, they will be used as a guide and will be modified to better reflect the application.

Aluminium

From the ASM Handbooks a wealth of information is available on the fatigue and fracture characteristics of aluminium alloys. The alloys which will be investigated are 5083 – H321 for the mounting plate and 6060 – T5 for the vertical members. In general, the ASM handbooks state that;

'… 5XXX and 6XXX alloys offer medium-to-relatively high strength, good corrosion resistance, and are generally so tough that fracture toughness is rarely a design consideration.' (Bucci et. al. 1996, Characteristics of Aluminium Alloy Classes)

This is reinforced by the 50 x10^7 fatigue limit of the 5083 – H321 alloy being 160MPa, 50% of the ultimate strength; based on laboratory tests, shown in Appendix 2 (Bucci et.al. 1996). Unfortunately there is no data available for 6060 alloys in the ASM handbook. The fatigue limit can be estimated using the graph shown in Appendix 2, of the general relationship between tensile strength and fatigue strength. This gives a fatigue strength of between 40 and 110 MPa (Bucci et.al. 1996). For simplicity the 0.5:1 strength ratio from 5083 alloy will be used, giving a fatigue strength of 75MPa for the 6060 – T5 alloy.

Stress corrosion cracking (SCC) is a concern in the fatigue life, as it can accelerate and cause cracking to initiate where it would normally not occur, when the material is exposed to a corrosive environment, as in the REVski (Bucci et.al. 1996). The ASM Handbook states that the 5000 series of alloys are resistant to SCC, but increase in susceptibility with higher magnesium content and at elevated temperatures (Bucci 1996). As the 5083 alloys have an Mg content of 4.5%, some adjustment needs to be made to the fatigue strength in the REVski (AS 1734 – 1997). The 6000 series of alloys are less prone to stress corrosion cracking, with the ASM handbook stating, '*The service record of 6XXX alloys shows no reported cases of SCC'* (Bucci 1996, Alloy Selection for SCC Resistance). In extremely corrosive laboratory environments, cracking has been demonstrated in particularly high alloy content alloys (Bucci 1996). As such, the effects of stress corrosion cracking must be accounted for in the fatigue analysis, though the impact on the materials fatigue strength will be minimal.

Stainless Steel

As with the aluminium alloys, a wealth of information on stainless steels fatigue properties is available in the ASM handbooks (Lampman 1996). However, this information is on the fracture toughness and notch sensitivity of the material. While fracture mechanics is a more rigorous and accurate approach to fatigue analysis, in the context of the REVski with a short operating life and operating loads far lower than the maximum load, this level of rigour is not necessary. As such, the endurance limit of 316 stainless steel was sourced from the International Nickel Company databooks and gives an endurance limit of 39'000ksi or

268MPa (INCO Databooks 1963). The same fatigue strength will be used for the bolts and standard material as data could not be found for the A4-70 grade bolt specifically.

Stress corrosion crack is also an issue for Stainless steels, with 316 being one of the more susceptible alloys of stainless (Grubb et. al. 2005). Stainless steel bolts are particularly susceptible due to the continued tension in the members. As the environment in which the materials will operate within cannot be changed and the stress cannot be removed, a reduction factor for the endurance limit will be applied and an inspection and maintenance schedule will be required.

Polycarbonate

From the data available in the ASM Handbooks in 'Fracture of Plastics', *Failure Analysis and Prevention*, polycarbonate failure is typically attributed to ductile, tensile failure, including creep (ASM International 2002). Creep is typically an issue when stress is applied for extended periods of time, such as a load bearing member, but is not such an issue in short transient load situations, as in the ski (ASM International 2002). Creep is usually visible to inspection through stress whitening, discolouration of the material as it stretches. In cyclic loading situations it is possible for crazing to develop in PC, though it is more typical in brittle materials. ASM Handbooks give an indication of the limiting stress at room temperature shown in Appendix 2. This gives a limit for 1'000-10'000 hours of 30-35MPa (ASM International 2002). As such, this will be the limit for fatigue strength of the polycarbonate, however this could be somewhat exceeded as the onset and propagation of crazing and creep is easily viable to inspection (ASM International 2002).

Material	Fatigue Strength Identified
Aluminium 5083 – H321 plate	160 MPa
Aluminium 6060 – T5 extrusions	75 MPa
Stainless Steel (Both 316 and 316 A4-70)	270 MPa
Polycarbonate	30-35MPa

Figure 4: Selected fatigue strength of materials identified for use

Design

Initial Design

Taking these factors into consideration, the initial design for the controller enclosure mount was similar to Clarks' 2013. Utilising the motor mounts proper, a stainless steel frame was to be made over the motor. A frame to fit around the enclosure was to be the main structure, with braced members going down to the motor mounts, fitting onto the motors mounting plates.

Stainless steel was selected for its superior strength, as the design was to be just a frame, using aluminium may have compromised the safety of the structure. After consulting with our industry representative, Brett Manners from TMT, this design was scrapped, due to the high price, fabrication difficulty and complexity of the design.

Full Re-design

Brett Manners, our industry advisor from TMT, encouraged the use of the available aluminium and suggested the possibility of utilising the fasteners already in place on the motor. Checking the technical drawings for the motor, it was found that these fasteners compress an O-ring seal on each end of the motor. They are tapped into the walls of the motor, providing strong fastening points.

Utilising the fastening points on the motor would give the enclosure mounting a strong fastening to the ski. From these a bridge over the motor had to be designed, consisting of vertical risers at each end and a mounting plate for the enclosure to fasten too. Assessing the available materials, it was proposed that the C-section extrusions be used for the verticals and the 3mm plate be used for the bridging structure. To improve the rigidity of the plate, a second layer was added, to be adhered to the underside of the plate at each end. This created a double thickness between the plate fastenings to the vertical members and the fastening points on the underside of the enclosure, where the major load zone is most likely to be. To assist the enclosure in resisting shearing on the plate plane; the feet of the enclosure were to be keyed into the plate.

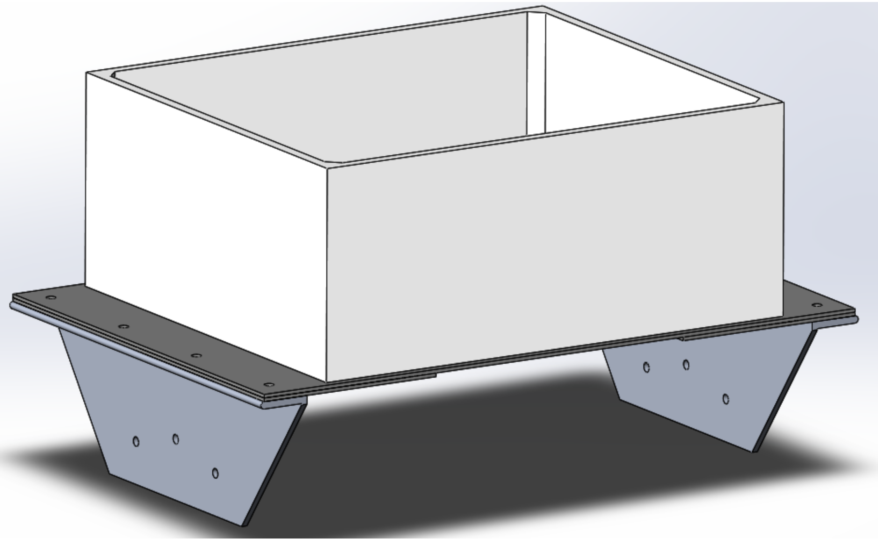

Figure 5: Assembled mounting

The major advantages of this design were that the materials are available for free and that the cutting required can be done with basic power tools. This makes the mounting essentially free, with the only cost the opportunity cost of the materials being used in another project. However, in this design, the contactors and fuse waterproof enclosures were to be mounted in bow of the ski, as simple mounting solutions existed in that location.

Final Design

Unfortunately, it became clear as the project progressed that additional components would be required to be positioned onto the mounting surface, as other options were found to unviable. This required a redesign of the above system. Two options existed for this; the first being a stiffened extension to the above system and the second being a new plate design.

New Requirements

The new mounting system would be required to meet all current requirements listed earlier in the document as well as the following additional requirements.

- Mounting and waterproofing of:
    - Contactors 1 and 2
    - Main fuse
    - Battery monitoring shunt
- Allow as much room as possible should any other systems be required in the area.

The weight of these additional components totalled 2kg, bringing the total component weight to 19kg.

Extension design

The first option was to extend on the original design and construct an extension for this system. This would have left the Integra enclosure in the same position and added an extension towards the aft of the ski, adding the required space.

This design would have been stiffened by right-angle section attached along the edges of the two plates. This would have reduced the extension plate's tendency to bounce or flap up and down as the ski was in use. The plate itself would be fabricated from the available 3mm aluminium plate. This would allow the plate to be constructed extremely cheaply.

The benefits of this design is the minimum of reworking required, reducing time wastage and uses the available material. It would also allow easier access to the motor and shaft than the full plate design which follows, by allowing partial disassembly for maintenance. However, the disadvantages to this design is the more complex nature, longer cable lengths and difficulties attaching the stiffening members flush to the plate and vertical members.

Full plate design

The full plate design would entail the fabrication of an entirely new plate, purchased and cut by a third party, and mount this too the same vertical members as the previous design. To maximise the utility of this design, the enclosure would be moved towards the back of the ski, minimising the length of cable required by positioning the additional components between the batteries and controller, where they are situated in the circuit. The bolts fastening the mounting plate to the verticals would be countersunk to allow components to sit over the top of them, maximising the available space.

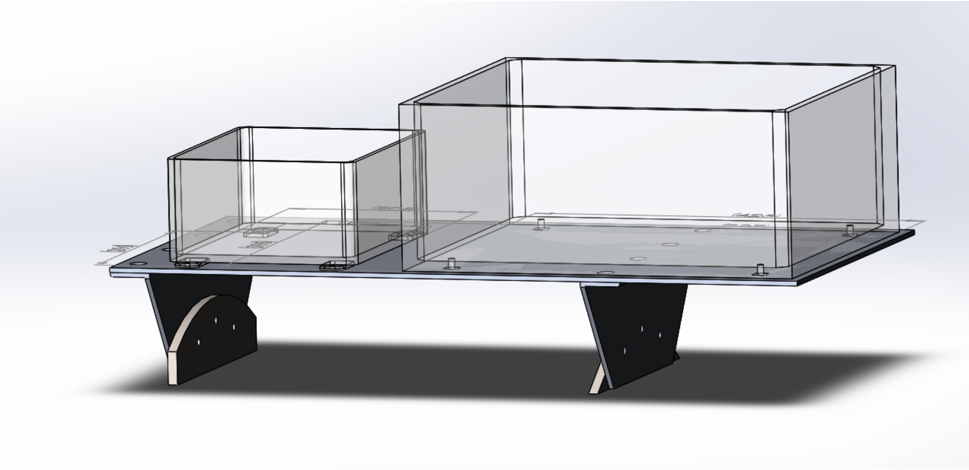

Figure 6: Final Design assembly, front of ski to the left of the image.

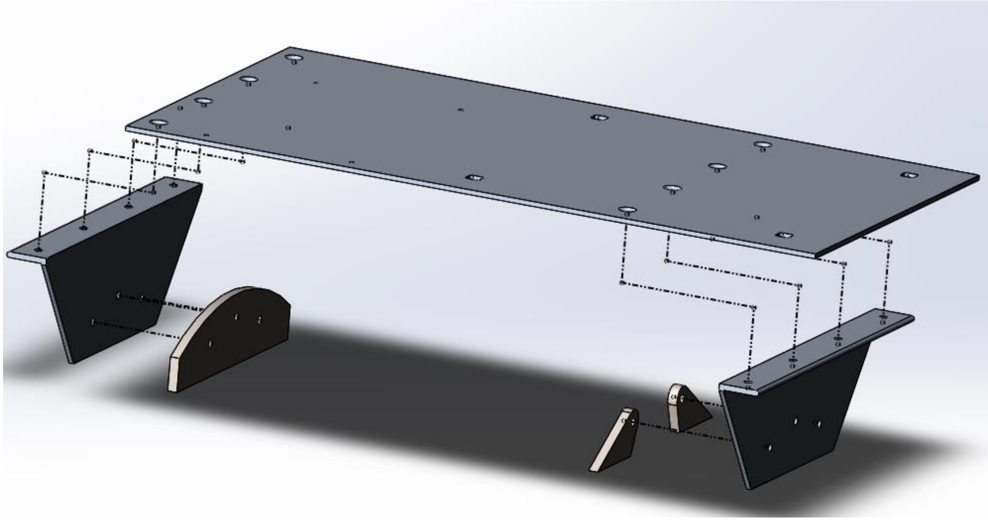

Figure 7: Final Design exploded view of mounting structure. Note, the small components to the bottom of the design are the representation of the mounting points on the motor.

To allow for the countersinking of the M8 bolts, the plate would have to be a minimum of 5mm thick as this is the depth of the countersinking. This also strengthens the plate a great deal over 3mm plate, reducing the flapping of the structure, but increases the total weight.

