

MECH 460: Final Report

Team 04C: Exterior Shell on Queen's Super Milage Team

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Executive Summary

The Queen's Supermileage team will be competing in the 2023 Shell eco-marathon regional competition that will be taking place at the Indianapolis Motor Speedway in the United States. Collaborating closely with the Faculty of Applied Science and Engineering and the Department of Mechanical and Materials Engineering to provide members with a supplementary learning for their in-class studies.

The Queen's Supermileage team, or QSM, is a student-run design team that aims to shape the future of fuel consumption. Shell eco-marathon has two separate classes of competition, prototype class and the urban concept class. QSM will be competing in the urban class which allows students to design and build energy efficient vehicles that are closer in appearance to modern passenger cars. The urban concept class will be focusing on "stop and go" driving in which the drivers will be driving at the minimum speed to allow the vehicle to complete the required laps in a designated time. The team who conserves the most fuel will win.

Our team is focusing on the design and build of the exterior shell of the urban concept class vehicle. This exterior shell will include the panels, windows, doors and other small accessories that the exterior of the car may need. This report will focus on the preliminary design strategies, design criteria and design ideas that will be incorporated in the exterior shell of the next years vehicle. By examining the previous proposal report of customer requirements, technical aspects and proposed designs that the exterior shell must exhibit, our group received feedback from the QSM team and faculty members to further improve our design and the next steps to be taken. In this report, finite element analysis is used to further justify our designs and show the effectiveness for the QSM team. There is also an economic analysis to ensure that the parts or designs that our team has chosen is justified and has a clear reason for why it is important for the QSM to have this design in their new concept class vehicle. With a budget of \$7000 CAD, it is vital that our team ensures the designs and ideas are kept well below the required budget to account for inflation, shipping and other fees.

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1.0 Introduction

Shell Eco-marathon is a global energy efficiency program and one of the world's leading student engineering competitions sponsored by Shell. The competition brings together Science, Technology, Engineering and Maths (STEM) students from across the globe to design, build and operate some of the world's most energy-efficient vehicles, all in the name of collaboration and innovation, as students' bright ideas help to shape a lower carbon future for all. Our clients are Katie Cooper-Gray and Savannah Gray, members of Queen's Super Mileage Team, as well as Keith Pilkey who is the Faculty Advisor at MME Capstone project. The exterior shell includes the panels on the exterior of the vehicle, a method for attaching the panels to each other and to the chassis, the windows, doors and their opening mechanisms, the bulkhead, and the floor of the vehicle. The team will be working closely with the chassis design team to design an exterior shell for the Super mileage vehicle that complies with the Shell Eco-marathon Rules [1]. There are two different types of vehicle classes that will compete in two separate races, prototype and urban class. For this competition and design, our team will be focusing on the urban class. The urban concept is where teams are designing for city driving which cars are closer to passenger cars in appearance. These cars are designed and built to cater to human needs such as driving comfort and space for luggage, and to more road-worthy specifications including four wheels and a windscreen wiper. With the added specifications, the harder the challenge becomes to creating an energy efficient design.

2.0 Project Scope

The team intends to design a lightweight, modular exterior shell based on the rules and regulations of the Shell Eco-marathon, and the chassis design for a four-wheel urban concept class. This design will be reliant on client observations and specifications. By the end of the project, the client will receive:

- I. A complete CAD model of the proposed design with selected materials.
- II. Complete Finite Element Analysis (FEA) results under a variety of loading conditions and panel configurations.
- III. An economic analysis or Bill of Materials of the cost of the exterior shell based off the CAD model.
- IV. Material specifications and key dimensions that the client can take to a manufacturer to be finalized.

As engineering students, no CAD or proposed design can be signed to manufacturing without the consent of the client or a certified engineer. This review by a certified engineer and/or manufacturer can finalize the design and deem it safe to be used and manufactured.

3.0 Design Criteria and Functional Specifications

The Shell Eco-Marathon has two classes of competition: prototype and urban concept. The prototype class showcases the pinnacle of efficiency, often at the sacrifice of practicality: seating positions are laying down and the shell is almost shrink-wrapped around the driver, with little more than bicycle wheels connecting the car to the road. The urban concept class, however, puts more of a focus on practicality and usability in everyday contexts, requiring certain amounts of visibility, ease of ingress/egress, and storage space to meet technical inspection. The QSM team competes in this latter class, and thus our team needed to make special considerations for these features when designing our exterior shell. In this class, track speeds in competition do not generally exceed 20 km/h: competitors often go as slow as possible while still completing the minimum required distance

in order to consume as little fuel as possible. Thus, aerodynamic considerations were minimal when designing the bodyshell, as pressure differentials created by laminar and turbulent flow as a result of smaller surface discontinuities (sharp angles, etc.) would be negligible.

The Shell Eco-Marathon technical regulations needed to be judiciously studied and referenced throughout the design process to ensure that the team's solution would pass necessary technical inspection. According to Article 25 d), body panels cannot change shape due to the wind: while aerodynamic considerations for drag reduction purposes were minimal, our team needed to ensure that body panels were appropriately affixed to the body without room to significantly deform. More importantly, according to Article 46 d), the urban concept vehicle requires two 500mm by 800mm doorways for convenient ingress and egress. Furthermore, according to Article 46 h), the vehicle requires a 200mm by 400mm by 500mm compartment for luggage space. This necessitated two things: firstly, panels for these applications had to be rigid enough to be freely attached on only one side (which, eventually, necessitated special preparation procedures for these specific panels); secondly, the hinge mechanisms and attachments our team chose needed to be sturdy enough to reliably allow opening and closing of these large apertures.

According to Article 52 a) and subsequent points in the same section, the vehicle needs to be runnable in wet weather conditions, which had multiple knock-on implications. First, the cabin should reasonably be water-tight to ensure that systems inside the cabin are not damaged: this necessitated consideration of a form of weather stripping between panels in case there were any gaps. Importantly, this would also help prevent excessive amounts of air from entering the cabin and building a high-pressure zone in the rear, causing drag. Secondly, the windscreen and other windows in the vehicle could not fog up (as specified in Article 52 e)): this necessitated a passive ventilation system to ensure circulation of fresh air in particularly humid conditions.

As the chassis for this vehicle is being designed by another MECH460 team concurrently with our design for the body, it is nearly impossible to coordinate the design of one, geometrically static body shell meant to fit one, geometrically static chassis, as there may be many iterations on the exact chassis configuration up until the final construction of the chassis. Thus, our team was tasked with designing a modular, geometry-agnostic body panel and fixture system for the QSM vehicle. Body panel shapes had to be entirely arbitrary when considering attachment points, while still creating a system where panels can fit together with a degree of seamlessness. The QSM team indicated to us early on that they prioritized smaller panels of simple geometry rather than larger, more complicated pieces that fill large spaces. Therefore, it was necessary to remember during the design process that there would be many individual panel-attachment assemblies making up the whole, complete shell. In addition to this, the QSM team indicated to us that they desired a simple solution that was relatively easy to manufacture: team members on QSM came from varying degrees of manufacturing experience and quality of manufactured parts may be varied, and so the team needed resilient design solutions that were tolerant to manufacturing error. Finally, the QSM indicated that previous design solutions for panel attachment had been unstable: thus, our team needed to ensure that there was not significant imbalance or movement when body panels were installed.

However, the largest and most important goal for the QSM vehicle is outright performance, which required a design solution that was, above all things, light. As aerodynamic effects are negligible at the low speeds and larger size of the urban concept class, lowering weight is paramount to improving performance and saving fuel during track time, as the propulsion unit will spend less energy pushing the car the same distance around the track. Unfortunately, this demand for lightness came extremely contrary to many other requirements in this section. For instance, the team

preferring more separate attachment points with smaller panels increases the versatility in different geometries the panels can be adapted to fit, but the extra hardware and attachment points required would drive up weight. Furthermore, more rigid panels for the doors and trunk (in addition to more robust hinges) would similarly increase weight. Thus, in designing and choosing components for this modular shell system, each was optimized for the best functionality-to-weight ratio to maximize competitive performance.

4.0 Design Solutions

4.1 Design for Panel Attachment

Traditionally, space frame structures in cars are constructed out of an alloy (usually a chromoly steel) where connectors between the chassis and panels can be easily welded to the tube. However, our team required an individual piece to mediate this connection. One of the most significant constraints on designing a method of attaching body panels to the chassis was that the bulk of the chassis is made of carbon fibre tubing, regardless of configuration. Carbon fibre itself is notoriously difficult to work with due to how brittle it is and how it tends to splinter and snap when being formed: furthermore, the tube shape makes it inconvenient to drill holes. However, as mentioned before, the QSM team desired a degree of structural stability, and the connector needed to be highly configurable in order to facilitate many different panel attachment angles. In addition to all of this, the attachment design still needed to be optimized for lightness.

Overall, our design matrix for this section weighted modularity, adaptability, and low weight extremely high to ensure that our solution was versatile and could be properly fit to many different body panel configurations. Manufacturing time, mechanical complexity, tolerance for manufacturing error, and cost were weighted less importantly but were still thoroughly considered in choosing a proper design alternative.

