UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

"Stingray" Submarine for Underwater Inspection of Structures Using Composite Materials.

Proyecto de investigación

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Ingeniería Mecánica

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RESUMEN

El presente trabajo de titulación se centró en el desarrollo y construcción de la coraza de un submarino de investigación para la Universidad San Francisco de Quito (USFQ), con el objetivo de tener una plataforma multipropósito, adaptable, sumergible hasta los 100m de profundidad, construido con un molde impreso en 3D con PLA y recubierto de material compuesto, en este caso fibra de vidrio. Para realizar este sumergible se realizó un diseño basado en formas hidrodinámicas, desarrollado anteriormente por el laboratorio de vehículos autónomos de la USFQ. Lo primero que se realizó fue construir un prototipo de un cuarto del tamaño real para hacer pruebas de hermeticidad, sellado con pernos, y el moldeado de la fibra de vidrio al molde impreso en 3D. Finalmente se diseñó el esqueleto en tamaño real, se lo imprimió por partes y ensamblo. Posteriormente, se recubrió con el material compuesto, y se instalaron los componentes de control: motores, cables de fibra óptica, y controladores. Con el diceño sumergible completo se volvieron a realizar pruebas de controlabilidad, hermeticidad, resistencia a la presión a 100m de profundidad, y pruebas completas con el modelo funcional.

Palabras clave: submarino, materiales compuestos, fibra de vidrio, impresión 3D, sumergible, PLA.

ABSTRACT

The present graduation project is centered around the development and construction of an investigation submarine for the Universidad San Francisco de Quito (USFQ), with the objective of having a multipurpose, adaptable platform, submersible up to 100m of depth, constructed with a mold printed in 3D with PLA and covered with composite materials, in this case fiberglass. To make this submersible a design was developed based on hydrodynamic shapes, developed previously by the autonomous vehicles laboratory of the USFQ. The first thing to be done was to build a prototype a quarter of the size of the real dimensions to make tests to the hermeticity, sealing using bolts and the molding of the fiberglass to the 3D printed mold. Finally, the real size skeleton was designed, it was printed part by part, and was assembled. The mold was covered in composite materials, and the control elements were installed: motors, fiber optic cables, and controllers. With the submersible complete many tests were made such as maneuverability, hermeticity, resistance to the pressure at 100m depth, and complete tests with the functional model.

Key words: Submarine, composite materials, fiberglass, 3D printing, submersible, PLA, neutral buoyancy, hermeticity.

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INTRODUCTION

Antecedents

Autonomous Vehicles Laboratory at the The San Francisco University in Quito (USFQ) is in charge of the development and maintenance of an Unmanned Aerial Vehicle (UAV), an Unmanned All-Terrain Vehicle (UATV) and a Remotely Operated Vehicle (ROV). In the last seven years, the USFQ and its campus in the Galapagos Islands have been able to perform testing and operations using the ROV known as Orca II (Cabrera & Soria, 2011). Although it has been of great usefulness for shallow dives for research and investigation, the design and material used proved that immersions below 50 meters are not safe for the submarine, the material became corroded by the salty water, and it was difficult to handle and control.

Deep water immersion for inspection and exploration has been for a long time an unsatisfied need of the scientific community worldwide. To explore the diversity of nature, the underwater analysis of structures such as docks or piers, the analysis of condition of boat hulls, and the further mapping of the still unexplored sea bottom are just a few common problems difficult to address by human beings. These activities require high action risks, extremely trained personnel and high cost equipment. Hence, the solution of all the described problematic lies on the development and use of new submersible unmanned vehicles which can do all these tasks without the direct participation of humans.

The development of unmanned vehicles is one of the branches of robotics that has had an increased development in the past years, not only because it prevents the human beings from taking unnecessary risks, but also because it can reach places where humans can not. Remote Operated Vehicles or ROVs are a category of unmanned vehicles controlled remotely, and in the case of submarines, safely from the surface (Lin, Bekey, & Abney, 2008). This kind of vehicles work by transmitting information through an optic fiber chord known as Umbilical Cord (Cabrera & Soria, 2011). This connection is necessary for two reasons: first, the wireless transmission of information underwater is not easy: the water acts as a mirror deflecting the waves emitted from the transmitter without reaching the receiver (Lin, Bekey, & Abney, 2008). Advanced mechanisms use sonar-based communication, that can travel through water without any problem. However, these mechanisms bring out the second problem which is the budget. A sonar communication system can cost around 5000 USD, whereas the meter of optical fiber cable costs around two dollars per meter (Andrade, 2018).

Ecuador is one most biodiverse country in the world and much of this biodiversity lies in underwater regions such as the Galapagos islands (INEC, n.d.). It is of deep desire to learn what can be found in deep water without damaging its delicate ecosystem. Additionally, as an oil exporting country, Ecuador remains interested in developing technology that can help assist in surveillance and investigation of underwater structures, given that a big portion of Ecuador exportation products lies in the deep ocean as well. Seafood such as shrimp, fish and oysters belong to around 20% of the total Ecuadorian exported products (The Observatory of Economic Complexity, 2018). Based on this information, it is intuitive that there is a big area of application for ROVs in Ecuador that can be used from maritime exploration to status analysis of underwater structures. Ecuador as a developing country does not have much investment in the area of robotics, nevertheless the application of the new upcoming technologies is huge in a country such as Ecuador.

In 2011, Universidad San Francisco de Quito and the laboratory of autonomous vehicles introduced for the first time a submarine capable of deep-water investigation and underwater inspection named Orca. In 2014 the model was improved creating the new version Orca I (Cabrera & Soria, 2011). Both models were functional and successful for deep water inspection; however, their difficult maneuverability and need for more resistant materials have pushed us to develop a new design with a more hydrodynamic shape for better control and increased resistance by using better and lighter materials.

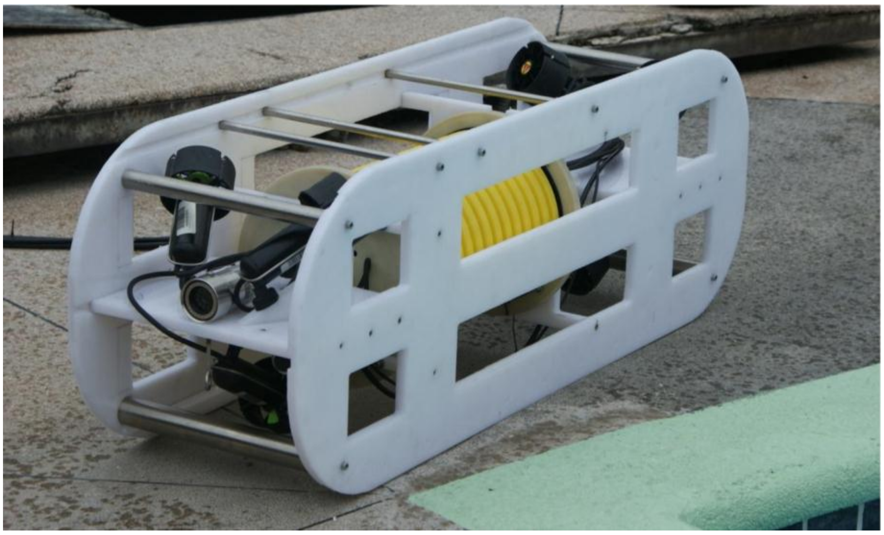

Figure 1 ORCA I finished model (Cabrera & Soria, 2011)