The benefits of this design are that it maximises the available space inside the ski, as it is larger than the extension design, and removes the interference between the components and fasteners. It also likely to be stronger than the previous design, simpler to fabricate and install and will have a greater aesthetic appeal. However, it is heavier and more expensive than the previous design, uses less of the available materials and severely restricts access to the area below the plate, making any work on the shaft or motor difficult and time consuming.

Selection

As both designs meet all of the applicable design requirements prior to testing, the comparative benefits and weaknesses of the designs were examined to select the superior of the two.

Due to the greater available space and minimisation of cable length, a major factor in the efficiency and range of the ski, the full plate design was selected for construction.

Strength Testing

From selection, the design was strength tested to ensure that it was able to withstand a single instance of the crash accelerations outlined in NCOP14, as well as the additional 15g impact from below. These accelerations and the force generated by the structure in each event is given in Appendix 3. Testing was conducted whenever a significant design change was made.

Due to the indeterminacy of the structure with fixed supports at each end and complex interactions between components, it was decided that utilising computer simulations would be the least erroneous option to test the strength of the system. The Simulation Toolbox in the Solidworks® software program was selected due to its simplicity, ease of use and the author's familiarity with the package. To simulate the accelerations, the equivalent reaction forces were applied to the structure, with the mounting points modelled as fixed points. This should result in an accurate representation of the deformation and stresses experienced as the structure will be able to deflect in a more natural way. This reaction force will be applied to the structure in a static simulation and the stress on the various components determined by the program and interpreted. While this is a simplification of the system, as it does not account for dynamic effects of the acceleration event, it is an effective method of checking the system for like likelihood of failure and will be sufficient to meet the requirements of the NCOP14 and those self-imposed should the majority of the members remain below yield. The structure is accurately represented in the simulation model, with the only simplifications made being the shortening of the plastic enclosures to reduce the computation time.

The details of each test are available in Appendix 3. The highest stress of any of these tests was found in the front impact or aft acceleration test. This is a sensible result as it is the highest of the single acceleration tests and will result in the most bending in the vertical members where the highest stress is found.

Aluminium results

The yield strength of the 6060 aluminium is 110Mpa with an ultimate strength of 150Mpa. A review of the results of the simulation, focusing on the Aluminium is shown below.

Acceleration Direction	Maximum Von Misers Stress	Minimum Safety Factor Al structures	Maximum Stress Location Description and Interpretation
Aft (Front Impact)	150MPa	< 1	The maximum stress is highly localised just above the bolt and washers. This is a sensible result as the bending in the vertical member will be resisted by the bolts and stress concentrations will result.

Table 6: Highest stress result from simulations and interpretation

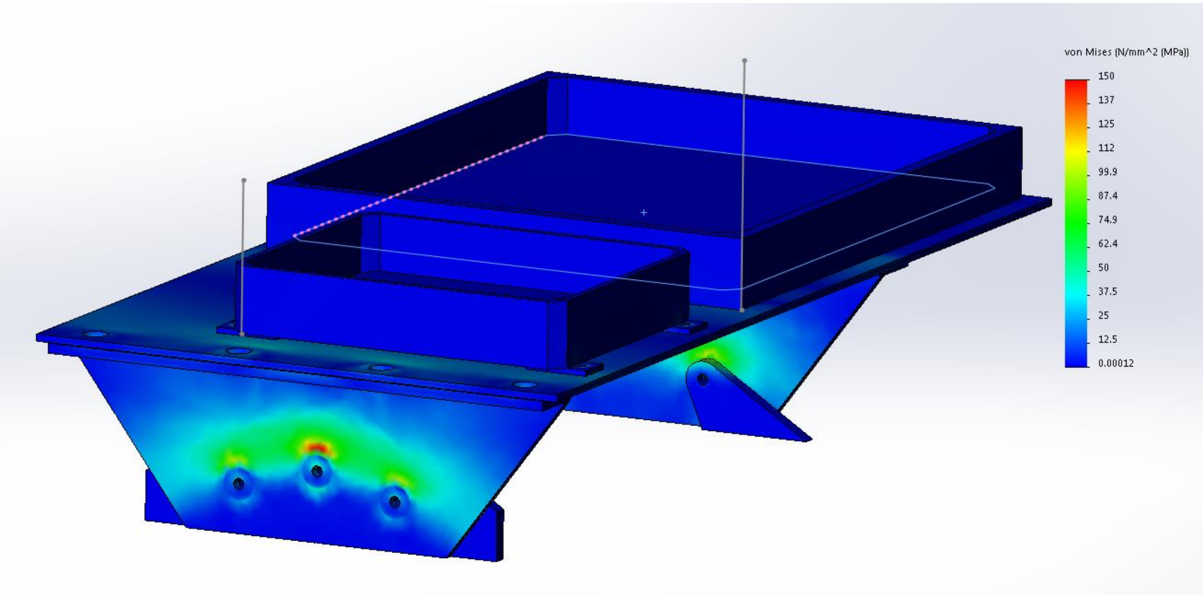

Figure 8: Von Misers stress distribution of the design undergoing highest stress test. Note, maximum stress is 150MPa shown in red.

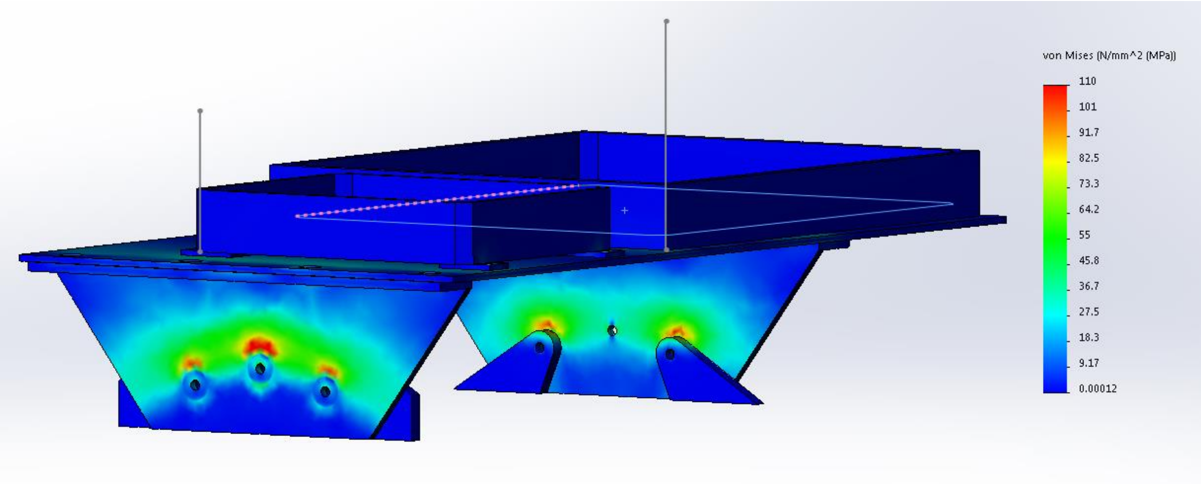

Figure 9: Von Misers stress distribution of design undergoing highest stress test. Red highlighting any area over the yield strength of the material. Note large areas of vertical members below 70MPa suggesting localised but not total yield.

While the major stress concentrations are at or approaching the ultimate strength of the 6060 aluminium, the vast cross-section of the vertical members is well below the yield strength of the material. The stresses in the plate are well below the yield of the 5083 grade aluminium and have not been shown. This result suggests that while the structure is likely to permanently deform in the vertical members under this acceleration event, the structure is extremely unlikely to break away from the mounts. As the structure must only survive one instance of the extreme accelerations, this was deemed to be acceptable, though not ideal.

Stainless Steel Fasteners Results

The fasteners must also be checked for failure. The Solidworks® Simulation outputs the forces which the bolts experience as part of the simulation. Using the specifications provided by a stainless steel fastener manufacturer, the bolts were pre-tensioned to their respective values in the simulation (Schaefer-Peters 2009). From the simulations, the highest forces applied to the bolts was also during front impact acceleration, with the results outlined below.

Bolt Size	Maximum Tensile Force from Simulation	Maximum Shear Force from Simulation	Von Misers Stress	Safety factor to Yield
M5	3135 N	285 N	223.7 MPa	2
¼ in	5396 N	507 N	272.5 MPa	1.65
M8	11186 N	1348 N	310 MPa	1.5

Table 7: Resultant bolt forces and calculated values from highest stress simulation

With high safety factors for yield, the bolts are extremely unlikely to fail and well within the requirements of the mounting system.

Polycarbonate Enclosure Results

The large Integra enclosure and the smaller enclosure used in the final system are both made from polycarbonate. The ultimate strength of polycarbonate is 62MPa, this was checked against the results from the simulations and is shown below.

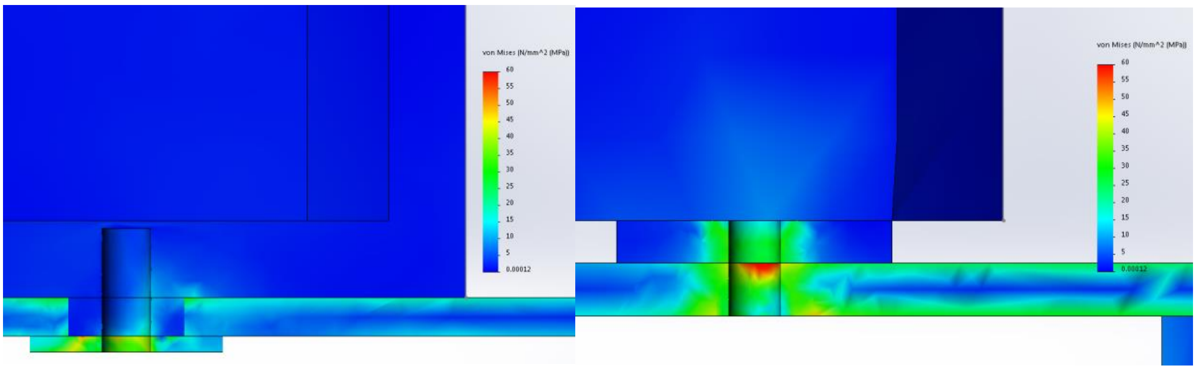

Figure 10: Von Misers stress in mounting points of plastic enclosures, large enclosure on the left and smaller enclosure on the right. Note scale set to maximum of 60MPa and stress in plastic below 40MPa.

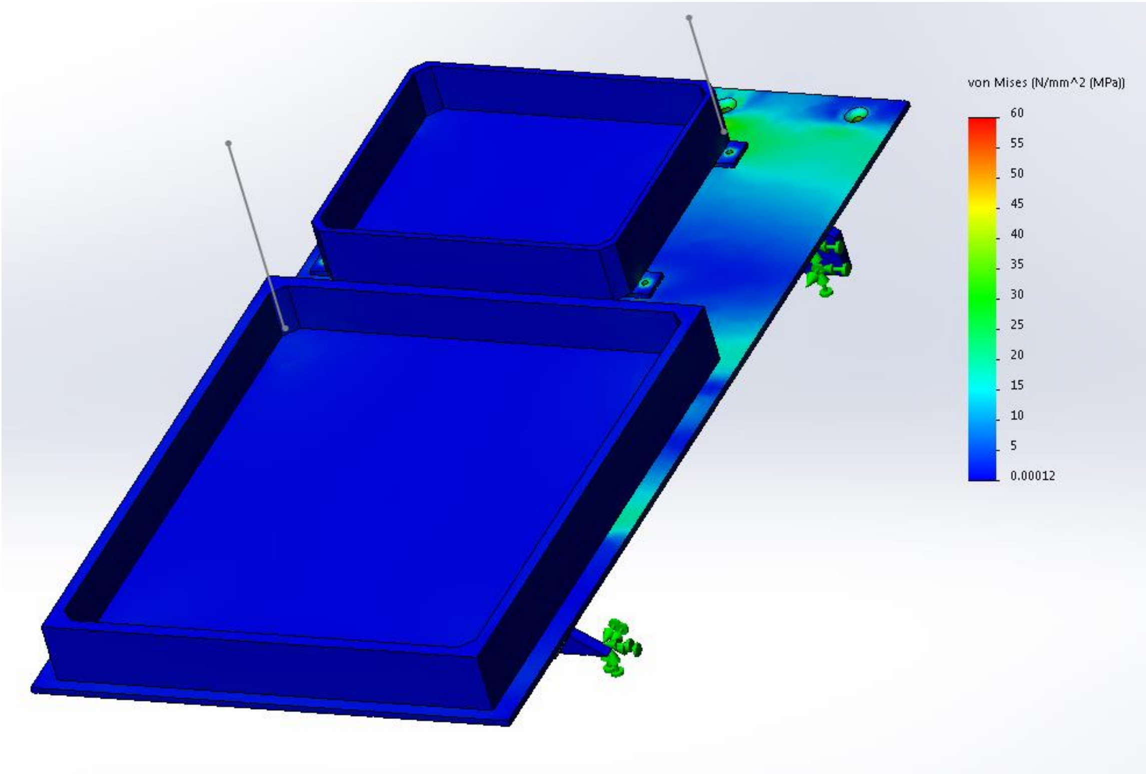

Figure 11: Von Misers stress in structure with scale set to 60MPa maximum. Note very low stress in plastic components.