Unfortunately, to achieve the necessary stability for the body panels, our group settled early on that we would have to drill into the carbon fibre tubing in order to secure the attachment points. One alternative originally devised was simply using friction to secure the attachment points through a clamp mechanism, but manufacturing a textured surface to better adhere to the carbon fibre would be prohibitively difficult and vibrations experienced while running the vehicle may possibly loosen clamps significantly. Another option was to secure the panel attachments with epoxy, but our team was worried about how irreversible that may have been if panel configurations needed to be iterated upon, as well as how epoxy may have deteriorated under different storage and operating conditions. However, it is still important to acknowledge that drilling into the carbon fibre tube to secure panel connectors creates a degree of irreversibility in and of itself (i.e. connectors can only be attached to points where holes are drilled, holes cannot be un-drilled where they are not needed) as well as structural implications regarding stress concentrations.

One of the ways our team tried to counteract the irreversibility of drilling holes through the carbon fibre tubing was to devise a system to attach panels at different angles. Our team closely analyzed the Nanyang Venture VIII from Nanyang Technical University, an Eco-Marathon battery-electric urban concept three-year champion that made use of modular 3D-printed body panels for the cockpit segment and door cladding. Our panel connectors needed to sustain similarly small loads while being light and, most importantly, have somewhat complex and highly variable geometry. Thus, our team decided to design 3D-printed ABS plastic panel connectors attaching to both the tube and the body panels. While sheet metal was considered as an alternative early in the design process due to the cheap nature of materials and manufacturing, it was determined that, for creating situations where panels would be angled, bending the sheet metal to create such an angle would not

be exact enough considering the possible variability in manufacturing quality. Furthermore, machining parts from alloy billet would be both very heavy and prohibitively expensive. Thankfully, while ABS 3D-printed parts can be manufactured in-house using either the ILC printer or the McLaughlin Hall Shop printer, there is also the option of sourcing a new manufacturer without having to change the part design at all.

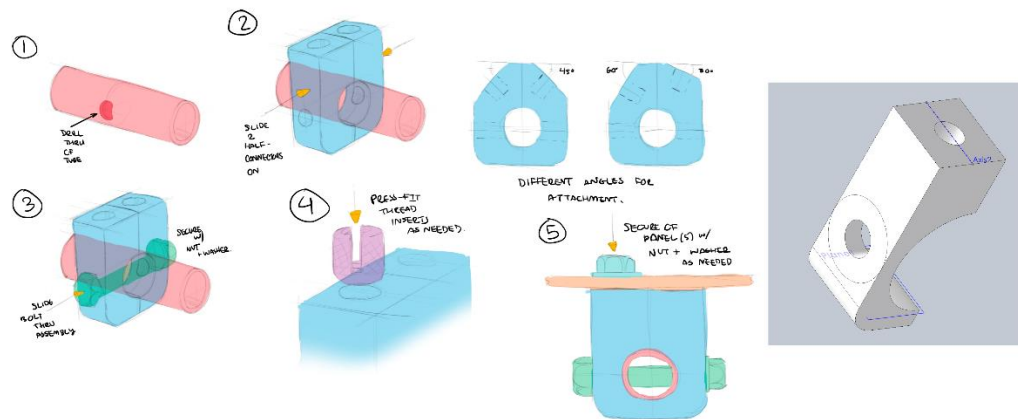


Figure 1: Design sketch showing geometry variations and assembly of panel connectors.

The general part geometry and manufacturing/assembly process for the 3D-printed connectors can be seen above. The main assembly of the connector is made from two halves: each half is perfectly symmetrical front-to-back (allowing any half to be used on any side of the tube) and can possess one of many top-face angles so that two panels can be connected to one tube at an angle from each other. A previous design allowed for variable angle at each connector, but this design was deemed much too mechanically complex and expensive. Each top face has a hole for a threaded insert, through which a securing bolt can be secured to affix a body panel. It is important to note that both to reduce the amount of support material and to increase strength in the loading direction, panel connectors will be printed with the long side down. In more detail, the manufacturing and assembly steps are as follows:

0. Before manufacturing begins, panel locations and angles as well as drilling points into carbon fibre tubes are determined using a CAD software package. This should minimize confusion when manufacturing and allow for the exact number of necessary printed components to be determined well in advance.
1. A hole will be drilled through the entire carbon fibre tube where a panel connector is to be located. A drill press is recommended to get a perfectly straight hole providing the tube can be properly secured in a vise. Proper ventilation and PPE during this step is necessary to ensure no hazardous particulates are inhaled or otherwise ingested.
2. Two half-connectors are placed at the location of the hole on either side of the tube. These can be any two connectors with any combination of top-face angles.
3. Both half connectors are secured to the tube and compressed together with a hex bolt, washer, and nut. A pin was considered for use, but a well-torqued nut will provide more compressive force keeping the two connectors together against the tube.

4. Threaded inserts are press-fit into the top hole in each panel connector as needed (for example, if a connector is using two flat-top connectors with one large panel, only one threaded insert may be needed rather than two). This prevents needing to tap the 3D-printed ABS which would likely reduce durability due to cutting into infill.
5. The body panel is secured to the connector by a bolt and washer through the threaded insert.

It is necessary to acknowledge that this attachment process involves a large degree of pre-planning, and assumes that much of the decision-making when it comes to chassis and body panel configuration will be done digitally. Furthermore, manufacturing many 3D-printed connector parts may incur long manufacturing time penalties, further increasing the degree of pre-planning needed. However, our team believes this is made up for in the sheer number of possibilities of configuration our design offers that can be experimented with and optimized during this pre-planning phase.

Our team designed four connectors at first: a flat-topped connector and connectors at 30, 45, and 60 degrees from the horizontal. The flat-topped connector was stress-tested in SOLIDWORKS, simulating a sharp transient load of 50N at 7.5 inches away. To approximate assembled conditions, approximations were made in fixing geometry. Firstly, the bolt hole was fixed in the radial direction to simulate the constraint of the bolt shaft. Secondly, a reference geometry constraint normal to the side face using a split circular face was instituted to simulate the distributed force of the nut and washer assembly. Finally, virtual wall constraints were added to simulate the presence of the tube and another half-connector.

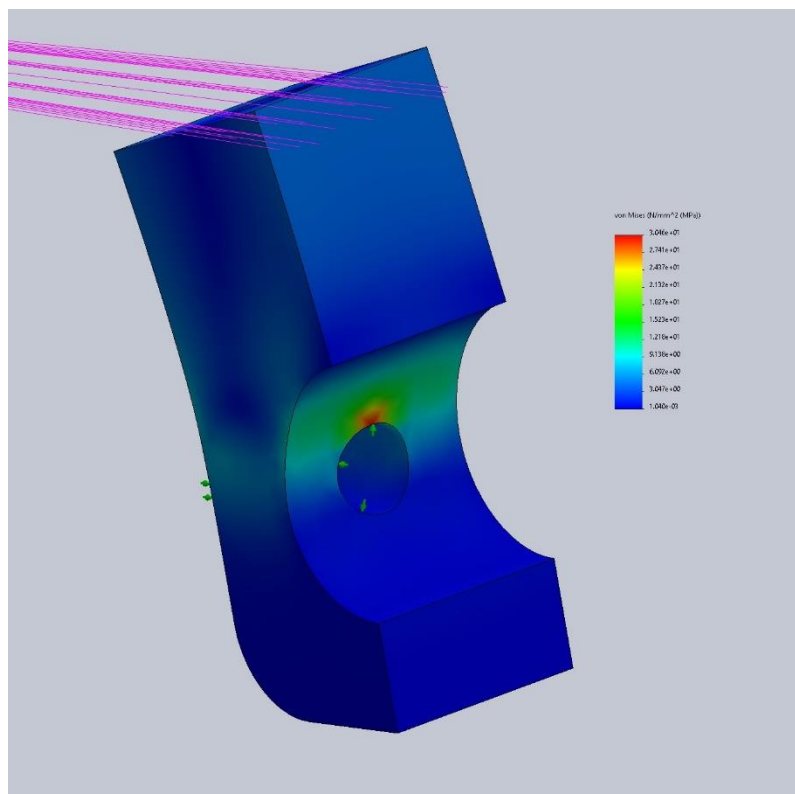


Figure 2: FEA test on flat-topped connector.

The stress results are shown in the figure above. From these results alone, it can be seen that 50N load represents the maximum load this component can handle *alone* before yielding, particularly due to the sharp stress concentration at the top of the inner edge of the bolt hole. However, this simulation neglects the distribution of stress across multiple connectors supporting the same panel.

This would likely lessen the force experienced by one singular panel attachment point and introduce a larger factor of safety.

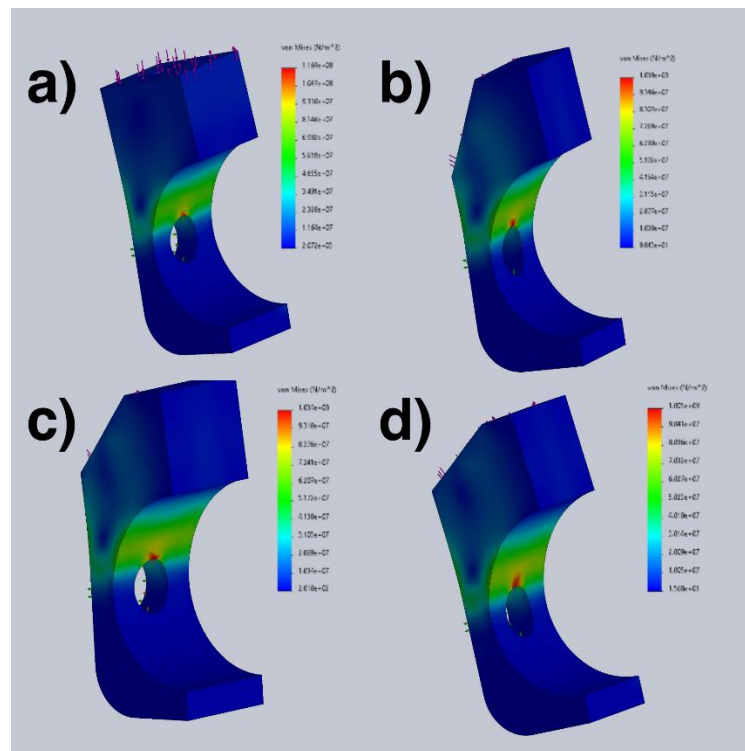


Figure 3: FEA tests on connectors with various panel geometries. The flat-topped connector represented the highest stress scenario but results were fairly invariant between cases.