Stingray, as the new model was named, has an improved design, naturally shaped as a stingray, so that it is more hydrodynamic when moving underwater using a streamlined body to reduce friction with the water, in the same way as the body of a stingray does, this can be observed in Figure 2 Drag coefficients on objects of different shapes . The external shell will be built using 3D printing polymers as a base and cast, and then covered with fiber glass and vinyl ester resin. 3D printing gives us the advantage of making fewer parts for the assembly and thus giving us less stress concentrators in the moment of assembly. The use of composite materials, such as fiberglass, will increase the submarines resistance to deep water pressures and its structure will be lighter than the previous models (Sikora, Gaff, Hysek, & Babiak, 2018). The composite shell is expected to reach a dept of 100 meters under the sea surface.

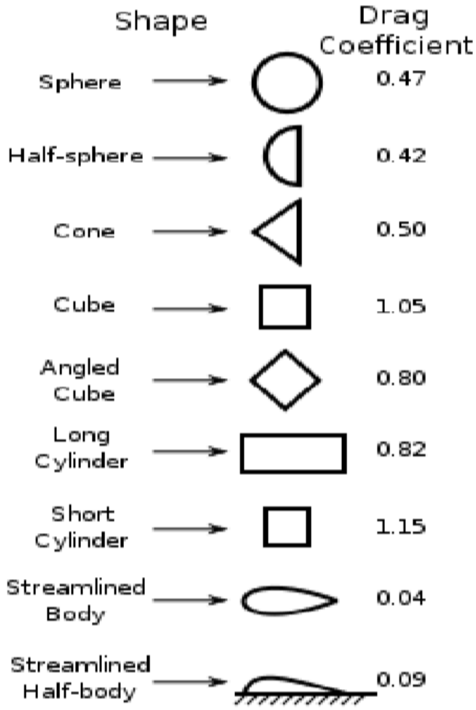

Figure 2 Drag coefficients on objects of different shapes (Cabrera & Soria, 2011)

To guarantee that the submarine hull will resist the high pressures, a prototype will be created and tested before the construction of the actual design. This prototype will have to prove to be hermetic and resistance to high pressures in order to build the actual model. The final version of Stingray will be tested in for conditions that are essential for a submarine, such as hermeticity, floatability and resistance to high underwater pressures. Finally, the whole submarine will be assembled using the motors and camera of the previous model, Orca I, to realize an open sea under water submersion to prove the validity of the new design.

Theoretical framework

Stingray will have to operate in harsh underwater environments with high pressure, elevated salinity and various obstacles. For this reason, the submarine will have to be designed considering a number of factors. Such factors include buoyancy, water pressure, hydrodynamics, sealing, mobility, steering, stability and materials.

Water pressure.

In an incompressible fluid, such as water, pressure generated by the fluid around any point increases constantly with depth (Gerhart, Gerhart, & Hochstein, 2016). This phenomenon, also called hydrostatic distribution, comes from a direct relation between the depth of the point being examined, and the specific weight of the fluid:

$$p = \gamma h + p_i$$

Where p and p_i are the pressure at one point and the pressure at the surface respectively, γ is the specific weight of the fluid (9.807 $\frac{kN}{m^3}$ for water), and h is the depth of the point being examined (Gerhart, Gerhart, & Hochstein, 2016).

This is important for the project being developed, for it is this equation that gives us the biggest challenges. As mentioned in the scope, the objective of the present investigation project it to develop the hull of a submarine capable of reaching a depth of 100m below the water. This would mean that the submarine would be experiencing pressures of up to 980.7 $\boldsymbol{kPa}$ or 10 atm. Pressures strong enough to put any object under stress and heavy forces.

Buoyancy.

Buoyancy is a force that any body experiences when submerged in a fluid that acts upwards, or against the force of gravity (Gerhart, Gerhart, & Hochstein, 2016). This force is the resulting net force generated by the difference of pressure generated by the fluid on the object that increases with depth, so that the force acting because of the fluids pressure on the bottom of the object is greater than the force acting on top of the object.

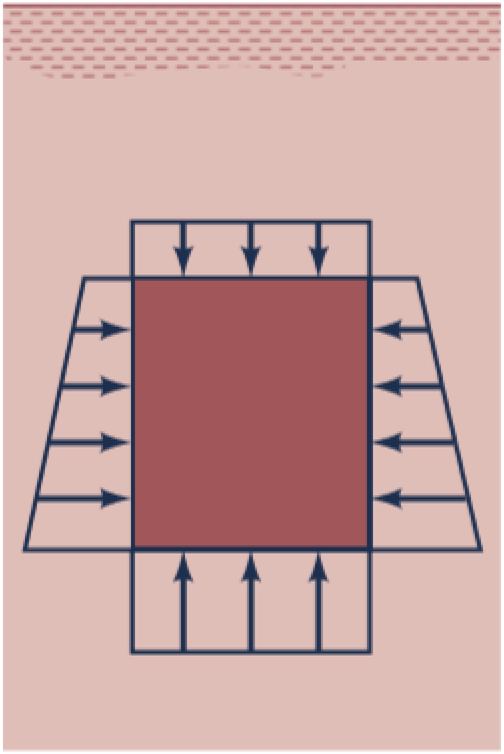

Figure 3 Pressure on a submerged body (Gerhart, Gerhart, & Hochstein, 2016)

In simple terms, the buoyant force experienced by the submerged body is a direct relation between the body's volume, and the specific weight of the fluid it is being submerged in:

$F_b = \gamma V$ (Gerhart, Gerhart, & Hochstein, 2016)

Where γ is the specific weight of the fluid, and V is the volume of the submerged object. This force acts on a geometrical point inside the submerged body called the center of buoyancy, which is the point resulting from the moments of the forces acting on the body from all sides.

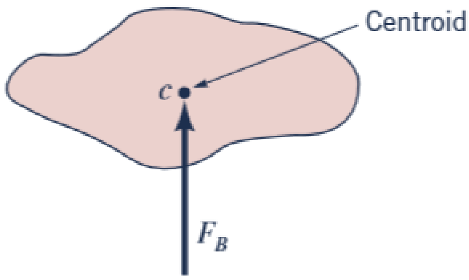

Figure 4 Center of buoyancy on a submerged body (Gerhart, Gerhart, & Hochstein, 2016)

Stability.

The term stability comes from the result of the action of different forces on the submerged body. As it is known, a submerged body experience the effects of the gravitational force (weight) acting on its center of gravity, and a buoyant force resulting from being submerged in a fluid acting on its center of buoyancy. These two forces act in different directions, and most of the time the centers, in which these forces act, are not in the same point. This causes moments and forces that intend to place the weight of the body directly beneath the center of buoyancy (Gerhart, Gerhart, & Hochstein, 2016).