The stresses exhibited in the plastics by the simulation are surprisingly low, with most of the stress indicated likely due to the bolts. As most of the forces were applied to inside the enclosures, as in the real situation, this force needed to be transferred to the plate by the feet. This is not being reflected by an associated high stress, though there is an indication of higher stress on one side of the large enclosure feet as would be expected. This result may be explained by the comparatively low elastic modulus allowing the plastic to deform without building stress concentrations. As this is the best approximation available and it is indicating a healthy safety margin before failure, the plastic was found to meet the design requirement.

From these simulations, all structures were found to meet the design requirements; though the safety margin on the vertical members is lower than desired.

Fatigue Analysis

To insure that the selected design would be serviceable for the required 1000hrs of operation, the structure was subject to a basic fatigue analysis.

Material	Fatigue Strength Identified
Aluminium 5083 – H321 plate	160 MPa
Aluminium 6060 – T5 Vertical members	75 MPa
Stainless Steel 316 Bolts	270 MPa
Polycarbonate Plastic Enclosures	30 – 35 MPa

Table 8: Fatigue endurance limits identified

These values will firstly be adjusted to better reflect the true situation using the Marin Correction Factors (Budynas & Nisbett 2015). This correction method multiplies correction factors, such surface finish, size and loading factors, to the laboratory test results identified in the material review. These adjusted values will then be used in conjunction with the simulation results to find the Modified Goodman fatigue safety factor (Budynas & Nisbett 2015).

$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{n}$ (Modified Goodman Criterion) - (1)

Where:

$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$ - (2)

$\sigma_a = \frac{|\sigma_{max} - \sigma_{min}|}{2}$ - (3)

S_e = Fatigue Endurance Strength

S_{ut} = Ultimate Material Strength

n = safety factor

The Marin correction factor calculations are detailed in Appendix 4; these corrections result in new fatigue strengths given in the table below.

Material	Adjusted Fatigue Strength
Aluminium 5083 – H321 plate	94 MPa
Aluminium 6060 – T5 Vertical members	50 MPa
Stainless Steel 316 Bolts	130 MPa
Polycarbonate Plastic Enclosures	28 MPa

Table 9: Adjusted fatigue strength limits using the Marin Correction factors.

With the corrected fatigue limits identified, the maximum and minimum stress in the components had to be calculated. Simulations were again used to simulate the stress conditions for the components, this time under the normal operating accelerations identified in the literature review and the minimum stress condition of only gravity.

The results of these simulations are given in Appendix 4, with the highest stress resulting from the vertically upwards and aft accelerations or an impact from the front and from beneath, similar to ploughing into a wave. This will also be the most frequent acceleration event. The simulation results for the highest typical stresses and the minimum stress condition are shown below.

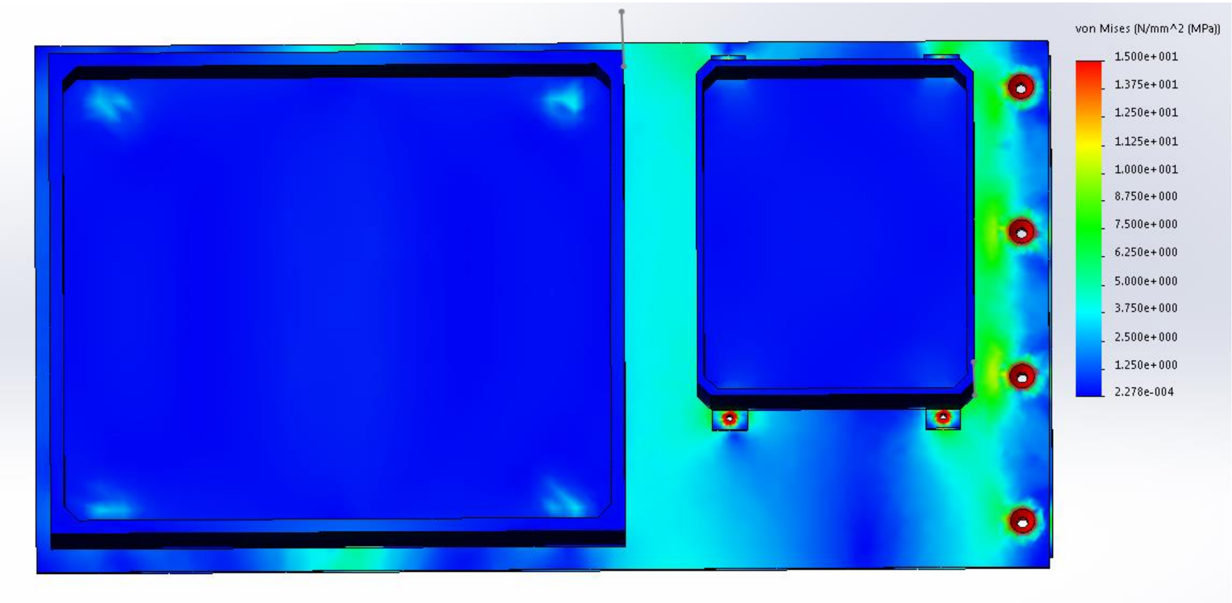

Figure 12: Highest stress typical load condition. Note, maximum of scale set to 15MPa.

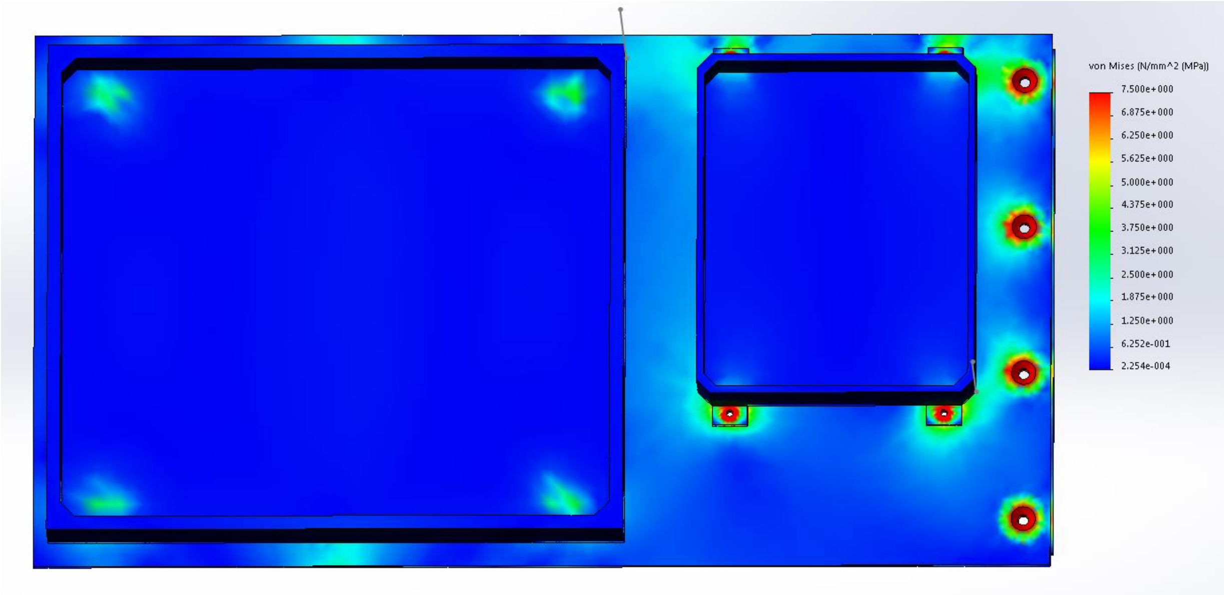

Figure 13: Minimum load condition of gravity force. Note, maximum of scale set to 7.5MPa.

From the simulation results, the maximum and minimum stress in each material can be identified and the modified Goodman safety factor can be calculated. Note that the high stress concentrations under the fasteners will be ignored, as they represent a compressive clamping force and will not affect fatigue.

Material	σ_{max}	σ_{min}	σ_a	σ_m	Safety factor
Aluminium 5083 – H321 plate	10MPa	3MPa	3.5MPa	6.5MPa	17
Aluminium 6060 – T5 Vertical members	8MPa	2MPa	3MPa	5MPa	10
Stainless Steel 316 Bolts	276 MPa	273MPa	1.5MPa	274.5MPa	2.5
Polycarbonate Plastic Enclosures	6MPa	4MPa	1MPa	5MPa	8

Table 10: Fatigue analysis results

From the safety factors calculated, the structure is highly likely to be safe from fatigue under typical load conditions indefinitely, exceeding the requirements of the structure. To ensure the ongoing service of the structure and to guard against corrosion effects on the fatigue life, an inspection regime is outlined in Appendix 5.

Installation

Fabrication

The vertical members were cut into shape from the extruded C-section available. These were drilled to align with the motor end cap bolts and to fasten to the horizontal mounting plate. The new design required purchasing the 5mm plate, cutting to size and drilling the fastening holes. Robert Cameron was able to supply and cut the plate for around $50. The fastening holes were drilled and de-burred to align with the vertical members and the top surface was countersunk to allow the fasteners to sit flush with the mounting surface. To allow the large Integra enclosure to sit flush with the mounting surface, the small feet were keyed into the mounting surface by cutting appropriately sized holes through the plate; as shown in the image below. This allows the large enclosure to have much greater clamping friction on the mounting surface as well as allowing the feet to assist shear resistance and also stiffening the plate.

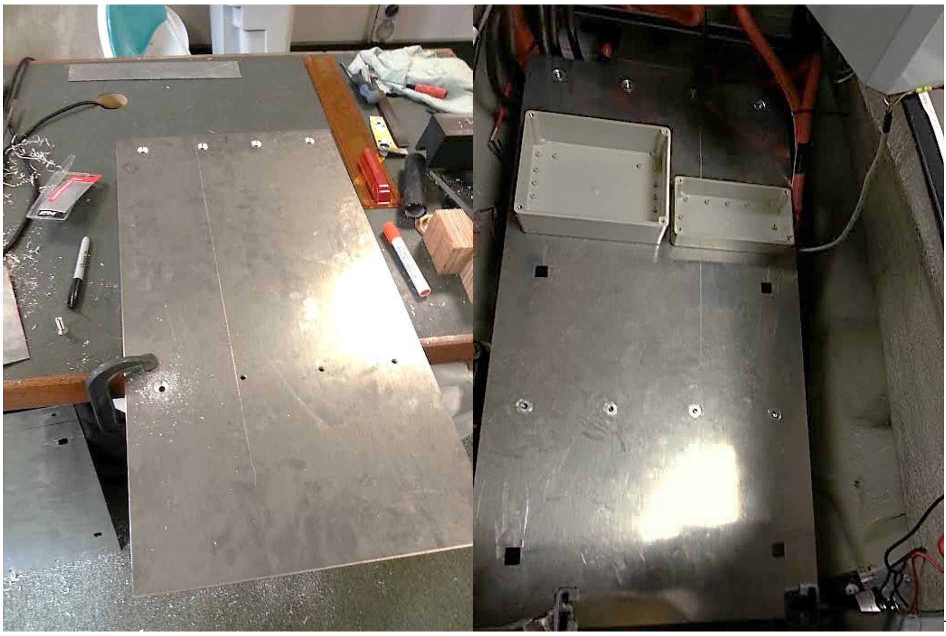

Figure 14: Mounting plate fabrication showing counter sinking on left and the system installed with keying for the large enclosure visible on the right. Note, the two small enclosures shown is not the final layout

Marine grade stainless steel fasteners were sourced from Searle Fasteners. The vertical members used M8 hex-head bolts into the motor and the mounting surface used M8 threaded countersunk cap-screws. Nuts, spring washers and flat washers were also sourced from Searle Fasteners.

Mounting Structure Installation

The mounting structure was simple to install by design. The vertical members were bolted into place on the end faces of the motor. Thin rubber sheets were installed between the stainless steel motor and aluminium structure to limit the potential for galvanic corrosion by isolating the major surface areas. The mounting surface was installed onto the verticals with the countersunk bolts. The large Integra enclosure was then attached onto the plate using the previously cut keyholes and fastened from below. For the additional components, several iterations of the component layout and enclosure requirements was necessary, with the final enclosure selected was a single 250x200x130mm enclosure rated to IP65 ingress protection. As this was a significant design change and load redistribution, the testing simulations were changed to reflect this. While this enclosure is less than ideal, as the ingress protection is lower than would be preferred and the introduction of a heightened short circuit risk; it was the best option available at the time. This box was mounted using the matching mounting feet, fastened down with 5mm bolts. Loctite was applied to all bolts to lower the chance of them coming loose and also limiting the chance of galling occurring between the bolts and thread.

Component Installation

Motor controller and DC-DC Installation

The internal layout of the large Integra enclosure was dependent upon the interaction between the DC-DC converter and the Curtis motor controller. These two components could only be located in two configurations, with only one providing adequate access to the components, shown in the model below.