A previous FEA study with different geometry studied all four top face geometry as shown above. This study, while representing a failure condition, showed that the application of a moment on the top surface created the highest stress scenario in the flat-faced connector, and thus, that connector would be the one to yield first under excessive transient loading scenarios.

4.2 Design for Doors

The door features will be a critical part for the exterior shell design as the rules and regulations need to be standardized for the door features, and failure to comply will result in not competing for the Queen's Supermileage Team. The rule as it states "It is imperative for Drivers, fully harnessed, to be able to vacate their vehicles at any time without assistance in less than 10 seconds". This rule is important for our team to take note of as the door must be large enough for the user to vacate the vehicle with ease and sturdy enough to keep the elements of the race outside of the car. The door design will consist of three main subgroups, and within each subgroup, three designs have been chosen to undergo design analysis and the design that will best suit Queen's Supermileage Team's needs will be picked. The three subgroups are door handles for the user to enter and exit the vehicle, door latches to keep the door secured and door hinges to pivot the door to open and close. The latches will help keep the door handle simple and the sheets for the exterior shell are relatively thin, using a door handle such as the one commonly found in your household would not be sufficient enough to keeping the exterior vehicle door closed.

The designs demonstrated below have undergone a design process with brainstorming of requirements, and picking different designs to be reviewed by the team. The different designs were reviewed by each member and placed in a design matrix. The design matrix takes the functional

specification shown in 3.0 Design Requirements, and adds weights to the designs. The larger the weight, the better the design, the lower the weighting, the design will need improvement or will not be selected. The weighting was out of 10 and the largest number out of all designs was chosen for the exterior shell.

4.2.1 Door Handle

Three potential design solutions were first chosen for door handle. These were plastic recessed pull handle, yacht flush handle, and circular latch. Recessed pull handle was chosen out of three potential solutions from the design matrix shown in Figure 4. Cost and manufacturing time are two most essential factors. Recessed handle scored the highest mark compared to the other options. Recessed handle has the simplest structure which brings it highest score in the complexity. The design scored well in usability because it is easy to access and has no moveable structure. Three potential solutions all received low score on modularity. They are finished parts from different sources, it is hard to make them customized. The plastic material makes the handle lightweight and decrease the time to manufacture compared to the metal materials.

Design Matrix: Door Handles								Total
Items	Cost	Manufacturing/Inst all time	Tolerance for error	Complexity	Modularity	Usability	Weight	
Weighting (%)	27	24	6	22	3	10	8	
Marine Latch	5	7	8	8	3	8	7	672
Circular Latch	8	6	5	7	3	7	8	687
Recessed Handle	7	7	8	9	3	9	8	766

Figure 4 design matrix for door handle

The recessed door handle is made from black plastic which pre-machined holes for easy mounting. This handle is 92mm x 61mm which is a favorable size that a user can still use with ease but not cause enough drag to be noticeable. The temperature rating of this design can withstand temperatures up to 140 degrees Celsius which is above any temperatures the vehicle could encounter. Using plastic as the main material can help keep the cost and weight of the overall vehicle low as plastic is very easy to manufacture.

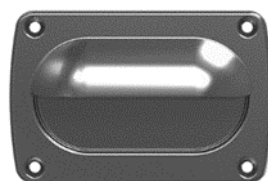


Figure 5 Recessed Door Handle

The assembly process of the recessed handle is straightforward. The handle will be installed at the outside of the door. A square cut-out with 72.73mm x 42.67mm will first be cut on the door panel. The depth of the cut-out should be 15.88 mm which is the depth of the recessed part on the handle structure. This depth is larger than the depth of the door. Therefore, the door will be cut through as shown in the CAD. There are four unthreaded through holes at four corners of the handle design as shown in the CAD design. The center of the mounting hole is 5.9 mm from the edge in longitudinal

direction and 8.7 mm from the edge in transverse direction. Drill four holes at these dimensions on the door with diameter of 3.81 mm since the mounting screw size was designed to be No. 6. Then embed the recessed handle into the cut-out. Four 6-32 threaded hex bolts will be used to immobilize the handle. Insert four bolts into the four holes at four corners. Then use four 6-32 hex nuts to fix the bolts.

4.2.2 Door Latch

With any good design, iterations from feedback are a critical part of creating and designing the perfect part. The door latch design began with a brainstorm various design dimensions and attributes would play into choosing a latch. Three different latch designs were chosen. A feedback session was held in week 7 to discuss the various designs of the latch and how it would work in the real-world setting. Feedback from the client was extremely helpful to help our team see flaws in the design and ways that it could be improved. The new latch was improved and redesigned to include important features and functionality. The new latch design surpassed our old designs and improved the quality of the door and overall design.

The latch functionality is simple and easy for the driver and outside users. It is understood that the driver will be wearing gloves while in the car, which requires an easy to open latch. The gloves eliminate the use of any small parts and require a design that is large enough that a person with gloves can easily open. The user must simply push the handle toward the frame connection on the panel coincident with the door to lock the door. To unlock the door, the user must simply push the handle in the reverse direction towards the center of the door. The latch design removes any gripping or complex motion for the driver and outside users to make the door lock simple and fast in order to exit the vehicle.

The latch is completely custom using a mix of 3D printers, aluminum and off the shelf hardware to secure the latch together. Figure 6, highlights all the parts of the latch. The base frame will be made out of carbon-fiber infused filament which will keep the latch base lightweight while keeping the strength of the material. The frame of the latch was designed to have extras and ease of manufacturing rather than waiting on suppliers and companies who can be unreliable. The handle will be 6061 aluminum rods machined on the lathe with a threaded hole in the center to secure the handles to the latch. The threaded rod will be an off the shelf item from McMaster-Carr and a ¼-20 threaded rod. The 6061 aluminum is easy to machine, lightweight and has enough strength to resist deflection or stresses brought upon the handle. 6061 aluminum [2] is commonly used for engineering structural applications such as truck frames. The latch itself will sit between the housing frame, a center cut-out for the latch to lay in and slide, and the door itself. The latch will be made from 6061 aluminum where it can be cut using any of the wide variety of machines available on campus such as a waterjet, CNC or bandsaw. The latch will have a high coefficient of friction to enable the latch to “stick” into place and keep the door locked. Common ¼-20 bolts and nuts will be used to fasten the latch frame to both the door and panel to keep the door secure. Holes will be cut through the door and panels where the latch frame must be placed. The CAD design for the doors and panels will already have pre-planned holes for a waterjet to cut the door and panels to shape and cut out holes for mounting and a space for the handle to slide with the latch. An important aspect of the design of the QSM vehicle is to keep the interior dry in any conditions. The latch will have a cylindrical cut-out for the latch handle to slide but will be water tight from the latch itself being of high friction and keeping any water from entering the vehicle.

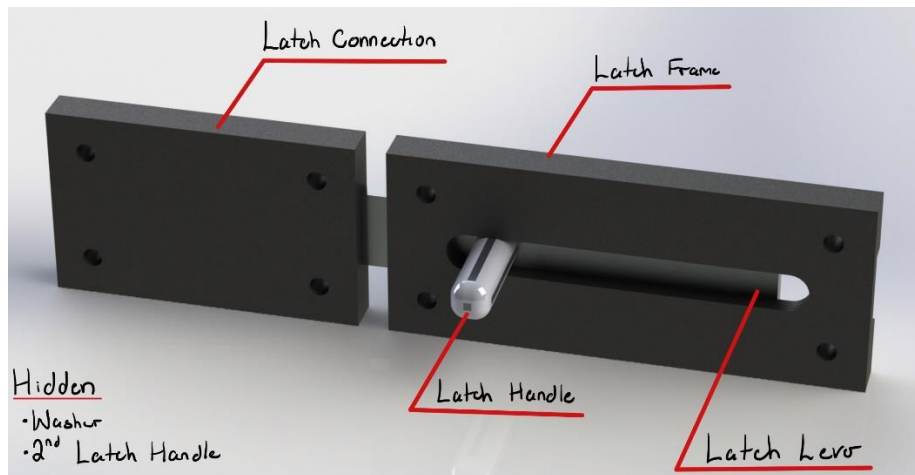


Figure 6: Render of the door latch.

The design for the latch was iterated at the end of week 7 and took the consideration of many design variables and aspects that will allow the driver to open and close the door quickly and in minimal movements. The design specifications for the latch have been outlined below:

- i. Allow the driver to open and close the door in less than 10 seconds
- ii. Allow the user to lock and unlock the door from both sides of the door
- iii. Easy manufacturability
- iv. Durability
- v. Modularity

With the above specifications kept in mind for the design of the latch, our team was able to design a latch that meets all the above specifications. The latch was design using the student edition of SolidWorks 2021 but can be exported to any file extension needed. The main latch dimensions measure a length of 152mm by 64mm while the connection latch frame measures a length of 102mm by 64mm. The latch itself measures 200mm which is greatly larger than the main frame to be able to easily connect to the connection frame. The weight of the latch system including the latch connection frame is 5.07Kg. This weight is an approximate measurement given by SolidWorks and does not depend on the type of filament used, the type of fill or any tolerances needed in the manufacturing.