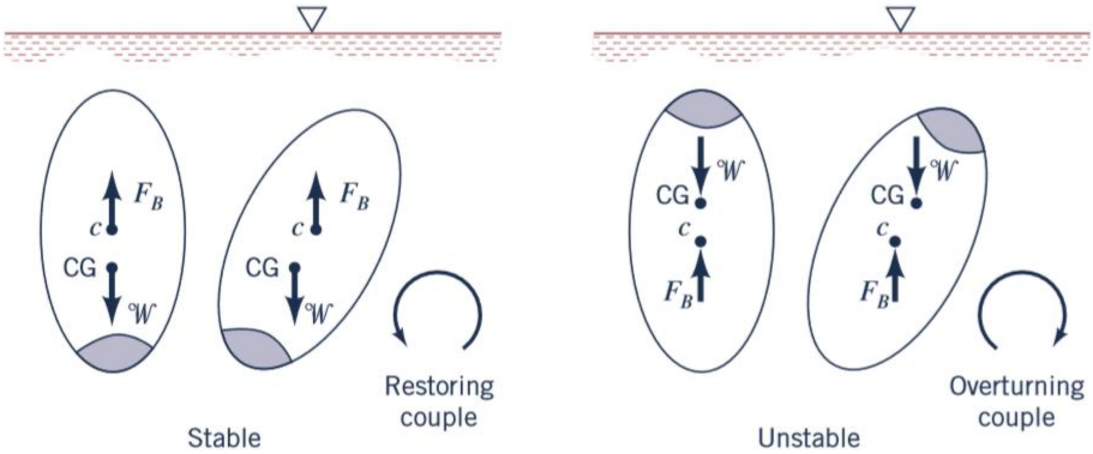

Figure 5 Stability of submerged bodies and restoring couples (Gerhart, Gerhart, & Hochstein, 2016)

As Figure 5 Stability of submerged bodies and restoring couples shows, any case where the center of gravity and the center of buoyancy are not aligned and in which the center of gravity is not below the center of buoyancy, a restoring couple will appear to bring the bodies to a stable equilibrium (Gerhart, Gerhart, & Hochstein, 2016).

Hydrodynamics.

To understand the basic physics of how the fluid, for which the submarine is being developed, is essential for the correct definition of a variety of components within the project being developed. For the present fluid, in this case water, it can be assumed that it is an incompressible fluid, for which the density does not vary depending on the pressure (as it does with compressible fluids), and whose viscosity is low (Gerhart, Gerhart, & Hochstein, 2016).

The ROV being developed in this project will be subject to different flows of water through currents, some fast and some slower. For any fluid, it is necessary to understand that it can flow in two different ways: as laminar flow and as turbulent flow. Which one it is in reality depends on the speed in which the fluid is flowing, and the consequence of this is going from the steady, orderly flow of a laminar flow (in which streamlines in water flow in parallel to one another), to a distorted, disorderly flow of the turbulent flow (streamlines maintain no similar direction between them) (Gerhart, Gerhart, & Hochstein, 2016).

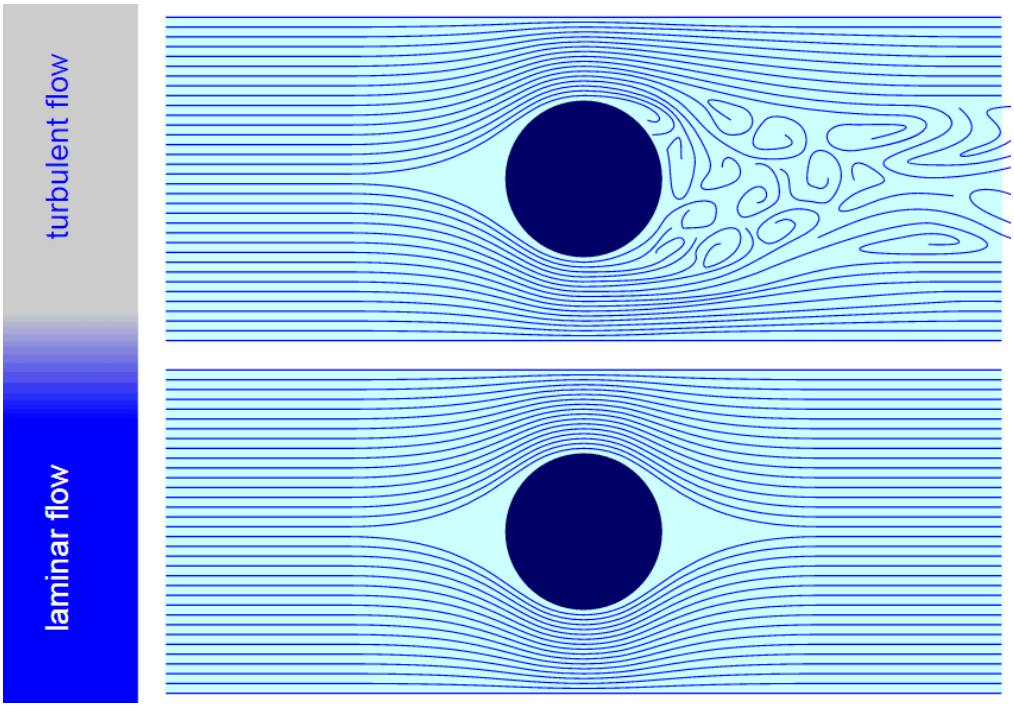

Figure 6 Comparison between laminar and turbulent Flow (Gerhart, Gerhart, & Hochstein, 2016)

Thanks to the Streamlined design of Stingray, the friction between the ROV and the fluid will be smaller than in other designs such as Orca (as seen in Figure 2 Drag coefficients on objects of different shapes), and the shape will allow to avoid loss of controllability created by the vortex created in fast moving fluids around objects like this submarine.

Sealing.

This part of the design of the *Stingray* will carry the heaviest burden regarding testing and control. The submarine will need to have a dry compartment inside where all the electronics, in charge of monitoring and controlling the submarine, must be safely sealed and maintained away from humidity that can damage them. This means that many tests will need to be conducted demonstrating the seal of the submarine before including any control elements.

The present task will need to be achieved by finding the best way to guarantee a hermetic seal around the vessel. For this, the team has designed joints using rubber and silicone as isolation and nutted bolts to assure a strong closure that can avoid the filtration of water, even at the highest depths and with 10 atm of pressure around the hull of the submarine.

Materials.

In this project being developed, two main material groups will be required. The main objective of the development of this submarine is to test the suitability of composite materials for underwater applications that require resistance to high pressures and extreme conditions. Additionally, to this, 3D printing techniques will be utilized to make the base structure for the submarine. These two groups of materials have a variety of differences, but this research will try to prove if together, the materials can accomplish the objectives of this project.

3D Printing using PLA.