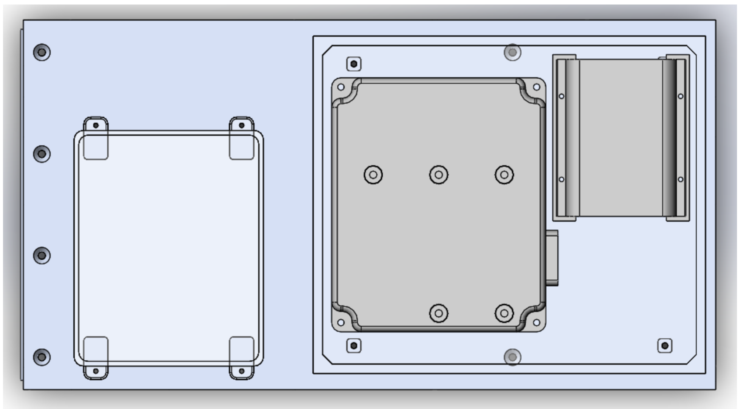

Figure 15: Mock-up of component layout in the large enclosure and general layout of mounting surface for the final design

This allowed cable access to all controller and DC-DC connections as well as giving room for a junction box for the controller data cables. As can be seen in the image below, IP68 cable glands seal the cable entrances these require significant room outside the enclosure but are compact internally. The final layout of the Integra enclosure is shown below.

Figure 16: Final Integra enclosure layout

Additional Component Installation

Initially, the components were to be installed in separate boxes. This would allow for the positive 96v potential and the ground potential to be completely separate and ensure a very low risk of short circuit, particularly if only one box was opened at a time. However, this proved unfeasible as the cable glands take up significant room and the cable could not bend between the components and between the boxes, despite being incredibly flexible. This resulted in the adoption of a single larger box, which would enclose all of the additional components, shown below.

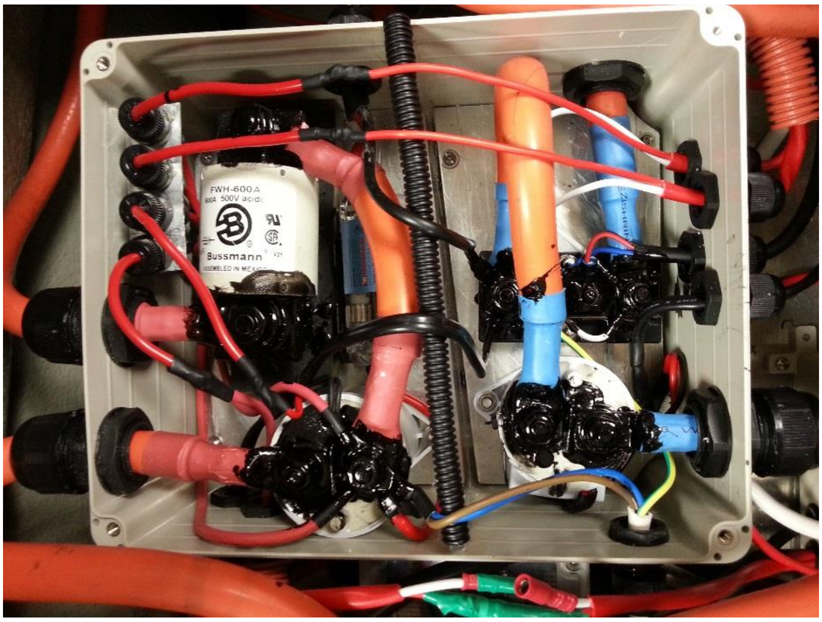

Figure 17: Additional components in their final installation. Note, waterproof partition between the two potentials, with 96v on the left and ground to the right.

The use of a single box carries an inherent risk, both potentials of the system will be enclosed in this box, as will the main fuse. This means that one terminal in the enclosure will be unfused and the opposite potential will be in the same box. Several steps were taken to reduce the risk of a short circuit, which was identified as having two likely causes, water ingress and dropped tools. Firstly, the two potentials were completely separated by creating a waterproof non-conductive barrier between the components and internal mounting plate. A plastic sheet was cut to size, glued into place and waterproofed. This sheet extends above the seal of the lid and will prevent water bridging the gap in all but the worst incidents. The waterproofing was tested by filling one half of the enclosure with water for an hour and now leaks were found.

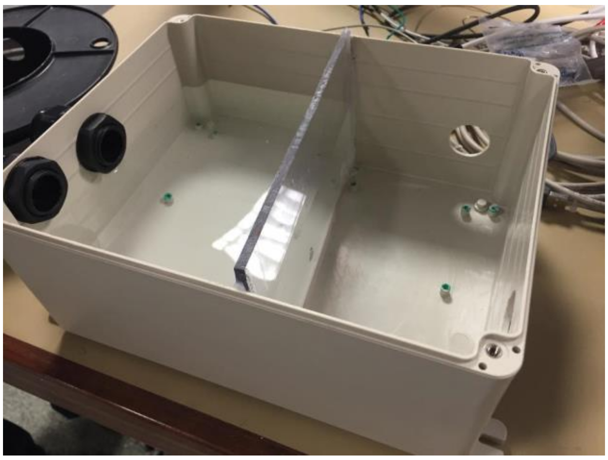

Figure 18: Waterproof testing of small enclosure partition

This partition also makes it unlikely for a dropped tool to bridge two terminals as one end would be forced to sit up preventing the short circuit. Secondly, all terminals have been heavily painted with a waterproof insulation paint. This reduces the chance of anything coming into contact with live parts and creating a short circuit. Finally, an administrative control in the form of an isolation procedure has been implemented. The system must be isolated before the enclosure can be opened, unless for a specific reason and appropriate controls are in place. With these controls, the risk was deemed to be acceptable, though not ideal by the project team.

Evaluation

This project set out with the aim of building a reliable and cost-effective mounting solution for the key electrical components of the REVski and has successfully completed this goal.

Reviewing the key design parameters of the project;

- The strength requirements of the National Guidelines for Electric Vehicles 2014 have been meet in simulation testing. Ideally, testing to failure of the design would be better however, this is not feasible in the context.
- The fatigue requirements have been exceeded in simulation testing. The significant factors of safety in the fatigue testing ensures the reliability of the structure.
- All components within the scope of the project are securely mounted into the hull, sufficiently protected from water and connected as required.

To ensure ongoing reliability of the system, all components must be regularly inspected for signs of fatigue and for bolt loosening. An inspection regime has been included in Appendix 5.

From this evaluation, the project design requirements identified at the start of the project have all been meet or exceeded by this project and the REVski is now operational and undergoing testing.

Future Work and Recommendations

Future work for this project is for the application of the inspection regime given in Appendix 5. Future work on the REVski is varied and covers several areas, chiefly; moving weight back in the ski as it is currently nose heavy, displaying key information to the original heads up display and de-bugging all electronic components.

The first recommendation from this project is for the content of the smaller enclosure to be separated as originally intended. To do this, components may need to be moved to other parts of the ski and correctly sized and rated enclosures will need to be sourced for the remaining. However, the benefit of this is the removal of the short circuit risk. Secondly, should the opportunity arise, i.e. that the mount needs to be uninstalled for some reason, stronger vertical members could be installed to reduce the possibility of failure. While the members meet the design requirements, low factors of safety exist. Alternatively, physical testing to failure of a replica mount could be conducted to verify the simulations.

Conclusion

With the major milestone of operation accomplished, the evaluation and continuous improvement of the REVski can begin. The ski's performance will be compared to that of a traditional PWC and improvements made on the design to match or exceed a traditional PWC. The major limitation of the REVski, as with all electric vehicles, is current battery technology. This limits the REVski to between 5-30 minutes of operation, depending upon the vigour of operation. While the current battery technology may limit the efficacy of an electric PWC, the near silent operation and zero emissions are a huge benefits, making electric craft uniquely suited to operating in environmentally sensitive environments and where noise restrictions apply. The REVski is an exciting and innovative project pushing the boundaries of what is possible in the electric vehicle industry.

Word Count: 7993

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Appendix 1

IP Code Designations as per AS 60529 -2004

Solid Particles

First Characteristic Numerical	Brief Description (Protected Against)	Definition
0	No protection	No protection against contact and ingress of objects
1	>50mm	The object probe, sphere of 50mm Ø, shall not fully penetrate
2	>12.5mm	The object probe, sphere of 12.5mm Ø, shall not fully penetrate
3	>2.5mm	The object probe, sphere of 2.5mm Ø, shall not fully penetrate
4	>1mm	The object probe, sphere of 1mm Ø, shall not fully penetrate
5	Dust protected	Ingress of dust is not entirely prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of the apparatus or to impair safety
6	Dust tight	No ingress of dust

Fluid Ingress

Second Characteristic Numerical	Brief Description (Protected Against)	Definition
0	No protection	
1	Vertical drops	Dripping water (vertically falling drops) shall have no harmful effect.
2	Vertical drops when enclosure is tilted up to 15˚	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle up to 15° from its normal position.
3	Spraying water	Water falling as a spray at any angle up to 60° from the vertical shall have no harmful effect.
4	Splashing water	Water splashing against the enclosure from any direction shall have no harmful effect.
5	Water jets	Water projected by a nozzle (6.3 mm) against enclosure from any direction shall have no harmful effects.
6	Powerful water jets	Water projected in powerful jets (12.5 mm nozzle) against the enclosure from any direction shall have no harmful effects.
7	Temporary immersion in water	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1 m of submersion)
8	Continuous immersion in water	Ingress of water in quantities causing harmful effects shall not be possible when enclosure is continuously immersed in water under conditions agreed between manufacturer and user, which are more severe than numeral 7.

Appendix 2

Fatigue data

Alloys and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 50 mm (2 in.), %		Fatigue endurance limit[(a)]	
	MPa	ksi	MPa	ksi	1.6 mm ($\frac{1}{16}$ in.) thick specimen	1.3 mm ($\frac{1}{2}$ in.) diam specimen	MPa	ksi
5083-0	290	42	145	21	...	22	160	23
5083-H11	303	44	193	28	...	16	150	22[(e)]
5083-H112	295	43	160	23	...	20	150	22[(e)]
5083-H113	317	46	227	33	...	16	160	23[(e)]
5083-H32	317	46	227	33	...	16	150	22[(e)]
5083-H34	358	52	283	41	...	8	...	...
5083-H321, H116	315	46	230	33	...	16	160	23

(a) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen.

(b) Tempers T361 and T861 were formerly designated T36 and T86, respectively.

(c) Based on 10 cycles using flexural type testing of sheet specimens.

(d) Unpublished Alcoa data.

(e) Data from CDNSWRC-TR619409, 1994, cited below.

(f) T7451, although not previously registered, has appeared in literature and some specifications as T73651.

(g) Sheet flexural. Sources: *Aluminum Standards and Data*, Aluminum Association, and E. Czyryca and M. Vassilaros, *A Compilation of Fatigue Information for Aluminum Alloys*, Naval Ship Research and Development Center, CDNSWC-TR619409, 1994

Figure 19: Excerpt from Table of Typical Tensile Properties and Fatigue Limits of Aluminium Alloys and Table Notes. From 'Selecting Aluminium Alloys to Resist Failure by Fracture - Fatigue Life of Aluminium alloys' (Bucci et.al. 1996)

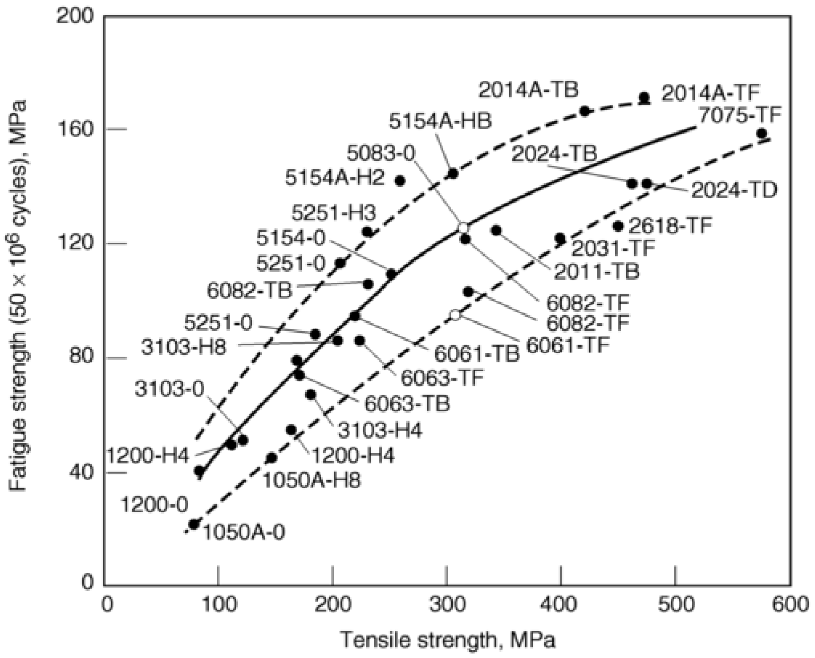


Figure 20: Relationship between the fatigue strength and tensile strength of some wrought aluminium alloys. From 'Selecting Aluminium Alloys to Resist Failure by Fracture - Fatigue Life of Aluminium alloys' (Bucci et.al. 1996)