The parts to manufacture and assemble the latch can all be found on McMaster-Carr. McMaster-Carr is a large provider of a wide variety of hardware, raw materials, tools, industrial materials and much more. All parts and hardware can be found laid out in the Bill of Materials along with the price and quantities of each part. The bill of materials can be found in 5.0 Economic Analysis. The total price of 2 latch designs will be \$127 Canadian Dollars with more than 50% of the total price being spent on filament and hardware. The price with filament and hardware is assuming the QSM team will have no hardware or filament to be used. The latch design has been designed to be versatile and adaptable to the hardware is available in the shop and to the QSM team.

With the completion of the initial latch design and a finished CAD model of the design, manufacturing can begin on the part. Most of the manufacturing can be done in house to eliminate extra costs and to be able to make the quantity needed if more is needed. Manufacturing instruction for each part are outlined below:

- i. Download the parts from the file given to the QSM team to have the CAD and design files needed for the 3D printer and waterjet. The 3D printer will need a STL file to be uploaded to the printer while the waterjet will require a DXF vector file as it will only cut in two dimensions.
- ii. Latch frame and connection:
 - a. Upload the STL to the 3D printer and change the settings to the specifications required.
 - i. Infill should be above 60% to ensure the quality of the toughness and strength does not lower.
 - ii. Infill pattern should be honeycomb or next best.
 - iii. Change material to correct material being used on the 3D printer
 - b. Allow the 3D printed material to take form and build. Once complete, use a spatula to remove part from 3D printer base. Remove any excess material. Complete.
- iii. Latch lever:
 - a. Acquire DXF file and put into waterjet to setup G-code and specifications for part.
 - b. Apply correct settings for the waterjet and 6061 aluminum metal being used.
 - c. Run program and cut part. Once done ensure no sharp edges by using a file
- iv. Latch handle:
 - a. Acquire part drawing with correct tolerances from Team 04C.
 - b. Cut part 0.5" larger than needed with automatic or manual saw.
 - c. Place part in the lathe to be smoothed out to the correct dimension.
 - d. Drill hole 1 inch in depth into lathed part by using the tailstock and a #7 drill bit in order to tap the hole to ¼-20.
 - e. Once drilled, tap the hole to ¼-20 manually or automatically.
 - f. Repeat for both handles.
- v. Assembly:
 - a. Assemble the latch handle and lever together. This can be done by screwing in one end of the threaded rod into one of two latch handles. Put the threaded rod through the hole in the latch lever adding the washer and handle once connected to the door.
 - b. Connect the latch frames to the door and panel with ¼-20 bolts and nuts.

The final CAD, drawings as well as all the files needed to complete the manufacturing and assembly of the latch will be provided to the QSM team along with the bill of materials outlined in 4.0 Deliverables.

To ensure of a strong and reliable design the latch and door underwent finite element analysis or FEA. The FEA is to mimic the operation of the latch and door or any other conditions the latch or door could encounter. FEA is the simulation of any given phenomenon using the numerical technique. FEA is the use of calculations, models and simulations to predict and understand how an object might behave under various conditions.

SolidWorks simulation was used to analyze the latch assembly using static capabilities. SolidWorks uses a tetrahedral mesh in which the model is automatically meshed and covered in nodes. Nodes will be point on the structure where stress, deflection and other data will be obtained and analyzed. A tetrahedral mesh is not perfectly accurate such as a hexahedral mesh would be. For the analysis of

the latch and door, simple movements and forces are being analyzed, which the tetrahedral will be able to handle. Several other assumptions were made in order to properly model the latch assembly in SolidWorks Simulation. The materials used for the latch frame were assumed to be the next closest plastic material, in which ABS plastic was chosen. Another assumption was to put a virtual wall on the latch frame to keep the latch lever in a fixed sliding position as well as using a pin joint to connect the two handles together. The force being applied on the handle was assumed to be 15lbs or 68N [3] which was measured as a point load on one of the handles. This force is to mimic an opening motion by the user. Below in Figure 7, shows the deflections and strain applied on the latch handle.

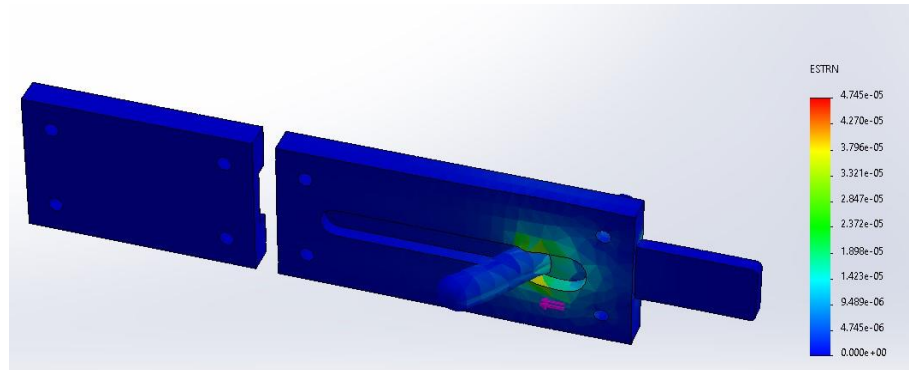


Figure 7: Strain and deflection shown with an applied force of 68N to the handle.

Once the FEA was complete, deflection stress and strain were all found in the most extreme cases. The maximum stress was found to be 2.3MPa which is acceptable along with the max strain being $3.8\text{E-}5$ which is acceptable number for this application. From the 68-newton force, the handle of the latch had a resulting deflection of $2.3\text{E-}6$ meters or 0.0023 millimeters which is an acceptable number. A deflection of less than half of a millimeter would be the maximum range in which the handle should be able to deflect when being used as our analysis was well below this limit.

4.3 Design for Hinges

The door hinges selected for the final design are a modified version of commercially available marine hinges. These can be attached to either chassis reinforced carbon fiber panels, non-reinforced carbon fiber panels, and Nomex honeycomb reinforced carbon fiber panels.

4.3.1 Hinge Selection

When selecting the hinges, there were three viable options. These were the marine hinge, a hidden circular hinge, and a custom locking lift off hinge.

Marine Hinge



Figure 8: Picture of the proposed marine hinge

The marine hinge is a commercially available hinge designed for use mounting hatches to boats and other marine craft. This design gets is made of 316 stainless steel giving it more than enough strength to handle the carbon fiber door of the vehicle regardless of it's design. With a footprint of 7 cm by 6.7 cm and the ability to be mounted inside and outside of the carbon fiber body panels, the hinge is highly versatile and adaptable to varying exterior shell designs. Additionally, the marine hinge also utilizes a removable steel shaft to rotate. This allows the design to be removable quickly without tools when the keyring securing mechanism is replaced with a cotter pin. The main disadvantage of this design is the weight of 216 g due to the material it is made of.

Hidden Circular Hinge



Figure 9: Picture of the proposed hidden circular hinge

Like the marine hinge, the hidden circular hinge is also commercially available with quick procurement times. This hinge design was designed for use in domestic applications for mounting interior fixtures including but not limited to cabinet and closet doors. These applications match the functional requirements for the carbon fiber doors on the exterior shell's design which will be larger than cabinet doors but will be made of a significantly lighter material. Another advantage of this design is the limited 90-degree range of movement. This will prevent the door from extending past its designated range limiting interference with other parts of the vehicle. Weighing 168 g, it is also the lightest of the three hinge options being compared. This is important to ensure that the vehicle remains under it's weight limit set out in the rules. Where this hinge falls behind some of the other options is in its complexity. Instead of pivoting around a shaft like the others, this hinge has wheels that roll along a circular track. This design leads to the higher chance of losing functionality due to being jammed up with dirt and debris, reduced repairability, and will require more time for installation and removal.

Locking Lift-off Hinge

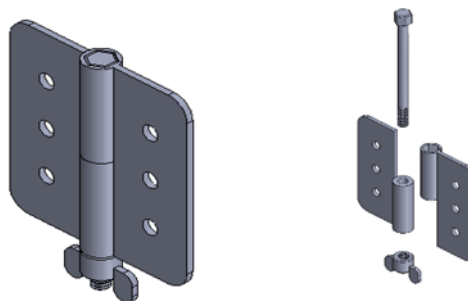


Figure 10: Picture of the proposed locking lift-off hinge

The locking lift-off hinge is the only custom-made hinge option that was considered. This design is roughly based on lift-off hinges used in HVAC and industrial generators that require regular maintenance and benefit from the quick and easy removal of doors. However, when assessing this

option, it was clear that they are only effective in stationary applications and the unsecured center shaft of the hinge can easily be shaken out of place when shaken. This led to the requirement for a locking mechanism that uses a bolt in place of the center shaft found in commercially available designs. This bolt will then be secured using a locking wingnut. This allows for the tool less removal of the hinge while also ensuring that it will not come loose during competition. Unfortunately, the custom-made nature of the design lets it down due to the cost and manufacturing time required. It would also increase the complexity of the manufacturing process for the car.