Throughout the last decade, 3D printing has become an accessible option for testing, prototyping and design open for both personal and commercial uses. This platform of great versatility allows for the creation of bodies and objects of great complexity in short periods of time, and with a variety of plastic materials that can be from (although, new methods are being developed to use 3D printing with metals and organic material). For this reason, a 3D printed cast of the *Stingray* will be created, taking into account its unusual shape that would have had a great cost if it were to be produced through common machining, and would have taken much longer to complete.

The material selected for this task, PLA (Polylactic Acid), is a "thermoplastic derived from renewable resources such as corn starch or sugarcane" (Giang, 2018). This material, after making comparison to others available to us, demonstrated to have the better properties for the project at hand. First, its tensile strength has been tested around 37 MPa (Giang, 2018), making it stronger than other materials for 3D printing, and because it has better part accuracy than other materials (Giang, 2018).

Composite materials – Fiberglass.

Composite materials is a rather new category of materials that work through the principle of combined actions, a principle under which through the combination of materials with different characteristics, the characteristics are combined in this new composite material (William & David, 2014). These materials, generally artificially made, are chemically dissimilar and have distinct interfaces, this allows for the creation of materials with lower densities, stiffer, stronger and better at handling corrosion than the normal plastics, polymers and metals, or to customize the characteristics desired (William & David, 2014).

Most composite materials are built and designed using normally two parts: a dispersed matrix that surrounds the whole material and is commonly continuous in the material, and a dispersed phase, which varies in geometry, dispersion, size and orientation, depending on the type of composite that needs to be achieved (William & David, 2014). The characterization of the composite depends if the dispersed phase is particle reinforced, fiber reinforced, structural (layer) reinforced, or nano-particle reinforced (William & David, 2014).

For this reason, the design process of this submarine included a phase in which the best material had to be chosen for the submarine, in the case of the proposal of the project at hand, the material chosen to be further analyzed and tested was fiberglass. Fiberglass is a fiber reinforced composite material, that uses glass fiber (thin strands of silica extruded through heating and drawing of glass (Martynova & Cebulla, 2018)) as the dispersed phase, and resin of different types as matrix over the glass fiber. Although Carbon fiber had better strength and lower density than fiberglass (Innovative Composite Engineering, n.d.), in the medium there is no provider for the amounts that were required for the project, the price was beyond the proposed budget, and the material properties exceeded largely the technical requirements of this project.

Table 1 properties of fiberglass

Properties Fiberglass		
Description	Units	Value
Elastic modulus	N/m^2	7.20E+10
Poissons ratio		0.21
Shera modulus	N/m^2	3.00E+10
Density	Kg/m^3	2550
Tensile Strength	N/m^2	1.95E+09
Yield strenght	N/m^2	2.75E+09
Thermal conductivity	W/mK	1.20E+00
Specific heat	J/KgK	8.00E+02

MATERIALS AND METHODS

The purpose of this project is to improve the design of the previous version and enhance the best qualities it presented. In order to do so, the focus must be on what were the main problems Orca I and II presented and what it can be done to correct them, once the solutions to the problems are clear the methodology to reach to the final model of *Stingray* will be discussed.

The first problem Orca I faced is that it did not have a good hydrodynamic profile due to its shape. The body of Orca I was built so that it would resist the high underwater pressure without compromising any of the components in its structure, however this shape is not a good design to move easily in underwater conditions. According to engineer Carlos Andrade (operator of Orca I at GAIAS center at USFQ) this design was difficult to control and had little maneuverability at the moment of testing it. It is essential to correct this aspect, important in any ROV, because the submarine should be able maneuver easily in different environments without an operator struggling with its control. *Stingray* will be designed with a more natural, hydrodynamic profile based on the shape of a stingray. The new design allows the hull to cut water so that it can move better in water than the previous version.

A second improvement from Orca I tried to achieve is the depth at which it can dive. Orca I was able to submerge 50 meters underwater without failure, for the design the team wanted to push this limit further by making *Stingray* capable of submerging up to 100 meters. To do so, the design will use more advanced and tougher materials capable of resisting bigger loads of pressure. The best materials for this application are composites. Using hybrid materials such as composites will provide the new design with more strength to resist high pressures of 100 meters underwater. The hybrid combination of a matrix and a reinforcement of a composite guarantees us that the design will have an increase strength, but it also will be light (Fleisher, et al., 2018). The use of a matrix such as resin to bind the fiber reinforcements increases the resistance of the material and decreases its weight, making it easier to move underwater and using less energy in the motors to move it.

Finally, the design has to improve the accessibility to the electronic components in *Stingray*. Because *Stingray* will be assembled with two identical shells using screws and bolts so that it will be easier to open to get access to the main components inside it in the dry compartment, thus making it more efficient to maintain. This is why the design was changed into two identical parts which are assembled into one prior to each immersion. The design was changed (which was made as a solid) and emptied it so that the design looks like a hull. A surface is needed to be drilled to place the screws and make the assembly possible. To solve this a flange was added into the bottom surface.

Design

Next, the methodology that was used in this project to reach the final design of Stingray will be discussed. The first step is to guarantee the improvement of the CAD model made using the software Autodesk Inventor. The version of the model on which *Stingray* was based on was developed by Javier Caceres and Salome Saldaña, mechanical engineering students at USFQ, as a new design proposal for the class "Investigación y Desarrollo" (a class taken by senior mechanical engineers at USFQ) (Saldaña & Cáceres, 2018).

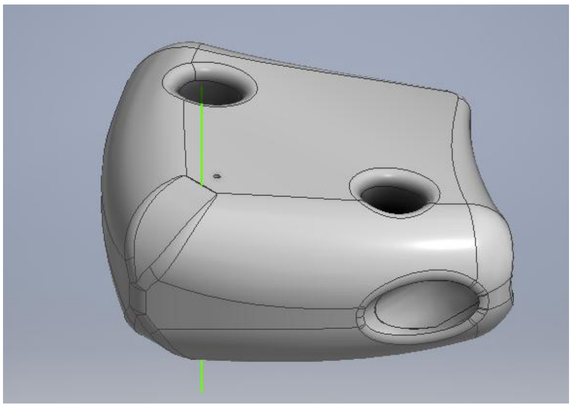

Figure 7 Design as handed to us

Selection of design and profile

To achieve the desired hydrodynamic characteristics for stingray, the next steps were followed. First, as mentioned earlier, a streamlined profile had to be the base for the design, because it has the lowest friction with any fluid flowing around it. For this, the shape of a symmetrical airfoil was chosen as the base for the design (Saldaña & Cáceres, 2018).