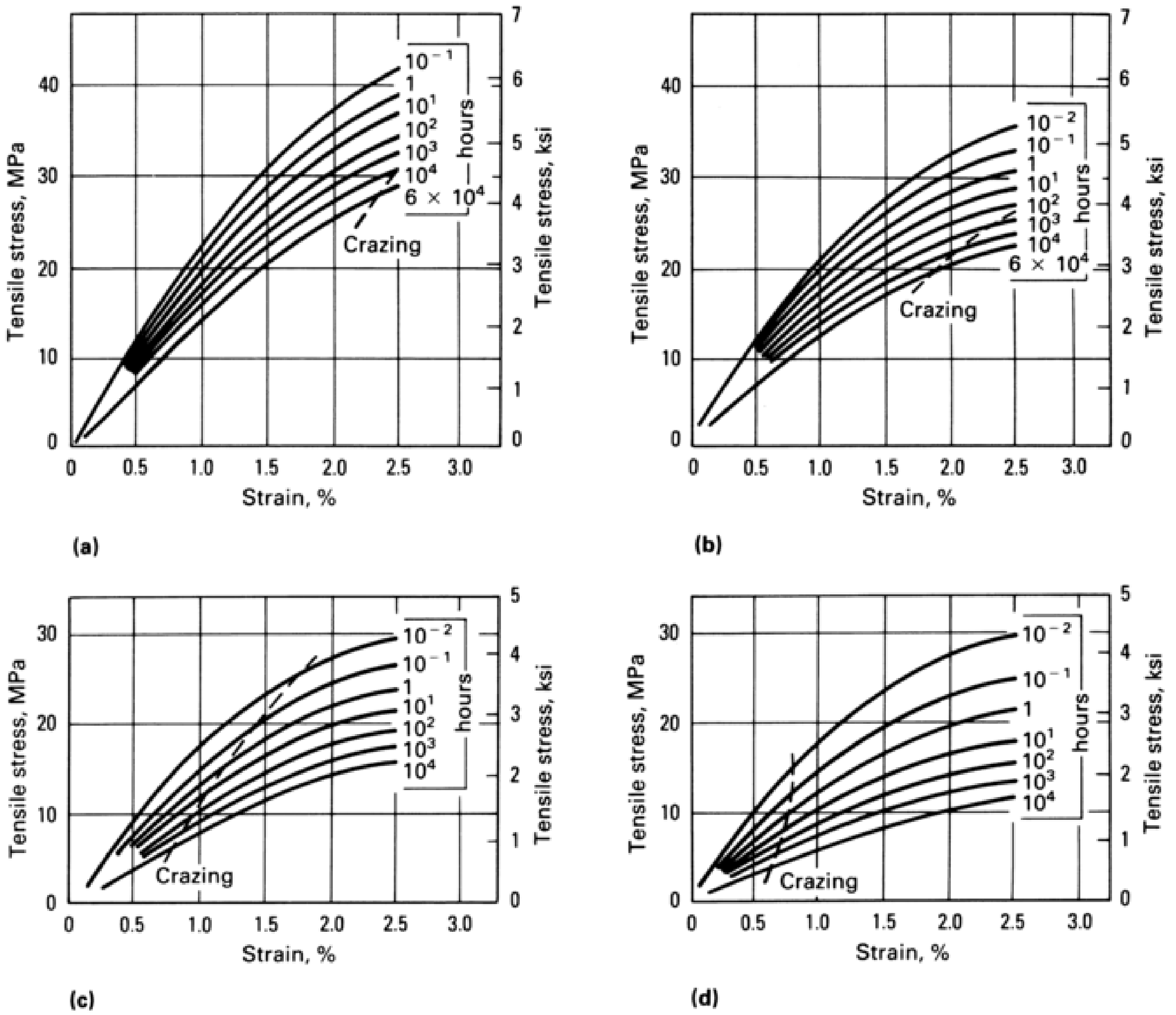


Figure 21: Isochronous plot of polycarbonate stress-strain behaviour as a function of temperature. (a) 23 °C (b) 40 °C (c) 80 °C (d) 100 °C. From 'Fracture of Plastics – Failure Analysis and Prevention' (ASM International 2002)

Appendix 3

Strength test force values

REVski acceleration direction	Acceleration	Equivalent forces		
		Large Enclosure	Small Enclosure	Self-Weight
Acceleration towards aft (front impact)	20g	2950N	400N	1750N
Towards bow (aft impact)	10g	1500N	200N	900N
Transverse (side impact)	15g	2250N	300N	1350N
Vertically down (impact from top/ rollover)	10g	1500N	200N	900N
Vertically upwards (impact from below)	15g	2250N	300N	1350N
Aft and transverse combination	20g aft & 15g side	2950N aft 2250N side	400N aft 300N side	1750N aft 1350N side
Aft and upwards combination	20g aft & 15g below	2950N aft 2250N side	400N aft 300N side	1750N aft 1350N side

Table 11: Strength test force values for simulations

Strength test results

Aft Acceleration (Impact from Front)

Component	**Location**	**Highest stress/force**	
Vertical Members	Bow mount, above bolts where highest bending expected	150MPa	
Mounting Plate	Just behind the bow mount contact area	35MPa	
M8 bolts	Axial: centre bolt to front mount Shear: centre two of front vertical to plate	11186 N axial	1386N shear
¼ in bolts	All very similar	5396 N axial	507 N shear
M5 bolts	All very similar	3135 N axial	285 N shear
Ploy enclosures	Small enclosure, where feet meet box	30-35MPa	

Table 12: Aft acceleration results

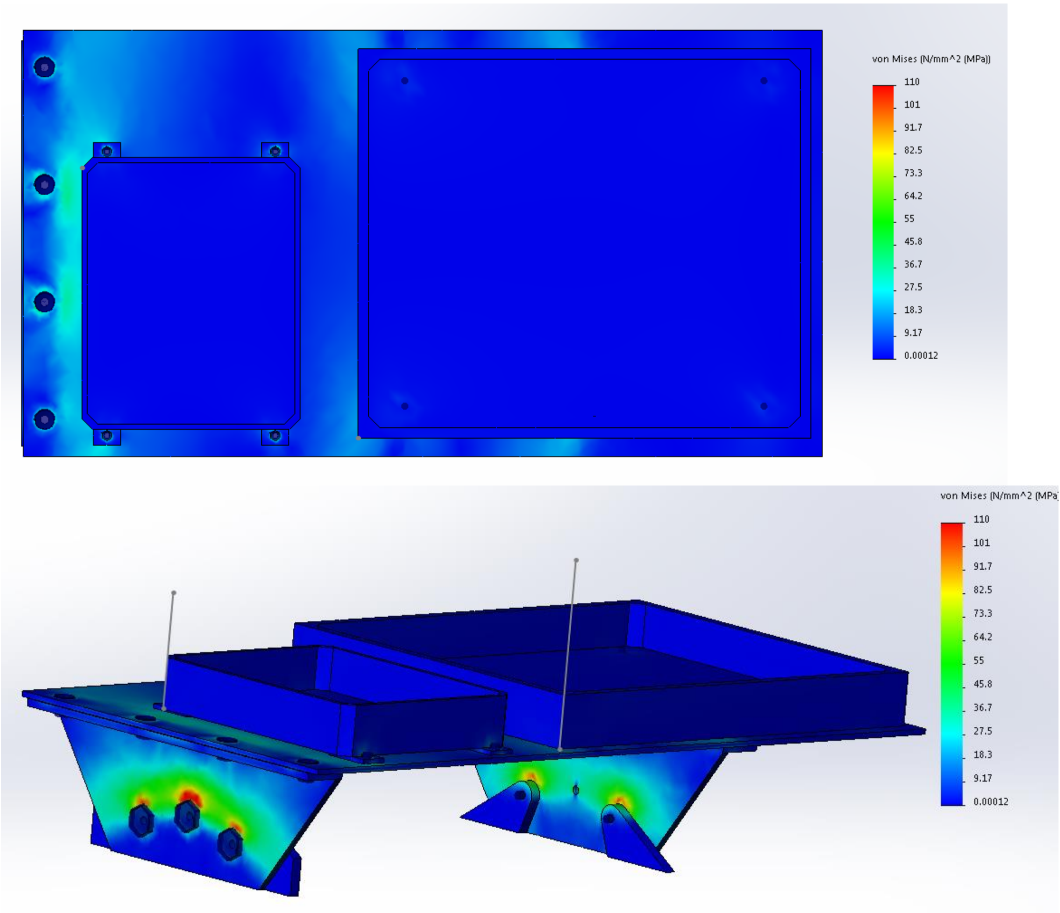


Figure 22: Aft acceleration results

Forward Acceleration (Impact from Rear)

Component	Location	Highest stress/force	
Vertical Members	Bow mount, above bolts where highest bending expected	55MPa	
Mounting Plate	Just behind the bow mount contact area	20MPa	
M8 bolts	Axial: centre bolt to front mount Shear: centre two of front vertical to plate	10126 N axial	762N shear
¼ in bolts	All very similar	5096 N axial	342 N shear
M5 bolts	All very similar	3021 N axial	179 N shear
Ploy enclosures	Small enclosure, where feet meet box	20MPa	

Table 13: Forward acceleration results

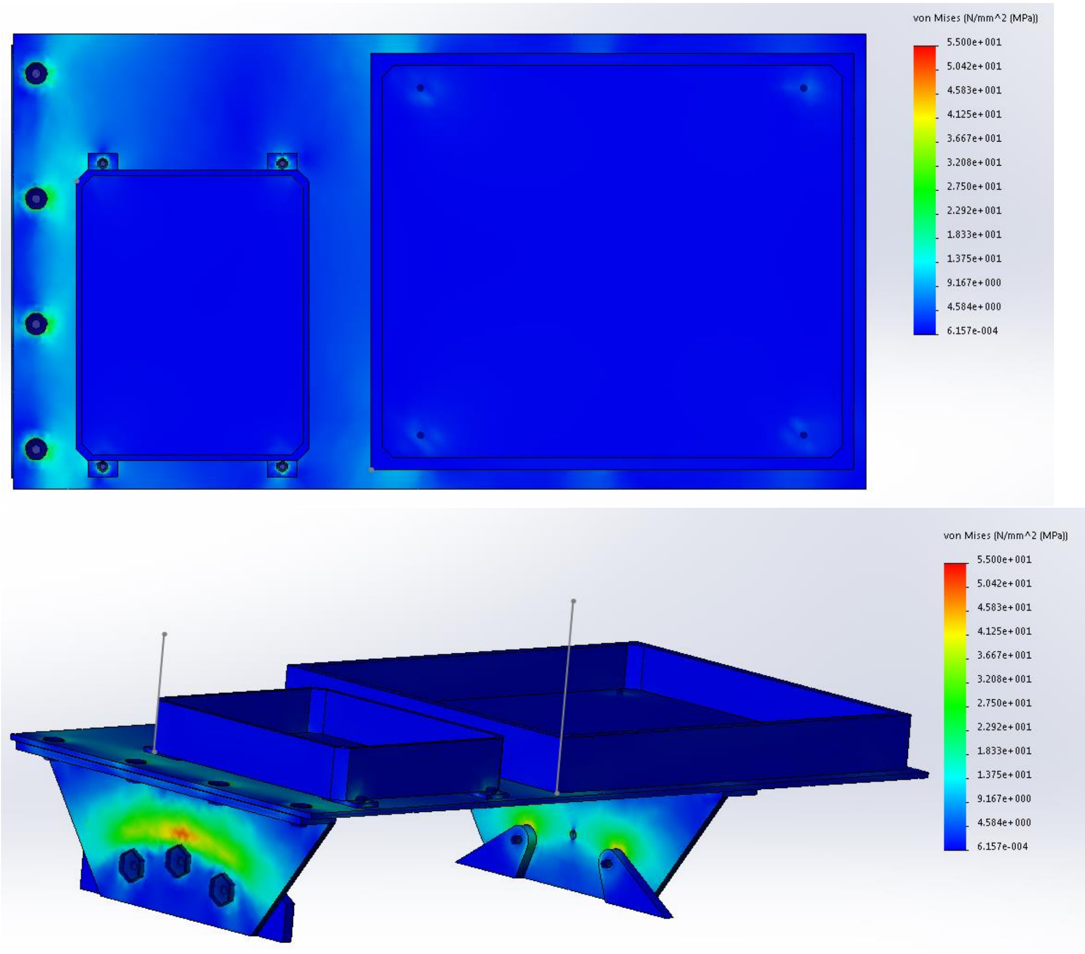


Figure 23: Forward acceleration results

Transverse Acceleration (Impact from Side)

Component	Location	Highest stress/force	
Vertical Members	Bow mount, above bolts where highest bending expected	20MPa	
Mounting Plate	Just behind the bow mount contact area	15MPa	
M8 bolts	Axial: back mount bolts Shear: centre two of back vertical to plate	10917 N axial	952N shear
¼ in bolts	All very similar	5128 N axial	426 N shear
M5 bolts	All very similar	3084 N axial	253 N shear
Ploy enclosures	Small enclosure, where feet meet box	20MPa	