These three options were compared using a design matrix with the attributes of categories of cost, manufacturing time, tolerance for error, complexity, modularity, adaptability, and weight weighted at 27%, 24%, 6%, 22%, 3%, 10%, and 8%, respectively. The categories of manufacturing time, cost, and complexity were weighted the highest, between 20% and 30%. It was important to give these categories a high weighting as they had the largest impact on the remainder of the project. Spending too much money, time, and design time on the hinges would detract from larger areas of the design such as the body panels which would better benefit from a larger budget and additional manufacturing time. The remaining categories were rated lower due to variance between designs implying the choice between one another would yield a small difference in performance. When researching the options, all the designs had roughly the same adaptability, modularity, tolerance for error, and weight.

Table 1: Design matrix used to select the hinge design

Design Matrix: Door Hinges								Total
Items	Cost	Manufacturing time	Tolerance for error	Complexity	Modular	Adapability	Weight	
Weighting (%)	27	24	6	22	3	10	8	
Locking Lift-off Hinge	5	5	6	6	8	8	6	575
Marine Hinge	7	9	8	9	8	8	7	811
Hidden circular hinge	8	9	8	7	7	7	8	789

These factors ultimately led to the selection of the marine hinge as the hinge for all hinged panels on the final design. This hinge design won out due to its favourable performance in the most heavily weighted portions of the design matrix. In the cost category it was only beat by the hidden circular hinge with a small margin with the locking lift-off hinge costing the most due to the complex manufacturing process. The marine hinge also scored well in manufacturing time being effectively zero as it was readily available for purchase online with fast shipping. It also scored the highest in the complexity category as it was the simplest design in amongst the viable options. The locking lift-off hinge could have approached the marine hinge in this category in terms of operation but is let down by the manufacturing requirements. The hidden circular hinge matches the marine hinge in manufacturing complexity as it is the other commercially available option but falls behind on operation complexity due to its design. The marine hinge also scored closely to the other options in the less heavily weighted categories cementing it as the best option considered.

4.3.2 Hinge Attachment – Chassis Side

When designing the best hinge attachment, the main request made by the clients was to maximize stiffness while minimizing weight. Initial designs planned to attach the hinge directly to the carbon fiber panels that made up the exterior of the car. This was done prior to getting an understanding of how the chassis was to be designed and what attachment methods were available to the exterior shell team. Later in the project however, it was discovered that some chassis designs would incorporate chassis tubes that would extend to the height of the doors and that it was possible to build lightweight extensions on the space frame to create additional mounting points. With this new information it was decided that the hinges would need to be directly mounted to the chassis of the

car. This would give the hinges the support needed to hold up the hinged body panels including the doors which would have a system of latches, handles and windows, all adding weight. It would also mean that the carbon fiber exterior panels could be kept thin and light to remain below the maximum weight.

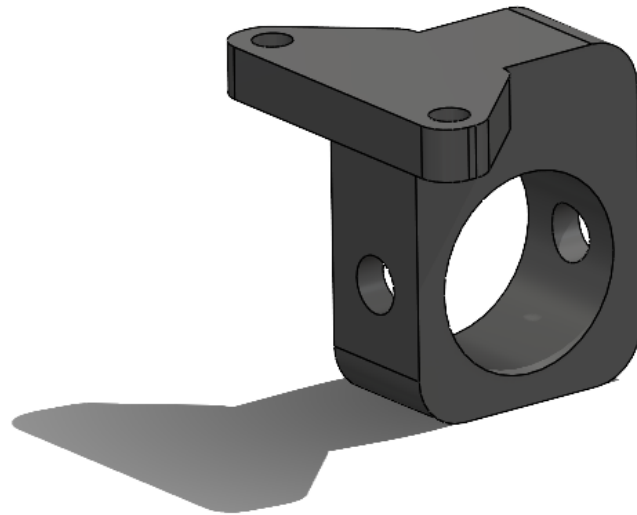


Figure 11: CAD design of the modified panel connector used for hinge mounting

With those goals set, the final design for the hinge attachment is a modification of the 3D-printed panel attachment mounts used to attach the rest of the body panels to the chassis. The mounts will be widened at the top to match the size and shape of the hinge's base with holes to match the outer mounting holes found on the hinge with chamfers along the stress concentration points generated by the widening. These holes will have threaded metal inserts glued in to ensure stability. Due to the placement of the holes, the connector's split design facilitating their easy removal must also be modified. This was done by the addition of a plate that sits above the connector supplying a third hole on the far side of the connector connecting both halves. The hinge will be mounted to this assembly with the carbon fiber body panel sandwiched in between.

4.3.3 Hinge Attachment – Panel Side

The hinged panels of the car including the door and trunk lid were initially assumed to also have chassis tubes as reinforcement. This was because the carbon fiber sheets proposed for the exterior panels were not strong enough to support the weight of the door while minimizing flex for the latch mechanism to remain functional. Using this assumption, the mounting mechanism for the hinges on the hinged panels would be the same as for the chassis mounts. However, additional research revealed the option of implementing carbon fiber panels that are reinforced using a Nomex honeycomb. This was a cost effective and lightweight alternative to running chassis tubes along the doors. It would also be strong enough to support the weight of the components mounted on the door. This change in design means the hinges can no longer be mounted using the method devised using the 3D-printed panel connectors. Instead, they will be secured using nuts and bolts holding the hinge to a carbon fiber panel. The stress exerted on the carbon fiber panel by the nuts will be distributed using a metal plate that connect the two nuts on either side of the hinge.

Having selected the hinge design based on the functional requirements and designing an attachment method for both the chassis and the hinged panel, the next step is to validate the design using FEA. The two key components of the assembly that need validation are the hinges themselves and the 3D printed panel connectors. These two components were tested individually for displacement under load. In order to pass validation, the parts must not deform to the point that other parts of the vehicle design no longer work as a result. One example of this would be the door latch on the other end of the door, which would be misaligned if the door were to sag too much under load.

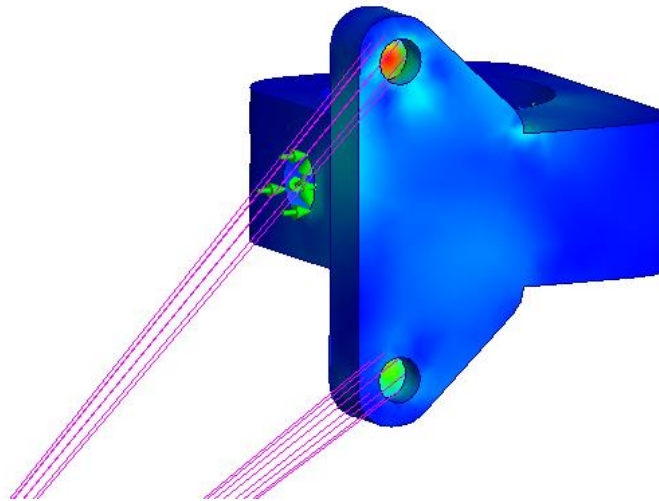


Figure 12: FEA model of hinge mount under typical loading

Testing the panel connectors 3D-printed in ABS plastic starts with constraining the part via the side cut hole for the securing pin. This is where the load connector will transfer all the load through to the chassis as the remainder of the connector is not attached to the chassis. A remote load of 100 N is applied as a point load at 250 mm away split between two connectors to simulate a two-hinge design. This load is made to simulate the 500 mm wide by 800 mm tall maximum door size estimated to exert a 50 N force using a preliminary door design, with the addition of 50 N applied to simulate someone getting in and out. This load was then applied to the two hinge mounting holes on each connector. The resulting analysis seen above shows a maximum displacement of 0.033 mm and no risk of failure with a maximum stress of 2 MPa compared to the material's yield strength of ~30 MPa. This shows that the part can support the weight of the entire door and typical loading when in use.

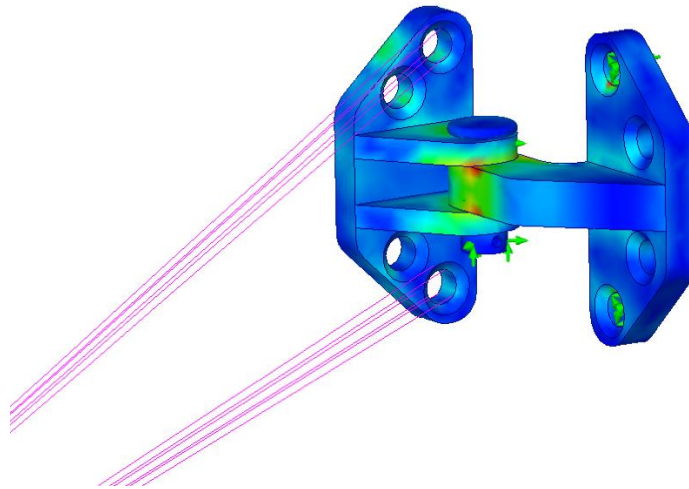


Figure 13: FEA model of the hinge under typical loading

The testing of the 316 Stainless steel hinge was approached with the same methodology. The same 100 N load was applied to the assembly through the two bolt holes of two hinges. However, this test differs from the previous with its constraining points. This assembly was constrained on the two bolt holes opposite to the ones being loaded to simulate attachment to the panel connector.

Additionally, the pivoting shaft of the hinge was also constrained as a hinged part for accurate simulation. After running this test, the results seen above show that the design is more than adequate for the intended application. The maximum displacement found on the part was at 0.00205 mm meaning that there is little to no noticeable displacement under loading. With a peak stress of 5 MPa, it is also well below the material's yield strength of 290 MPa.