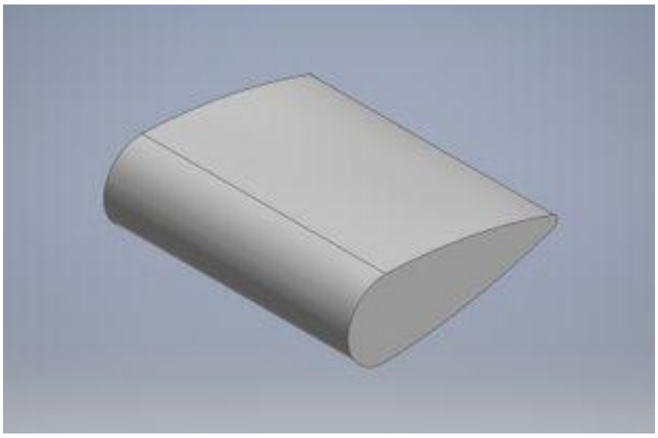

Figure 8 Airfoil used as base

Using the airfoil as base, the shape of a stingray was carved into the design, and using this, rough corners were eliminated and rounded, creating the design that can be observed in Figure 7 Design as handed to us (Saldaña & Cáceres, 2018). From this design, further optimization had to be made in order to make the design further streamlined, so that it can handle better in water.

Design optimization

The first step taken for the final design was to eliminate all the stress concentrators, such as sharp edges and corners that were included in the last design presented by Saldaña and Cáceres. The hull was emptied leaving a shell of 3mm of thickness, and an edge of 4 cm was added to the lower border of the hull so that the bolts have enough space to be assembled. Based upon the final CAD achieved for the design, the prototype could be designed by scaling the real size model or create the pieces to be printed in PLA. The Design can be seen in Figure

9 Final design. For the final design, two symmetrical halves were chosen so that the assembly and access to the interior of the submarine can be easier for the user.

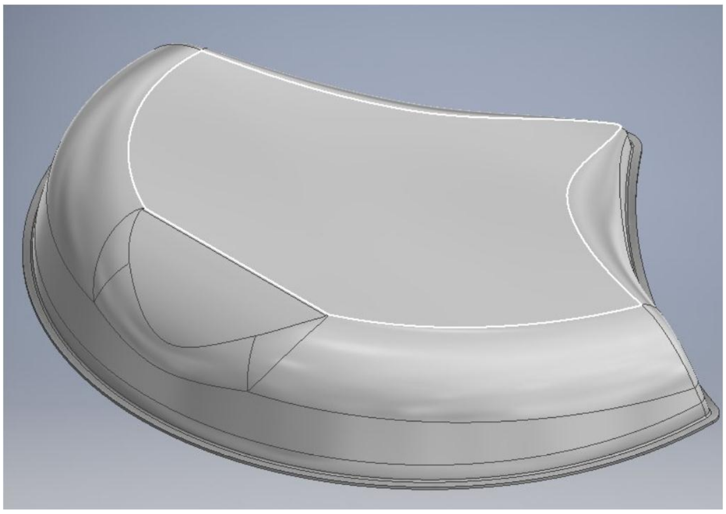

Figure 9 Final design

Prototype planification and construction

Once the design for the real size version was ready, it was scaled to 1:4 (0.25 times smaller) so that the prototype would have around 20 cm in wingspan. The 3D model was printed using a PLA fiber of 3 mm diameter, this printed version was the first scaled prototype created.

There are some tests that were made in this protype in order to validate the design. First, the adhesion of the fiber glass to the surface of the PLA material of the prototype was checked. Because fiber glass needs to be added to a cast, which is usually fabricated using polyester, the fiber glass was molded through layers using epoxy resin so that the layers of fiberglass would stick together. In order to economize the project, a test was planned to see if the cast could be made from 3D printed material using PLA: this would save the project a big portion of the budget by avoiding the creation of a polyester cast. The resistance of the coats of fiberglass will be tested to correctly measure the number of coats needed to support the pressure.

Figure 10 PLA cast

The original plan was to use the PLA as the structure for the submarine and use less fiber glass layers, nevertheless, on the first experiment, using only one layer of the fiber glass it was evident that the fiber glass will not stick together with the PLA plastic. This test made us change the initially planned idea of using the 3D printed body as structure by using it as a cast only. For the second test, unmolding grease was used to intentionally avoid the fiber glass and the PLA to stick together. The 3D printed model was covered with 5 layers of fiber glass (3 roving unidirectional fiber and 2 mat multidirectional fiber) using the epoxy resin. The team was careful to mold the fiber into the shape of the 3D print model so that the shape would not be compromised. After letting it dry for approximately 3 hours the result was satisfying. A resistant fiber glass hull with the desired shape was obtained.

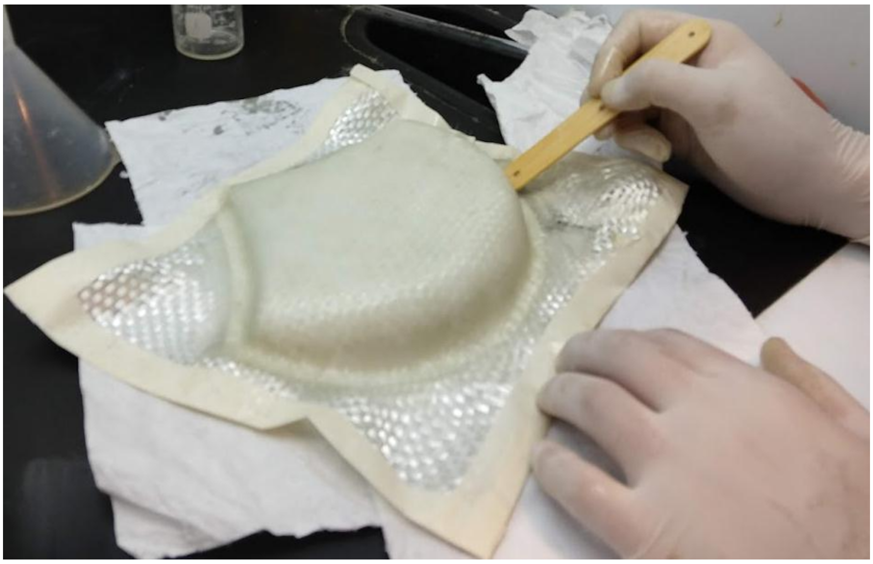

Figure 11 Prototype construction

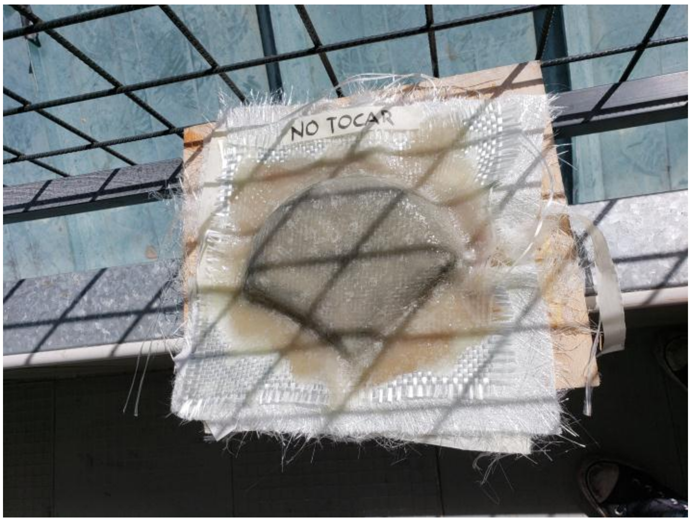

Figure 12 First try at fiberglass coating on PLA

Even though the shape and resistance of the hull was the desired, the fiber glass hull presented some issues that could compromise the future tests. Many bubbles were formed causing some parts to have irregular shapes and the epoxy resin was not spread evenly. In order to correct these problems, a second model was made using the same method and layers. This time the team tried to correct the problems from the previous model. The second model turned out to be better and perfect for testing. Because the submarine is symmetrical, a third model was made, using the same method as the first and second model, so that the two halves could be assembled, and tests could be run on the assembly. When both parts were ready, the excess of fiber glass was cut off and the surfaces were made even using sandpaper.