Table 14: Transverse acceleration results

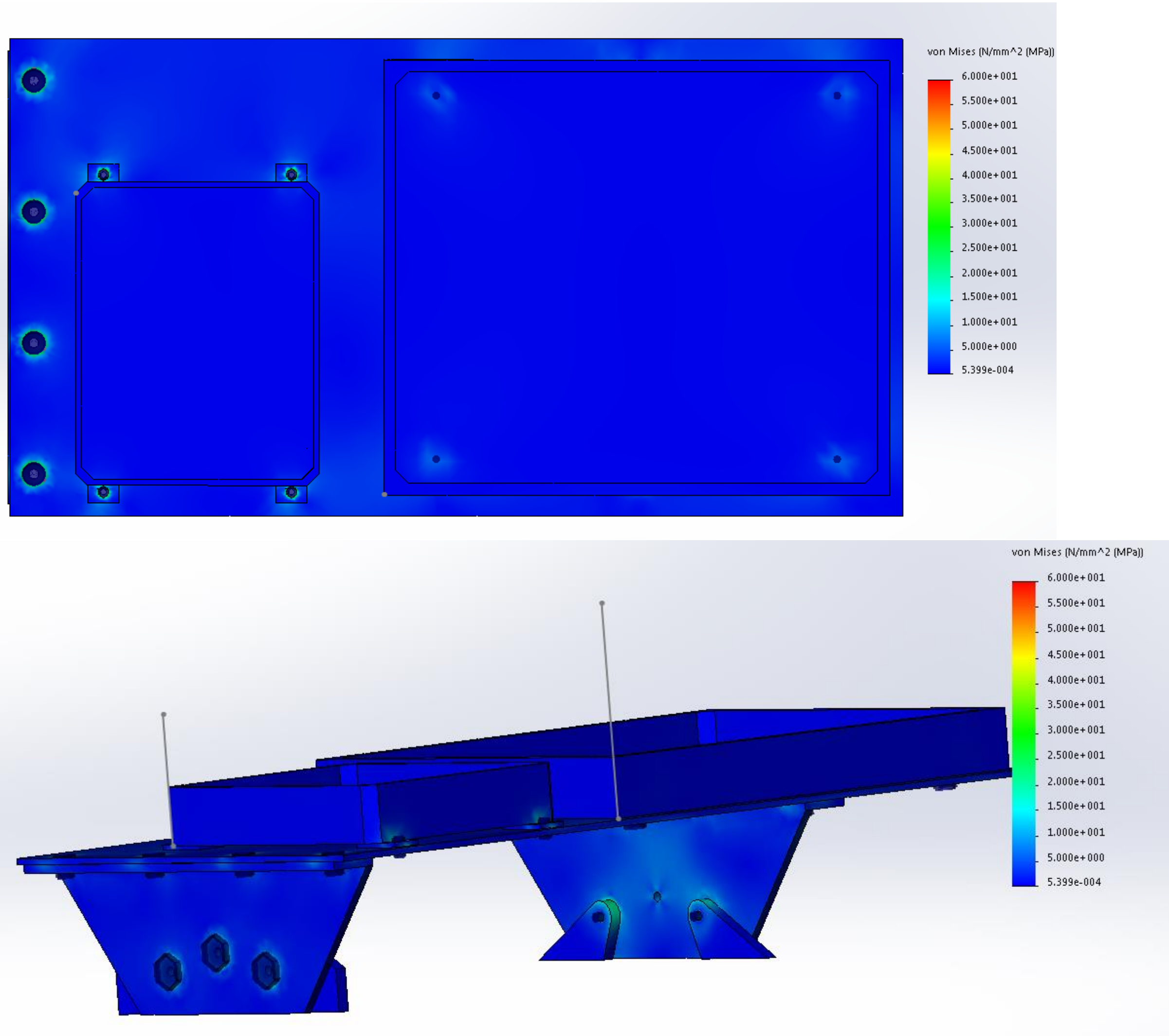


Figure 24: Transverse acceleration results

Vertically Down Acceleration (Impact from Above)

Component	Location	Highest stress/force	
Vertical Members	Bow mount, above bolts where highest bending expected	20MPa	
Mounting Plate	Just behind the bow mount contact area	90MPa	
M8 bolts	Axial: outer two of rear vertical to plate Shear: both rear mounts	10697 N axial	1213N shear
¼ in bolts	All very similar	5228 N axial	56 N shear
M5 bolts	All very similar	3091 N axial	46 N shear
Ploy enclosures	Small enclosure, where feet meet box	25MPa	

Table 15: Vertically down acceleration results

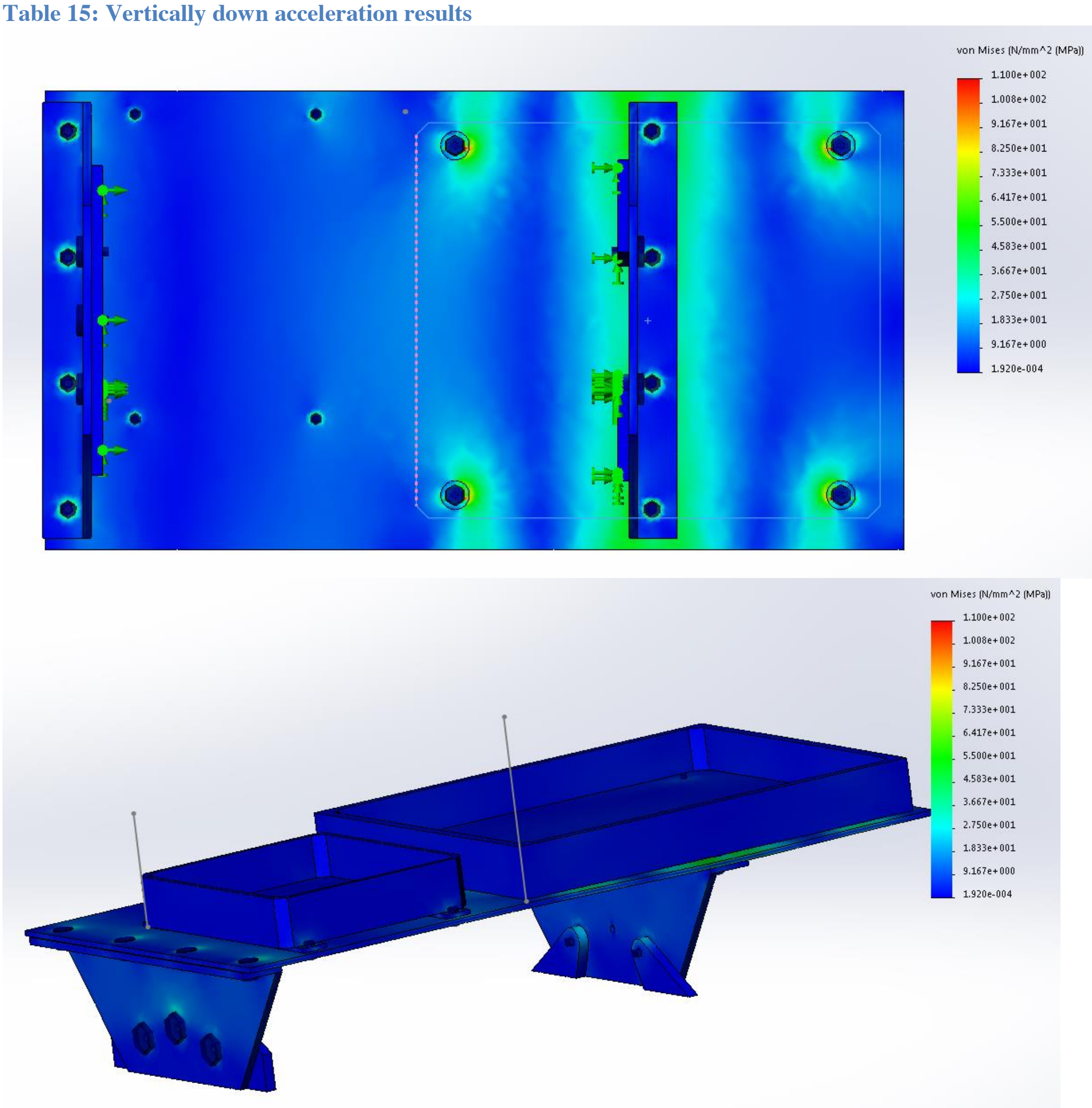


Figure 25: Vertically down acceleration results

Vertically Up Acceleration (Impact from Below)

Component	Location	Highest stress/force	
Vertical Members	Bow mount, above bolts where highest bending expected	20MPa	
Mounting Plate	Just behind the bow mount contact area	35MPa	
M8 bolts	Axial: outer two of rear vertical to plate Shear: both rear mounts	10291 N axial	1283N shear
¼ in bolts	All very similar	5028 N axial	49N shear
M5 bolts	All very similar	3013 N axial	33 N shear
Ploy enclosures	Small enclosure, where feet meet box	20MPa	

Table 16: Vertically up acceleration results

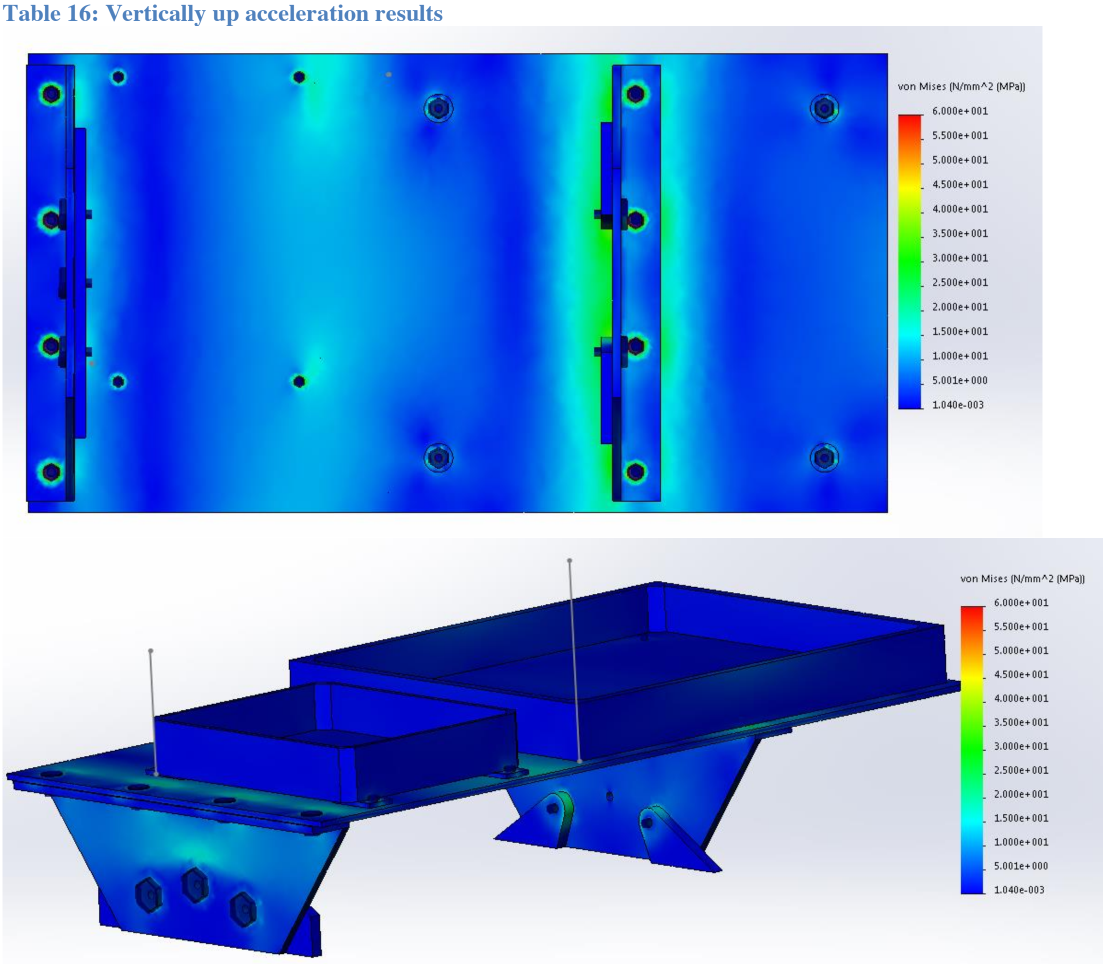


Figure 26: Vertically up acceleration results

Aft and Transverse Combination (Front and Side Impact)

Component	**Location**	**Highest stress/force**	
Vertical Members	Bow mount, above bolts where highest bending expected	140MPa	
Mounting Plate	Just behind the bow mount contact area	40MPa	
M8 bolts	Axial: outer two of rear vertical to plate Shear: both rear mounts	11097 N axial	1296N shear
¼ in bolts	All very similar	5239 N axial	473N shear
M5 bolts	All very similar	3094 N axial	210 N shear
Ploy enclosures	Small enclosure, where feet meet box	20MPa	