To help with the continuation of the QSM project in the winter semester, a set of manufacturing and assembly instructions have been laid out for the team. The set of instructions can be seen below.

Component Manufacturing

Although most of the components used for the hinge installation will be pre-manufactured or purchased from a vendor, some components are custom made.

The first components that need to be made are the adaptor plate for the 3D printed panel connector and the distribution plate for the nuts on the hinged panels. These can be cut out using a laser cutter or water jet out of aluminum.

The next part to be made are the 3D printed panel connectors. These are printed using a supplied CAD file of the modified connector design.

Component Preparation

Before assembling and attaching the hinges to the chassis and hinged panels, each individual components must be prepared from their purchased or manufactured state.

First, the hinges must be separated into their male and female sides. This done by removing the keyring that secures the shaft into the hinge and removing the shaft allowing the two sides to separate.

The carbon fiber must now be prepared to accept the hinges by drilling holes where the screws will be placed. This can be done by placing the hinges onto the carbon fiber panel where it will be mounted and marking holes in line with those in the hinge.

The chassis tubing where applicable must also be prepared to receive the 3D printed mounts. This is done by lining up the mounts to the chassis tubing where they will be when installed and marking a center point in the side holes designed for the connectors locating pin. A hole is then drilled through both sides of the chassis tubing to allow the locating pin to pass through the tube.

Finally, the 3D printed panel connectors need their threaded inserts installed. This is done by putting adhesive in the three holes in the connectors and placing the inserts in ensuring that they're flush and allowing to set.

After these steps are done it's time to move onto assembly.

Assembly

The first step in assembling the door hinges on the chassis side of the hinge is to attach the 3D printed panel connectors onto the chassis tube. This is done by locating both sides of the connector roughly where the hinge is to be placed and inserting the securing pin and attaching the cotter pin to lock it in place. Then, the adaptor plate is placed on the connector followed by the carbon fiber panel. Then loosely screw the single screw opposite the hinge mounting point to prevent the assembly from coming about but still allowing adjustment to line up the holes for the hinge mounting. Next, attach one side of the hinge to the assembly using the two screws.

The second step is to attach the other side of the hinge to the hinged panel. This is done by lining up the pre-drilled holes in the carbon fiber panel with the mounting holes in the hinge. Then the nuts and bolts are fastened with the distribution plate placed between the nuts and the carbon fiber panel.

Finally, the hinged panel can be attached to the car by connecting both sides of the hinges. This is done by lining up the male and female sides of the hinges and making sure the holes are lined up vertically. Then, place the pin through the hinges to hold them in place. The hinged panel should remain on the car unsupported at this point. The shafts are then secured by installing the cotter pin in the hole where the keying used to be.

4.4 Design for Windows

Windows are the critical component in the vehicle body parts as they mainly affect the safety and visibility of drivers. As Shell Eco-Marathon Competition Rule stated, 'Windows must not shatter into sharp shards. Protective film covering the windows is allowed but must not distort the driver's visibility. The side windows tinting must be light enough to allow the driver to be seen from outside the vehicle' [1], indicating that windows are the top priority for drivers to safely proceed driving manoeuvres. Windows includes front and rear windshields, side door windows and rear-view mirrors.

4.4.1 Window Material Selection

The team has a variety of material options for the window, such as polycarbonate sheet, film and acrylic sheet. Many considerations such as costs, manufacturing time and weight were included in the table weighing the scale from 1 to 10. The most ideal material of polycarbonate sheet scored 617 was then selected according to the one with the highest score of these three materials.

Polycarbonate Sheet

At only half the weight of glass, these 12' x 12' polycarbonate sheets are great fit for windows. They have excellent impact strength that meet UL 972 are rated as burglar resistant [2]. Better performance properties of the sheet are listed as clear vision, high strength, impact resistant, low thermal expansion, and weather resistant. Polycarbonate offers great light transmission compared to glass but lighter and more durable makes polycarbonate sheet stand out. Moreover, easy to install is another feature that allows the sheet to be attached to the door frame either using mount or clips.



Figure 14: Image of a polycarbonate sheet.

Impact-Resistant Polycarbonate Film

The polycarbonate film can protect window panels and other surfaces from shattering into sharp shards. It has excellent tensile strength and impact strength. The hardness level is Rockwell R118 which is classified as hard. This film is relatively cheap, only \$5.21 per 24" x 48" film [3]. However, the little thickness of polycarbonate film has become an issue to be installed to the support structure. The other issue was that thermal insulation of polycarbonate film is not as efficient as of the sheet. Improvements can be implemented by attaching the polycarbonate film onto the surface of sheet to prevent the sheet from shattering into sharp pieces in case of accidents.

UV-Resistant Cast Acrylic Sheet

This 48" x 48" sheet is made of acrylic plastic [4]. It has high tensile strength but poor impact strength. It stands up to outdoor use better than polycarbonate and maintains clarity over time. However, the acrylic sheet has low thermal conduction and is easier to scratch compared to polycarbonate sheet. In an environment aspect, acrylic can be recycled, however, not bio-degradable meaning that they can only be reused by becoming small pieces and forming them into other products.

4.4.2 Attachment Double-sided Form Tape

With polycarbonate sheet selected, the team needs a solution for the window to attach to the door frame. The team was seeking steady, strong and efficient attachment methods of windows. Two attachment methods were considered which were using double sided attachment tape and urethane glue. These can both apply and install to the mounting of the door frame. However, attachment tape is easier to attach and has economic benefits over urethane glue even though they serve similar purposes.

4.4.3 Window Vent

In order to achieve window defogging, flow needs to be circulated as desired flow of outdoor air to the vehicle. Although natural ventilation of rolling down windows is a defogging approach, it would be time consuming and not efficient depending on the weather conditions. The team came up with an idea of window vents installed on top of the windows. Below is the illustrated CAD model of window vent designed in Solidworks. There are three rounded entrances to allow air circulation. The bottom side of window vent is designed to be curved to ensure maximum air flow. The detailed annotated sketch is presented with three standard views and isometric view in the appendix.

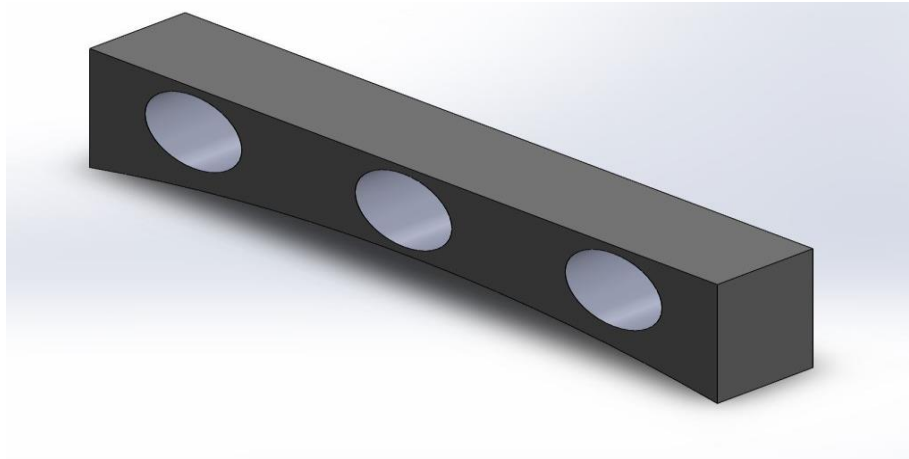


Figure 15: Overview of the CAD Model for window vent.

4.5 Carbon Fibre Panel Design

In early stages of the project, our team believed that modularity still implied a degree of predetermination of panel geometry, and thus planned to create defined, curved panels that would make up larger “modules” around the car. For example, our team planned to create a fender/wheel well module, a trunk module, and an overall cockpit module that were self-contained but had defined geometry within their scope. However, upon learning that the team desired an extremely variable approach regarding panel geometry, our team rapidly pivoted to the idea of discretizing the overall body shell shape using small, flat panels rather than larger, curved ones. A major constraint on manufacturing curved panels would be to create moulds to shape them, and that depending on the laying process, panel conformity to these mould shapes could be less than ideal. Our team was informed that previous teams had sought out third-party manufactures for better panel quality, but prohibitive labour costs had prevented them from getting more than half the body constructed at once.

While there was little doubt from the beginning that our panels would be made from carbon fibre to minimize weight, two other alternatives were considered. Firstly, fibreglass was considered as a cheap option with comparable stiffness to carbon fibre and a similar manufacturing process. However, while panel connectors consumed a large portion of the total allotted budget, there was still significant funding left over for a suitable panel material: this is further compounded by the fact that fibreglass is approximately twice as dense as carbon fibre, meaning that weight penalties in the name of cost savings would be very significant. The next alternative examined was natural fibre composites, namely ampliTex flax fibre. While these fibres are less stiff than carbon fibre, they are also lighter, and considering panels do not need to endure significant loading, the extra weight savings were a major allure. Furthermore, these composites were more environmentally friendly to produce and less hazardous to work with, making manufacturing slightly easier. The major

prohibiting factor is that flax fibre composites are still a fledgling technology, and thus sheets of fabric and their corresponding resin are extremely difficult to source, particularly in North America: this would have truly imposed unreasonable cost and delivery time penalties.