Prototype Hermeticity Test.

Another reason to use the prototype is to test its hermeticity. Once the prototype was assembled and put through several tests at different depths and for different amounts of time. The first test that was made on the assembled prototype submarine was the hermeticity test. Once the two surfaces in contact were completely leveled, eight perforations were distributed as evenly as possible so that the stress distribution in each part of the border was equal. To prevent the water from getting inside in the union of the two halves, a piece of rubber of the same material used to isolate doors and windows in cars was used. The two halves were assembled with the rubber in the middle and tied them using screws. A piece of paper was introduced inside to indicate if water was getting inside or not.

The first hermeticity test consisted in introducing the prototype approximately 30 cm under water for 15 - 30 minutes. The first test was not successful because the piece of rubber used was not a continuous piece, it had a union which was a weak spot for the water to enter. The second test a rubber sheet of 1.5 mm thick was used, with this material unions can be neglected. It was cut in the shape of the submarine, and the experiment was repeated: 30 cm under water for 15 minutes. It was unsuccessful again, this time it was concluded, that water got inside from the holes for the screws. For the final test thermoresistant silicon in layers was added between the rubber and the fiber glass shape. The test was repeated with the same conditions and proved that the design on de seal worked perfectly at shallow depths.

Figure 13 low depth hermeticity tests

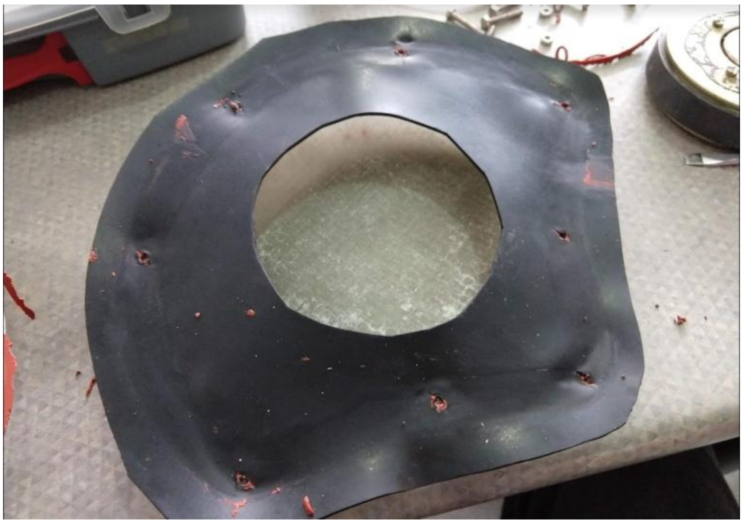

Figure 14 rubber seal

The final test of the prototype was to prove the hermeticity of the seal at lower depths. For this, the prototype was submerged in lake San Pablo, in Imbabura (Ecuador) at a depth of 10 meters. The protype and the seal worked perfectly after being submerged for over 30 minutes once again. With these tests validating the design the 1:1 scale model can be built.

Figure 15 preparation of hermeticity test

Prototype Compression Test.

In order to test the maximum load that the fiber glass will support, one of the halves was submitted to a compression test using the mechanical engineering lab's tools for compression testing, generally used to test loads in concrete structures. The prototype built for hermeticity testing of dimensions of approximately 23x20x4.5 cm (width, length and thickness) was used for this test. The machine compressed the fiber glass model until load fail occurred. The obtained graph was the one obtained in Figure 16 Compression test results on prototype.

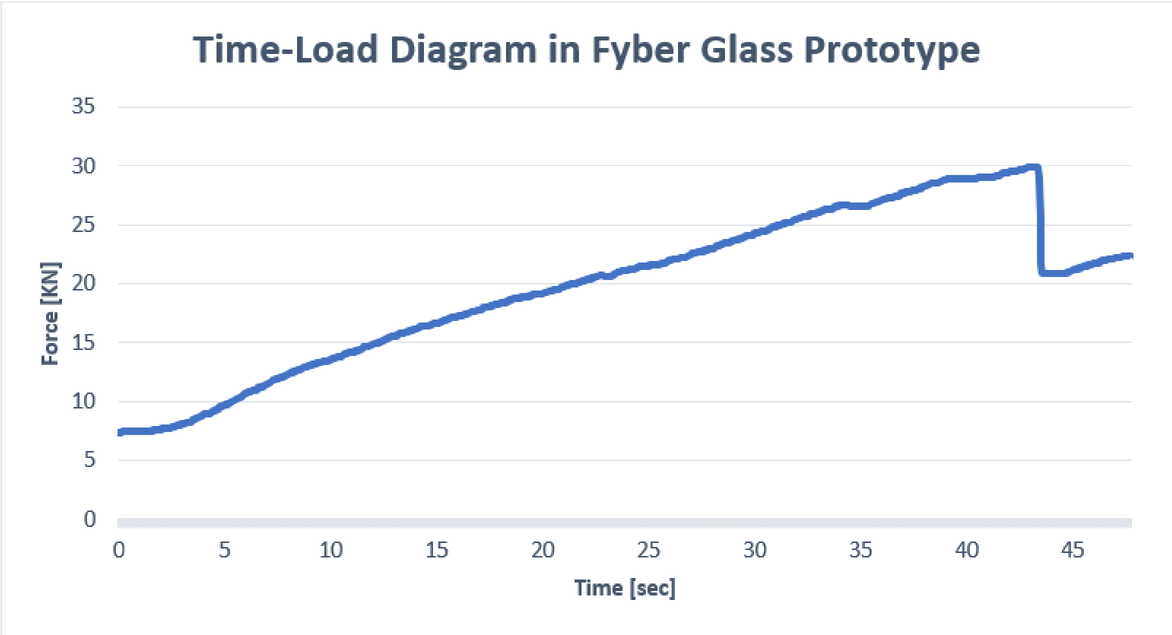

Figure 16 Compression test results on prototype

It can be seen that the fiber glass supported a maximum load of 29.923 KN in an area of approximately 10 cm in diameter in result this gives us a stress of 3.8099 MPa. Because of fiber glass are fragile, unlike metals like steel, the failure is abrupt. Knowing that the pressure 100 meters deep into water is 980.97 KPa it can be concluded that the material is going to resist the pressure at 100 meters using a safety factor of approximately 3.8838. This failure occurs when the fiber reinforcement, in this case glass fiber, is unable to resist the pressure and breaks in what could be described as a fragile failure. This is important because at this point the materials is unable to maintain its structural integrity and if it remains under pressure the cracks will propagate to the rest of the material.