Table 17: Aft and transverse combination acceleration results

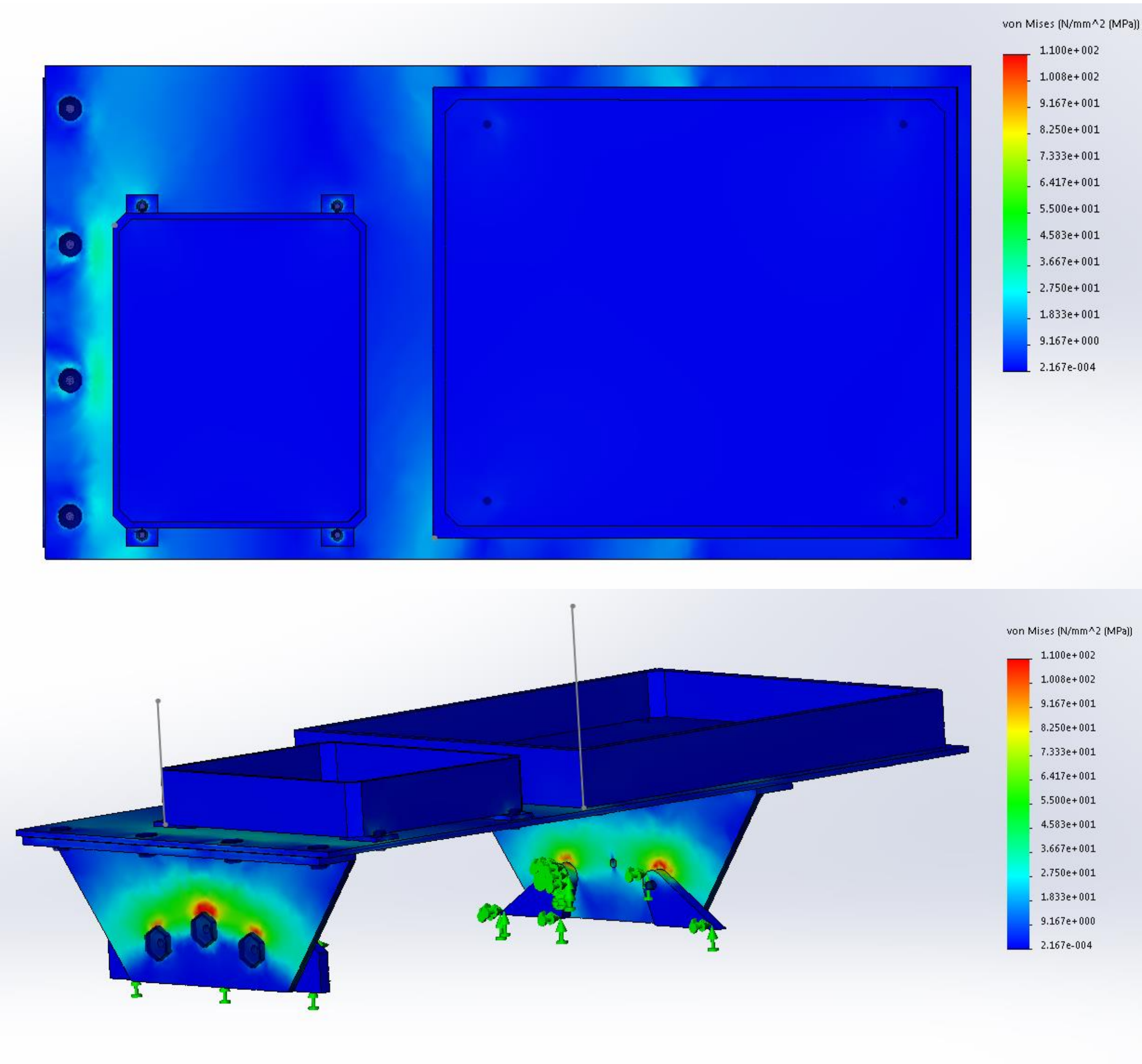
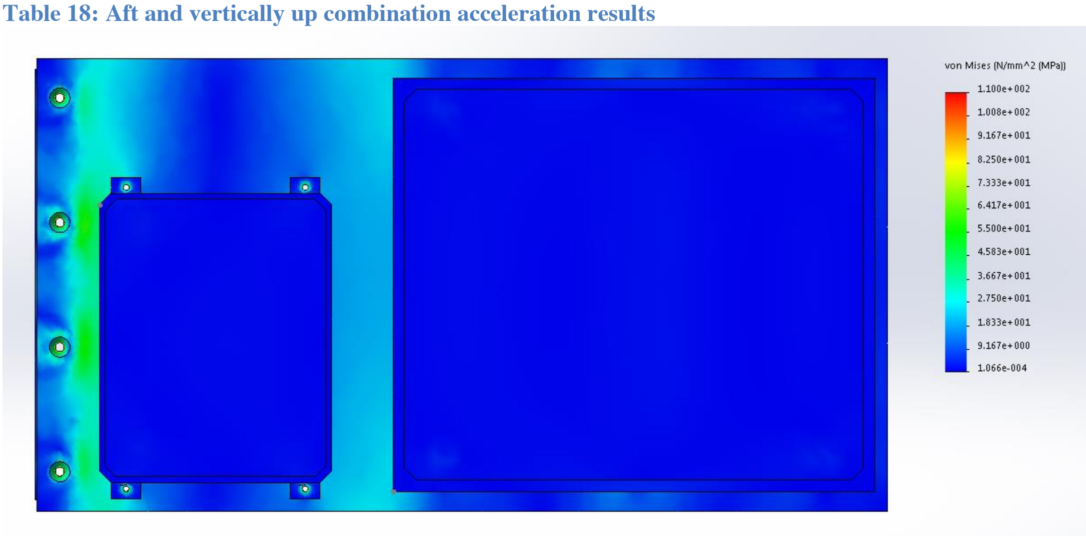


Figure 27 Aft and transverse combination acceleration results

Forward and Up Combination (Front and Below Impact)

Component	Location	Highest stress/force	
Vertical Members	Bow mount, above bolts where highest bending expected	125MPa	
Mounting Plate	Just behind the bow mount contact area	60MPa	
M8 bolts	Axial: outer two of rear vertical to plate Shear: both rear mounts	10825 N axial	1250 N shear
¼ in bolts	All very similar	5259 N axial	332 N shear
M5 bolts	All very similar	3126 N axial	121 N shear
Ploy enclosures	Small enclosure, where feet meet box	35MPa	

Table 18: Aft and vertically up combination acceleration results



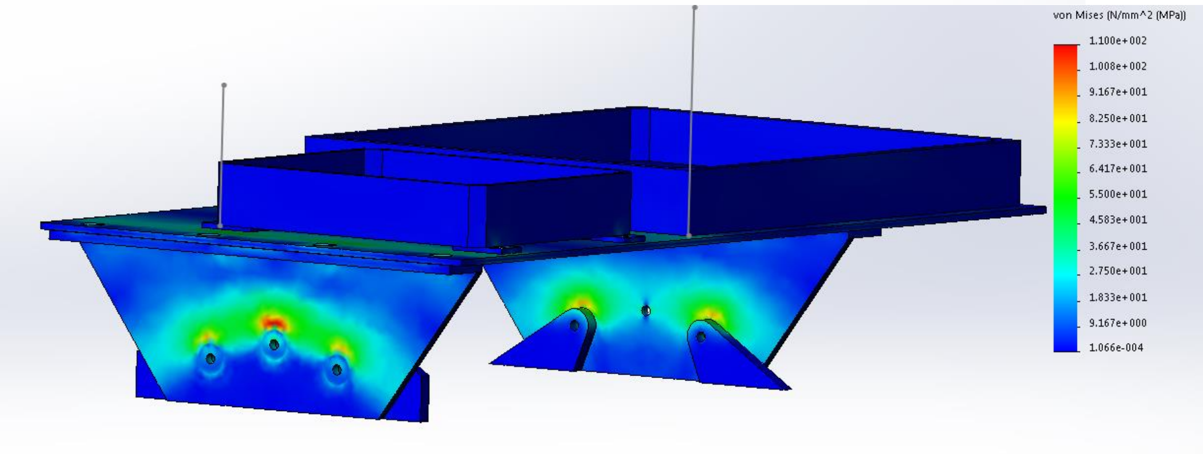


Figure 28: Aft and vertically up combination acceleration results

Appendix 4

Marin corrections

From Shigleys Mechanical Engineering Design (Budynas & Nisbett 2015)

$S_e = k_a k_b k_c k_d k_e k_f S'_e$

Where:

S_e = adjusted fatigue strength/endurance limit

S'_e = test sample fatigue strength/endurance limit

k_a = Surface condition factor

k_b = size modification factor

k_c = load modification factor

k_d = temperature modification factor

k_e = reliability modification factor

k_f = miscellaneous-effects modification factor

Material	**k_a**	**k_b**	**k_c**	**k_d**	**k_e**	**k_f (SCC)**	**S_e**
5083 Al	0.99 (machined)	0.85 (approx.)	1 (Von misers)	1 (room temp)	0.868 (95%)	0.8	94 MPa
6060 Al	1 (machined)	0.85 (approx.)	1 (as above)	1	0.868	0.9	50 MPa
316 SS bolts	0.795 (machined)	1 (mainly axial load)	1 (‘’)	1	0.868	0.7	130 MPa
Ploycarb	1 (ground)	0.9 (approx.)	1 (‘’)	1	0.868	1	28 MPa

Table 19: Marin Correction factors identified and resulting adjusted endurance limits

Fatigue Modelling

The most common and highest stress impacts causing fluctuating loads will be from below, front and sides. These in combination will be modelled, along with the minimum load condition of purely gravity.

REVski acceleration direction	**Acceleration**	**Equivalent forces**		
		Large Enclosure	Small Enclosure	Self-Weight
Minimum Load/ Gravity	1g	150N	20N	90N
Aft and Up (Front and below impact)	2g aft 4.18g up	300N aft 600N below	40N aft 80N below	180N aft 360N below
Transverse and Up (side and below impact)	2.63g side 4.18g up	400N side 600N below	55N side 80N below	240N side 360N below

Minimum Load/ Gravity

Material	Location	Highest Stress
Mounting Plate	Around vertical mounts and between enclosures	3MPa
Vertical members	Areas around and between bolts	2MPa
Stainless Steel 316 Bolts	M8 bolts into mounts	273MPa
Polycarbonate Enclosures	Areas around fasteners	4MPa

Table 20: Minimum stress results

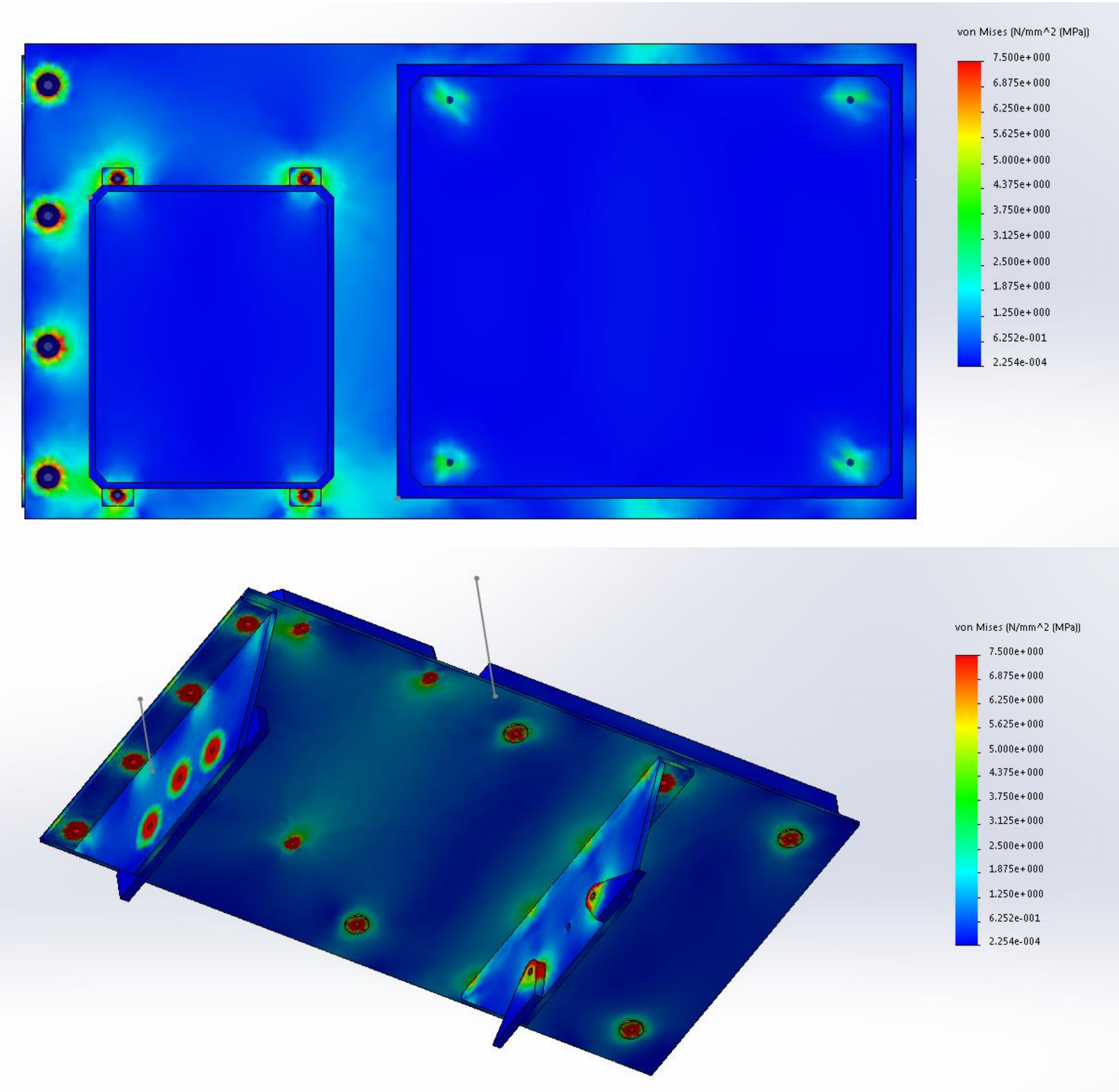
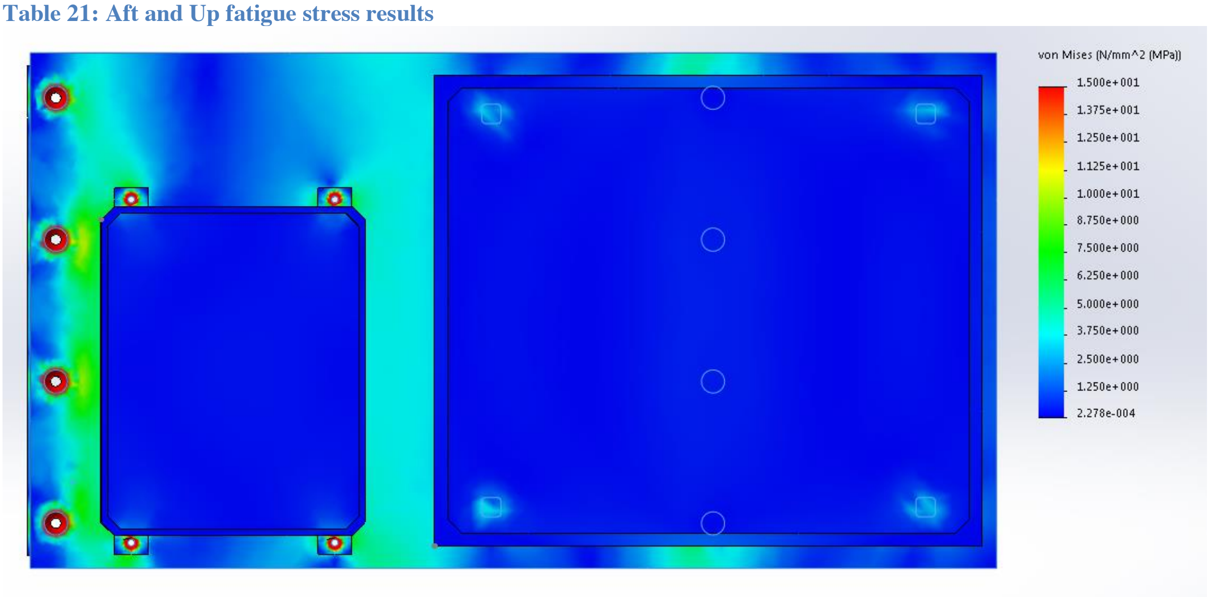