Once our team had decided on a material for the fabric, an appropriate fabric weave also had to be determined. Mechanical properties and anisotropy can vary drastically depending on how the fibres are oriented in the weave, leading to significant implications on structural capability and workability when manufacturing. A 2x2 “twill” weave (distinguished by its diagonal character) is used in traditional carbon fibre manufacturing as it is more easily bendable and facilitates the creation of curved pieces; however, this sacrifices overall stiffness for slightly less anisotropy. A 1x1 90-degree weave, on the other hand, has significantly higher peak stiffness at the cost of significantly less formability for curved parts. Thankfully, flat panels were the only requirement, and the decision to sacrifice unnecessary formability for significant gains in strength was very easy. Furthermore, a plain 1x1 weave was slightly less expensive per yard, saving approximately 800 dollars across an entire 100-linear-yard roll.

Understanding how expensive external carbon fibre manufacturing could become, our team wanted to constrain ourselves to manufacturing processes that could be conducted fully in-house. Thus, our team reached out to the Formula SAE team’s engineering director, Spencer Kalnicki, to gain insight into how flat, non-structural panels could be manufactured on site. Our team’s main concerns were as follows:

- What suppliers for fabric and resin the team recommended: the team firmly recommended Composites Canada for both, as multiple Queen’s design teams have a good relationship with them.
- Whether layups are done by hand or if the team sources pre-impregnated sheets (i.e. is the fabric loaded with resin on-site or externally): the team confirmed that they have the facilities to layup the fabric on-site to reduce costs.
- Whether the team has access to an autoclave: they do not, but the on-site layup allows for curing at room temperature in a vacuum bag, albeit for ~24-48 hours.
- If there are any dimensional restrictions: generally, the size of individual panels is limited only by room space, and a ballpark constraint is approximately 5’ by 5’.
- How many layers of fabric are used per panel: two layers of carbon fibre are used almost universally, and any extra reinforcement for certain panels comes from an intermediate layer of Nomex honeycomb. Furthermore, layers are misaligned with each other in order to even out anisotropic properties.
- How the team shapes and polishes panels: fabric is cut larger than necessary when laying up and is cut down to size using the water jet only after curing. Edge cleanup and polishing passes are done with a wetsand and polishing grinders.

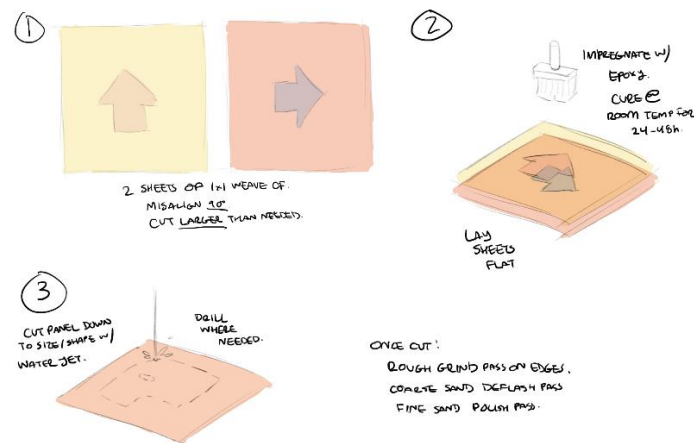


Figure 16: Assembly instructions for carbon fibre panels, as advised by the Queen's Formula SAE team.

Knowing this, a general manufacturing process for a carbon fibre panel is outlined in the figure above. Firstly, since 1x1 weave is used, 2 panels are laid on top of each other at 90-degree misalignment to cancel out the most anisotropy. In the case of more structurally significant panels like the doors and the trunk, these layers of fabric will sandwich a thin layer of Nomex honeycomb: the resin will be sufficient for affixing the fabric to the honeycomb as it cures. The carbon fibre fabric will be cut larger than needed before being impregnated with resin, being vacuum bagged, and cured at room temperature for 24-48 hours. Once panels are cured, they can be cut with the water jet in the McLaughlin Shop according to sheet-based CAD data. Holes can also be drilled afterwards using a drill press where needed for securing panels to connectors. Finally, once panels are cut, edges can be sanded down with a coarse grind, and polish can be achieved with a wetsand and buff. Our team estimates that one roll of 100 linear yards of carbon fibre fabric should be sufficient for an entire vehicle's worth of panels as well as spares in the case of damage or manufacturing error: this figure has been corroborated with advisors.

An FEA analysis was completed to test the structure integrity of the door due to forces that would be applied by the QSM team members. ANSYS simulation was used to model the deflection, stress and strain of the door. The analysis is to mimic a user pushing on the door or leaning on the door to ensure the door will not break under pressure. ANSYS modelling is able to use hexahedral mesh to analyze element more accurately for simple and linear parts. Several assumptions were made in order to analyze the part effectively. The carbon fiber material chosen is Toray T700S a common composite for panels. The Young's modulus was assumed to be 207GPa along with an assumed Poisson's ratio of 0.25. The panel is assumed to be mounted using 4 connections to the chassis and the point force being located in the center of the panel. The panel being analyzed is the maximum size of the door measuring 800mm by 500mm. The force being applied on the door is to mimic the force of a user leaning on the door which was approximated to be 70Kg or the mass of an average person on the QSM team. This mass was then converted to 680-newtons to be put into ANSYS. The deflection and stress intensity of the panel is shown below in Figure 17. The stress intensity is shown as a colour bar increasing in MPa from blue increasing to red.

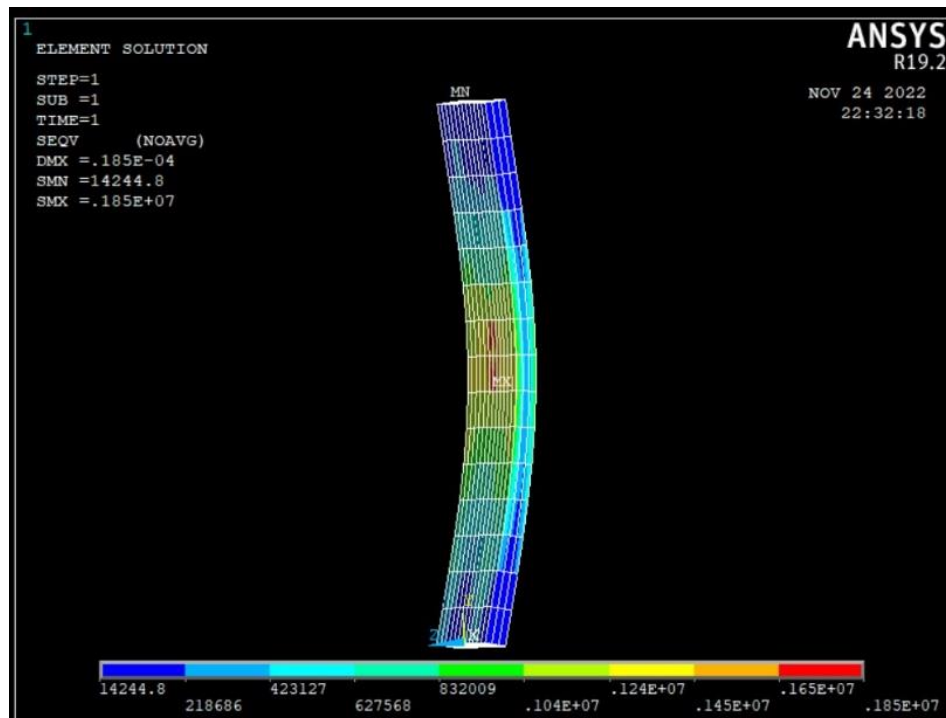


Figure 17: ANSYS model of deflection and stress on the carbon fiber panel.

The results of the ANSYS model yielded a max stress of 1.66MPa which is less than what is being outputting by the handle forces. The max deflection was calculated to be 1.85E-5 or 0.0185mm which is below the maximum range that was defined earlier. Overall, both designs resulted in deflections and stresses below what is the limit to be withstood for the application. Both the latch and door will be able to withstand any forces that will be undertaken from the QSM team.

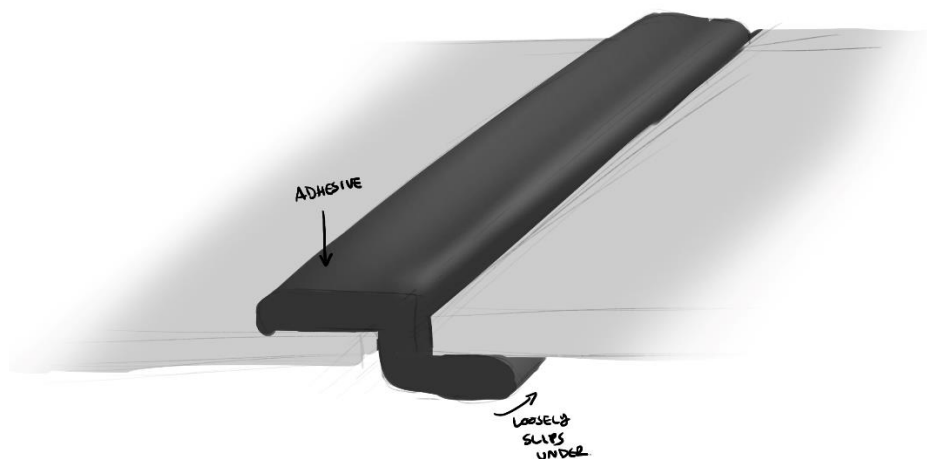


Figure 18: Adhesive rain shield for the panel connections.