Prototype Conclusions.

For all the present purposes, during the prototype and the final model, the agreed upon method of production is to create a skeleton with the desired shape using 3D printing techniques, and to reinforce it with several coatings of fiberglass and its resin, while varying the fiberglass' structure to obtain better results both in structural strength of the submarine and finishing. As it can be seen, the market offers different qualities of fiberglass with different characteristics, for it can be used as a structural element or a finishing coating (Arias, 2018).

CFD Stingray vs Orca II

With the CAD design finalized, other tests were conducted on the submarine by using computerized simulations that could be set using the maximum pressures, speeds and other external conditions that the vessel could experience underwater at 100m depth. To do this, simulations were run using Solidworks 2017 to simulate pressure and velocity using CFD (Computer Fluid Dynamics) over the hull, and hydrostatic pressure over the body to see stress points and bending on the submarine.

CFD – velocity and pressure simulations.

With the final computer model, several simulations in Computer Fluid Dynamics (CFD) were made using Solidworks 2017 to demonstrate that the design handles correctly when fluids are applied in different directions and at the theoretical maximum speed.

In order to prove that the design will not cause any undesired stresses in the new design, to prove its hydrodynamic behavior and to see the critical points when the new submarine design moves underwater some CFD simulations were run. Default conditions from the Solidworks library were used such as the water density, temperature and water behavior. The only parameter that was set is the water velocity moving in an x direction and crashing against the submarine hull at a velocity of 1.5 meters per second is the average velocity of the Cromwell current (Knauss, 1959) which is the fastest underwater current at a depth of 100 meter that the submarine will be facing, thus it was used as the velocity for this simulation. This was the only parameter that was changed, the other parameters such as pressure, temperature, water density, etc. were left constant. Each CAD of Stingray and Orca II were subjected to the same parameter of velocity and ran the simulations.

The following figures will describe the results obtained by doing the CFD analysis. First, some images of the flow trajectory described by the fluid at the moment of collision against the bodies were taken. A surface plot of the pressure generated by this collision was also added to see where the main concentrators of pressure were.

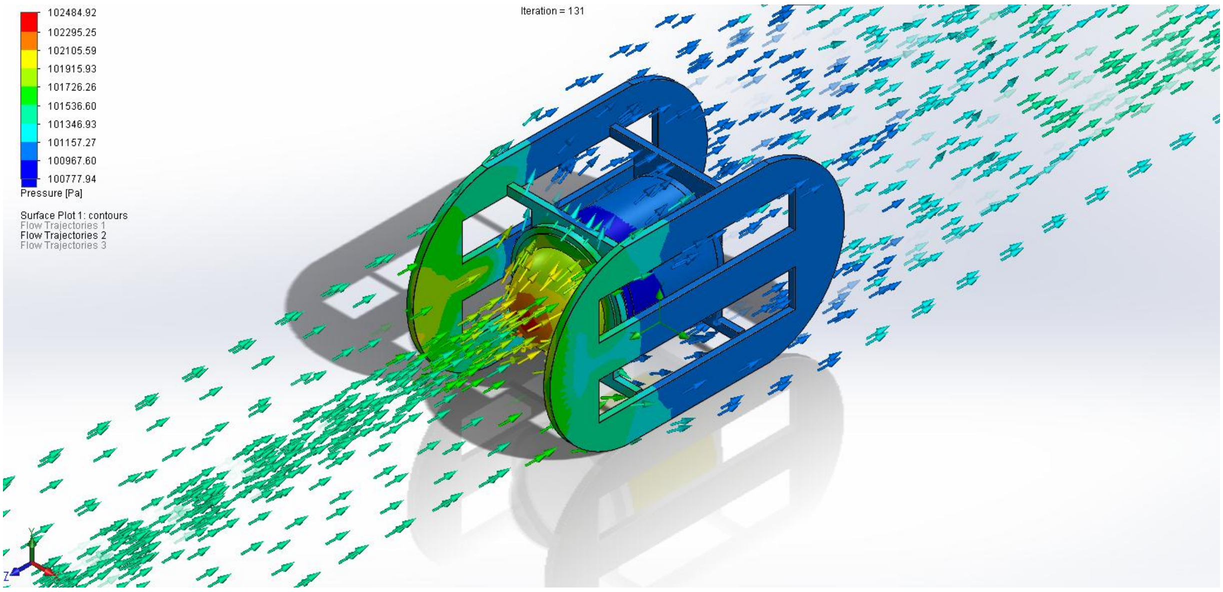

Figure 17 streamlines Orca II

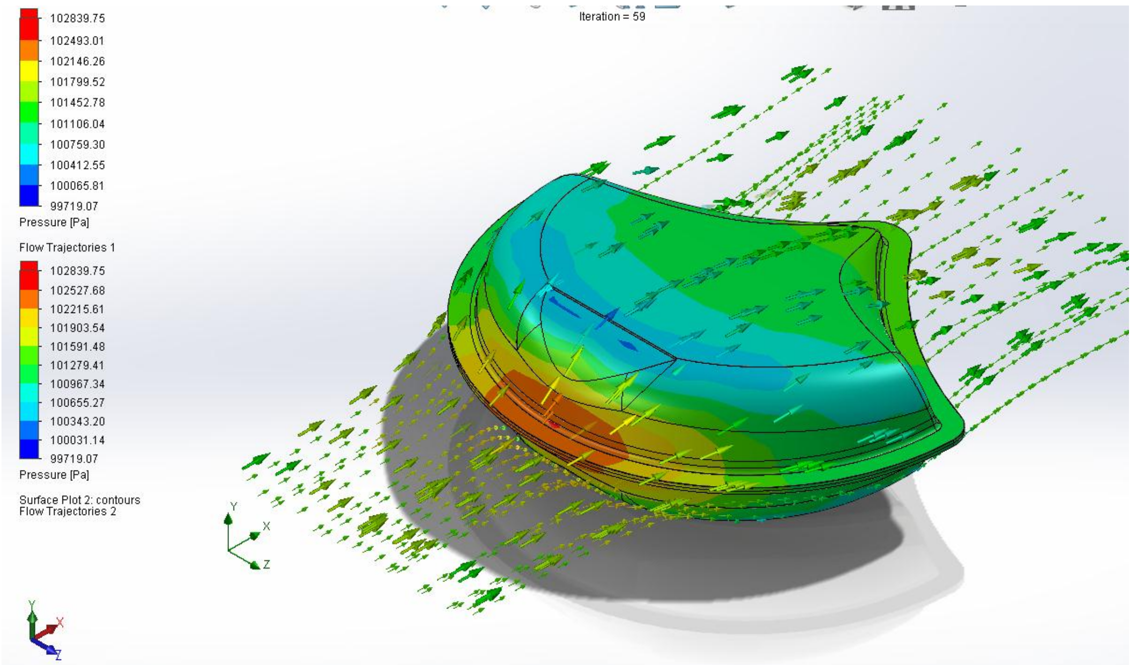

Figure 18 streamlines Stingray

By seeing the results of both Orca II and Stingray it can be seen that the streamlines in Stingray distribute better along the surface. It can also be seen that the only point that works as a stress concentrator is the front part, however this is not so meaningful because the pressure caused by the fluid's velocity is distributed uniformly across the surface.