Figure 29: Minimum stress results

Aft and Up Acceleration (Front and below impact)

Material	**Location**	**Highest Stress**
Mounting Plate	Around vertical mounts and between enclosures	10MPa
Vertical members	Above bolts into mounts	8MPa
Stainless Steel 316 Bolts	M8 bolts into mounts	276 MPa
Polycarbonate Enclosures	Junction between feet and box	6MPa

Table 21: Aft and Up fatigue stress results



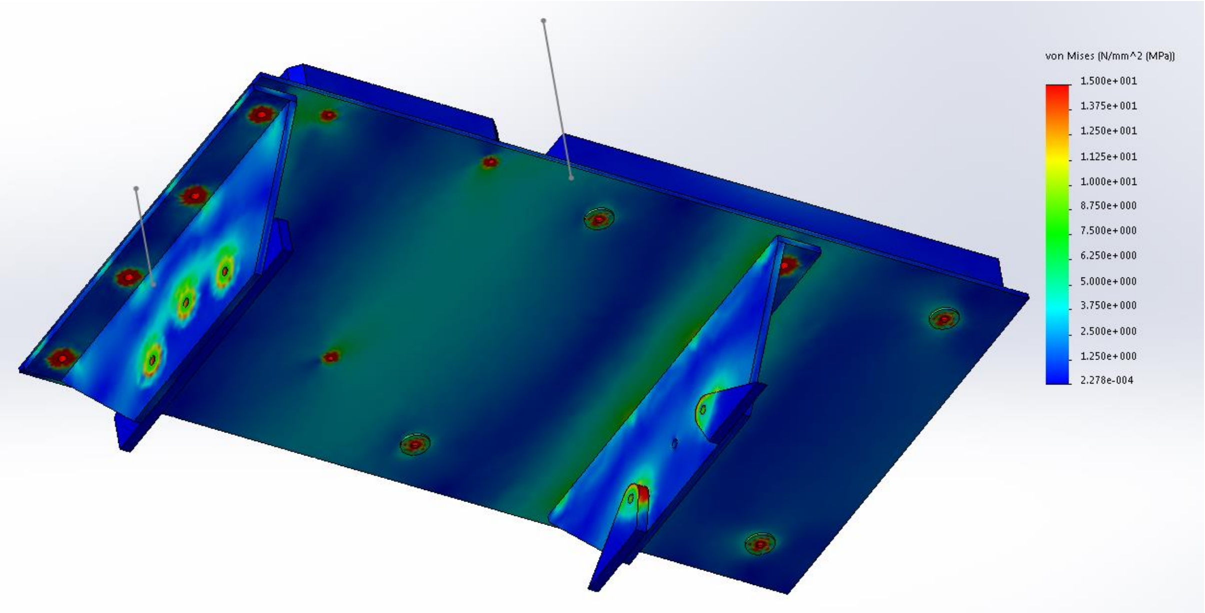
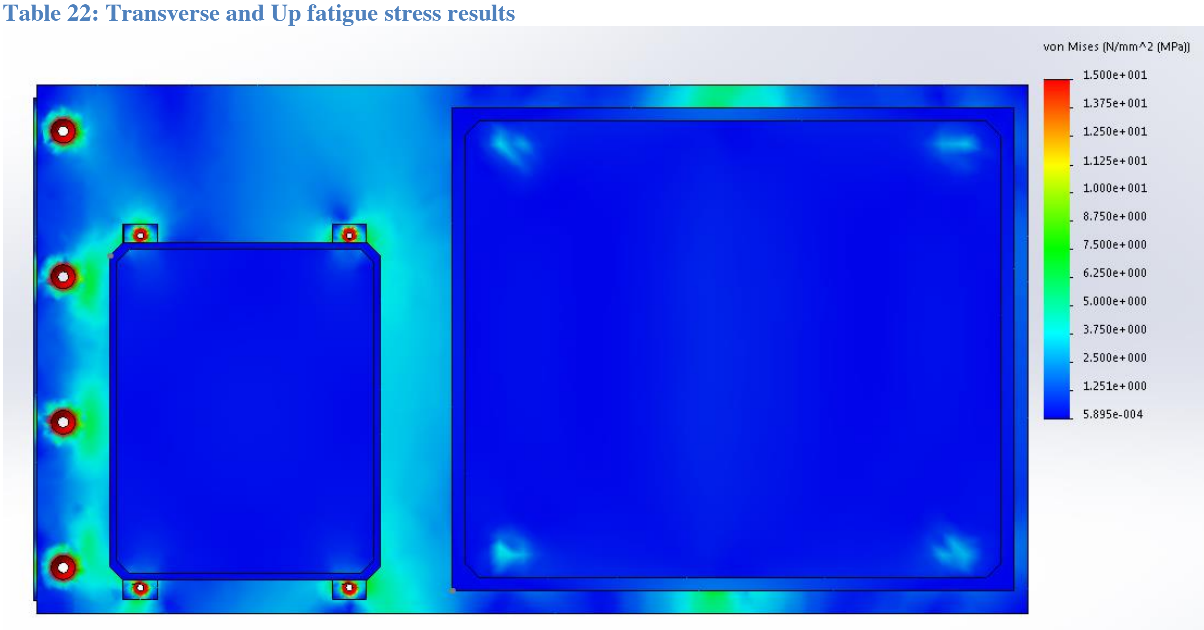


Figure 30: Aft and Up fatigue stress results

Transverse and Up Acceleration (Side and below impact)

Material	**Location**	**Highest Stress**
Mounting Plate	Around vertical mounts and between enclosures	7MPa
Vertical members	Above bolts into mounts	5MPa
Stainless Steel 316 Bolts	M8 bolts into mounts	275 MPa
Polycarbonate Enclosures	Junction between feet and box	6MPa

Table 22: Transverse and Up fatigue stress results



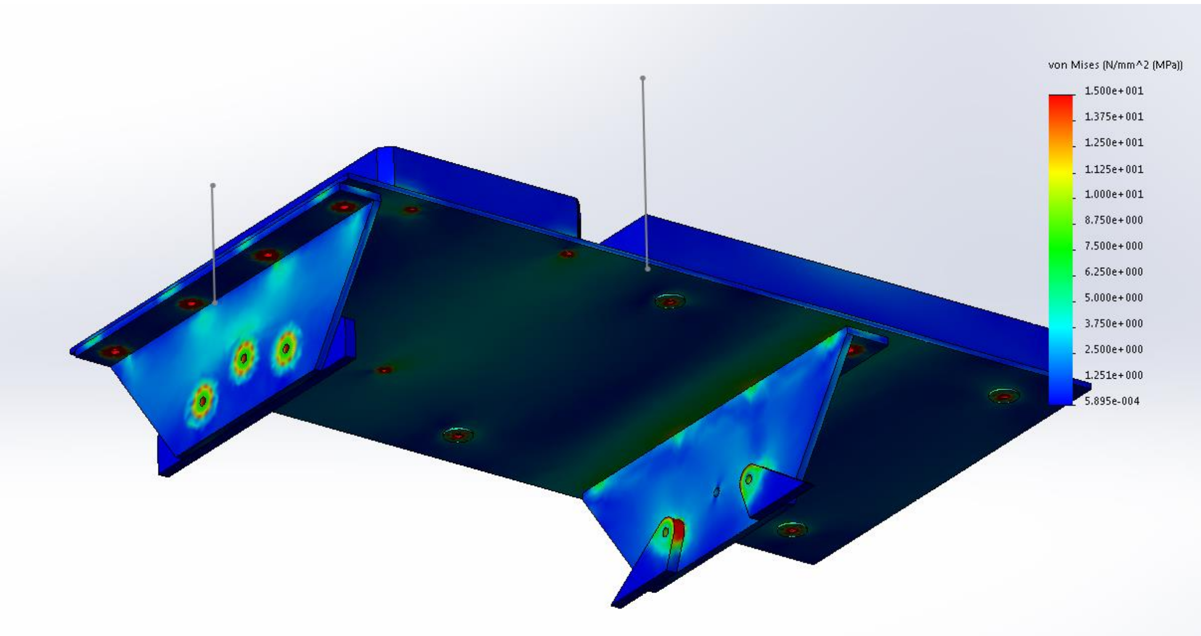


Figure 31: Transverse and Up fatigue stress results

Appendix 5

Maintenance Schedule for Mounting System

Charges are the approximate number of full charge cycles of the REVski. This give a good estimation of the duration and vigour of use, which together cause the damage.

Every 10 charges

- Check tightness of all bolts.
  - Do so by attempting to tighten the bolts gently, try not to break the Loctite
  - If loose, undo nut, reapply Loctite and re-tighten

Every 50 charges

- Check tightness of all bolts.
  - Do so by attempting to tighten the bolts gently, try not to break the Loctite
  - If loose, undo nut, reapply Loctite and re-tighten
- Inspect plastic fastening points
  - Undo and lift out plastic enclosures, leaving wires etc. attached
  - Stress whitening, characterised by a whitened milky appearance in the plastic
  - Crazing, visible as tiny cracks and can be felt to the touch
  - If either present, assess impact, i.e. spread, width, location, and replace plastic components as required.

Every 500 charges

- Inspect enclosures for fatigue
  - Un-fasten and lift out enclosures, leaving wires connected
  - Inspect enclosure bolts for signs of corrosion or fatigue
    - If damage suspected, replace bolt
  - Inspect plastic fastening points
    - Stress whitening, characterised by a whitened milky appearance in the plastic
    - Crazing, visible as tiny cracks and can be felt to the touch
    - If either present, assess impact, i.e. spread, width, location, and replace plastic components as required.
- Remove mounting surface

    - Unfasten and remove mounting surface from vertical members
    - Inspect enclosure bolts for signs of corrosion or fatigue
        - If damage suspected, replace bolt and nut
    - Visually and by touch, inspect mounting surface for any signs of fatigue or corrosion and assess damage if present
- Vertical members
    - Visually and by touch, inspect vertical members for any signs of fatigue or corrosion and assess damage if present
    - Supporting motor, individually remove bolts into motor, inspect enclosure bolts for signs of corrosion or fatigue, reapply Loctite and replace before moving onto next bolt
        - If damage suspected, replace bolt with new
- Reassemble
    - Replace mounting surface and re-fasten, applying Loctite to each bolt
    - Replace and fasten the enclosures, ensuring cables and hoses return to their original positions. Apply Loctite to all bolts.