As mentioned in prior sections, our team needed to design a system that was resilient to manufacturing error: one crucial way this may manifest is in panel gaps due to carbon fibre panels being manufactured to poor tolerance. Thus, our team proposes the use of automotive-grade rubber weather stripping to seal gaps as needed. These strips have a Z-shape profile, with adhesive to stick one side to the panel while letting the other side slip underneath an adjacent panel loosely. This

does not need to provide any structural reinforcement, but allows a wide tolerance in exact panel dimensions while preventing both rain and excess air from entering the cabin, providing safety to in-cabin systems and reduction in drag.

5.0 Economic Analysis

An economic analysis of each of the six designs have been evaluated below. The exterior shell teams have been given a budget of \$7000 CAD in which our team needs to stay below. It is important to note that the prices below are not fixed and do not have any shipping or any other additional costs with them. The analysis below does not take into account any spares or extra parts the shell may need throughout the competition to be replaced due to wear or damage caused by outside sources.

The first design is the attachment point. It is one of the most expensive sections in the manufacturing process. The attachment point is designed to be 3D printed. Each part is approximately 3 cubic inches in volume: assuming 100 total attachment points and a price of 9\$ per cubic inch from the ILC 3D printer, this results in 3D printed attachment points costing approximately \$2700. 100 M8 x 12.7 thread inserts from McMaster-Carr will cost approximately \$287. 100 M10 x 50 partially threaded bolts from McMaster-Carr to secure mounts to the tube will cost approximately \$128, while 100 M8 x 16 fully threaded bolts to secure the panel to the threaded insert will cost \$38. Nomex honeycomb core which will be used on the attachment on the door will cost \$120.75. The estimate shipping price for the bolts and inserts from McMaster-Carr would be \$14.68 and the estimate shipping for Nomex honeycomb core would be \$17.93. This adds up to a total cost of \$3306.36.

The recessed door handle from McMaster-Carr will cost \$3.45 per piece. During the installation, four 6-32 threaded hex bolts and four 6-32 hex nuts are required. One pack of each will cost \$21.69 in total. The total cost would be \$28.59 without additional shipping fee since they could be placed in the same order with threaded bolts and inserts mentioned above from McMaster-Carr.

The door latch composes of seven parts which all will be sourced from McMaster-Carr. The lever part of the latch consists of two lever handles, a lever frame, a lever connection, a 0.25ID Washer, and a pack of stainless-steel threaded rod which will cost \$83.21. The 1/4-20 threaded nuts and 1/4-20 threaded bolts used to fix the latch on door will cost \$37.06.

The marine hinges sourced from Amazon will cost \$24.72 for one piece. Two hinges are required, and the shipping fee was estimated to be \$6.3. The excess bolts and nuts from latches could be used to fix the hinges. This adds up to a total cost of \$55.74.

Exterior panel is the other costly part for the whole design. Plain carbon fibre will be purchased from composite Canada. The price was found to be \$34.49 per yard. One roll with 100 yards is required for the exterior shell which will cost \$3449. Water-jet cutting is planning to be used during the manufacturing process and the cost of cutting will be estimated during the manufacture.

The last part is the exterior window. Three polycarbonate sheets will be purchased from McMaster-Carr with total cost of \$145.92. Side window vent visor from Amazon to circulate the air in the vehicle will cost \$78.53 with shipping cost \$13.01. The exterior attachment tape from Amazon to attach the window will cost \$16.46. This adds up to a total cost of \$260.69.

So far, the total cost is added up to \$7227.97 which is above the given budget. The cost is calculated based on the assumption that all hardware and parts are required to be purchased. The total cost may vary during iterations at manufacturing.

Bill of Materials					Minimum Quantity Required	Minimum Parts Totals	Minimum Shipping Cost	Minimum w/Shipping Totals
ID	Name		cost / set					
1	QSM exterior shell					\$7,169.28		\$7,227.97
	Attachments					\$3,273.75		\$3,306.36
		3D print (part)	\$27.00		100	\$2,700.00	\$14.68	\$2,714.68
		M8 x 12.7 thread insert (pack)	\$2.87		100	\$287.00		\$287.00
		M10 x 50 partially threaded bolts (pack)	\$1.28		100	\$128.00		\$128.00
		M8 x 16 fully threaded bolts (pack)	\$0.38		100	\$38.00		\$38.00
		Nomex honeycomb core (roll)	\$120.75		1	\$120.75	\$17.93	\$138.68
	Door Handle					\$28.59		\$28.59
		recessed pull handle (piece)	\$3.45		2	\$6.90		\$6.90
		6-32 thread hex bolts (pack)	\$13.46		1	\$13.46		\$13.46
		6-32 hex thread nuts (pack)	\$8.23		1	\$8.23		\$8.23
	Door Latch					\$127.59		\$127.59
		Lever Handle	\$7.29		1	\$7.29		\$7.29
		Lever Handle	\$14.42		1	\$14.42		\$14.42
		Lever Frame	\$49.86		1	\$49.86		\$49.86
		Lever Connection	\$0.00		1	\$0.00		\$0.00
		0.25ID Washer	\$7.32		1	\$7.32		\$7.32
		Stainless Steel Threaded Rod	\$11.64		1	\$11.64		\$11.64
		1/4-20 threaded Nuts (pack)	\$19.26		1	\$19.26		\$19.26
		1/4-20 threaded bolts (pack)	\$17.80		1	\$17.80		\$17.80
	Door hinge					\$49.44		\$55.74
		marine hinge (piece)	\$24.72		2	\$49.44	\$6.30	\$55.74
	Exterior Panel					\$3,449.00		\$3,449.00
		5.7oz x 50" Plain Carbon (yard)	\$34.49		100	\$3,449.00		\$3,449.00
	Exterior Window					\$240.91		\$260.69
		UV-Resistant Cast Acrylic Sheet (sheet)	\$48.64		3	\$145.92		\$145.92
		Side Window Vent Visor (4pc)	\$78.53		1	\$78.53	\$13.01	\$91.54
		3M Exterior Attachment Tape	\$8.23		2	\$16.46	\$6.77	\$23.23

Figure 19: Bill of Materials for Exterior Shell.

6.0 Analysis of final design

The final design has undergone rigorous predicted testing and analysis to ensure the exterior shell will be able to withstand any forces that the QSM or supermilage competition might encounter. The design of the exterior shell had many goals outlined below in which the team achieved:

- I. Modular design to fit any chassis design and aesthetic.
- II. Lightweight.
- III. Cost of manufacturing.
- IV. Durable and high Strength of materials.
- V. Time and ease to manufacture and assemble.

Team 04C has come up with modular panels that are able to fit any chassis design. This is done by dictating the moulding process and the shape of the moulds. Changing the shape of the moulds will greatly help form the panels around the chassis of the vehicle. The panel attachments help with mounting the panels in any orientation and form the panels as tightly around the car as possible. This is done by creating easy to mount, any direction mounts that only take a singular bolt to install. The windshield and windows will be made out of polycarbonate which can help form and shape to any design. Polycarbonate can become very ductile when exposed to high temperatures and using this property, be formed to any shape of the vehicle. The panels and panel attachments being manufactured by composites and 3D printed material respectively, helps keep the vehicle lightweight and help to conserve fuel by being lightweight. By having the windows, panels, and panel attachments modular and durable allows for room for the QSM to have the vehicle the team wants and to help smooth the process of manufacturing and installing the exterior shell.

The door deliverables were measured in the same fashion ensuring the door is durable and easy to manufacture. Having most of the door be off the shelf parts makes manufacturing only the door latch. Having only the latch custom cuts time down and allows the QSM to work on the most important part of the exterior shell being the panels and attachments. Keeping all door parts simple helps the QSM minimize manufacturing time and keeps parts modular. The final design is achievable for the QSM team as our team succeed in achieving the four goals listed above. Our team has also provided any necessary documentation or drawings of the design to further aid the QSM team in the manufacturing and assembly stage of the design.

7.0 Conclusion

The goal of this project was to design a new and improved version of the exterior shell for the Queen's Super Mileage (QSM) team for use in the Urban Concept class of the Shell Eco-marathon. The requirements and restrictions applied to the design were provided by the QSM team and the competition rules for Shell Eco-marathon. These two sources outlined dimensional targets and performance goals for the final design to meet and be optimized for respectively.

This task was accomplished by splitting the overall exterior design into the six categories of panel attachment, door handles, door hinges, door latches, exterior panel material, and window material. These categories were laid out to make individual components that would not be restricted in how they were assembled leading to a modular product. The following designs and parts were chosen through a process of comparison through design matrices followed in some cases by validation through FEA.

The panel attachments chosen were a 3D-printed plastic connector that could be easily adjusted for angle and placement along chassis tubes. The door handles were simple recessed pull handle that could be placed wherever convenient and was cheap and easy to source. The door hinges were a commercially available marine hinge modified with a custom attachment method to ensure ease of installation and modularity. The door latches are a custom designed sliding latch that was designed specifically to be operated on either side of the door with gloved hands to improve safety and meet competition rules. Pre-impregnated carbon fiber panels were chosen for their low weight, high strength, and ease of manufacturing. Finally, a polycarbonate film was chosen for the windows as they were lightweight, flexible, and durable. This allows for variation in window shape and complies with the competitions rules as windows will not be able to shatter.

These various designs were then compiled into an overall exterior shell that demonstrated one possible application of the various individual components when assembled. This model also came with an economic analysis in the form of a bill of materials required to manufacture the demonstration model as well as instructions on how to assemble each part.

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