In the other hand, Orca II has a bigger stress concentrator in the front and as it can be seen in the simulation the streamlines do not distribute evenly along the surface. This is a problem because it can cause the creation of vortex or turbulent flow in the back of the submarine Orca II. After this analysis some cut plots were made to see how the hydrodynamic profile of each submarine behaves by analyzing pressure and velocity. The first two plots correspond to the pressure cut plots.

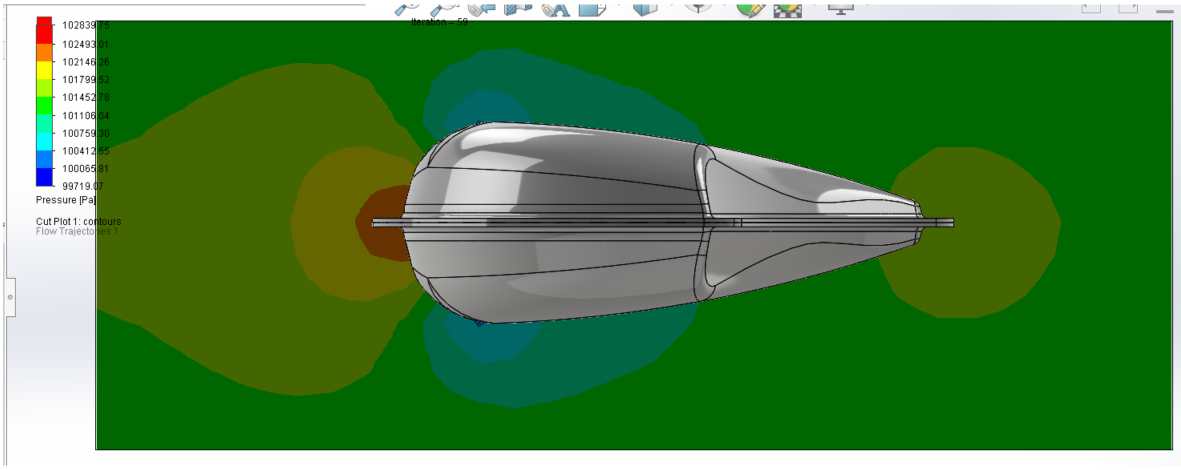

Figure 19 cut plot pressures Stingray

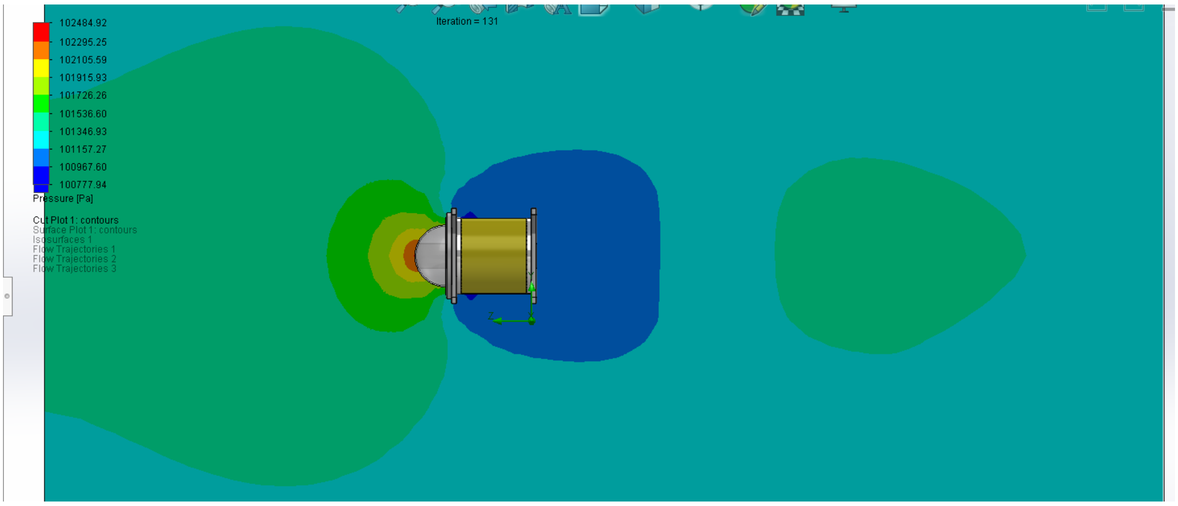

Figure 20 Cut plot pressure Orca II

As it can be seen in the pressure cut plot analysis the low-pressure points are in the change of curvature in the Stingray model. This normal in a profile such as this one. Orca II model has a low pressure point in the back which because of the difference of pressures causes the submarine to lose its forward velocity. Finally, the cut plot for the velocity was generated.

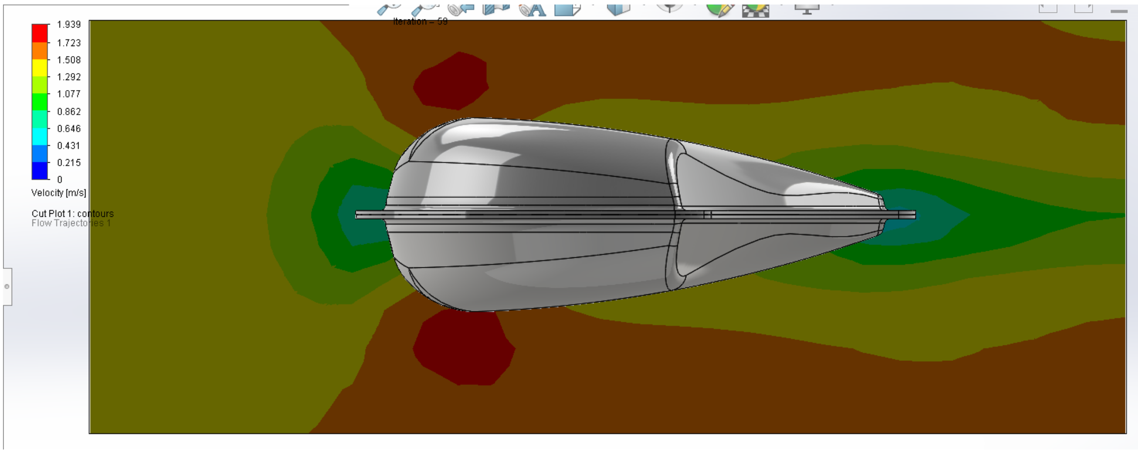

Figure 21 Cut plot velocity Stingray

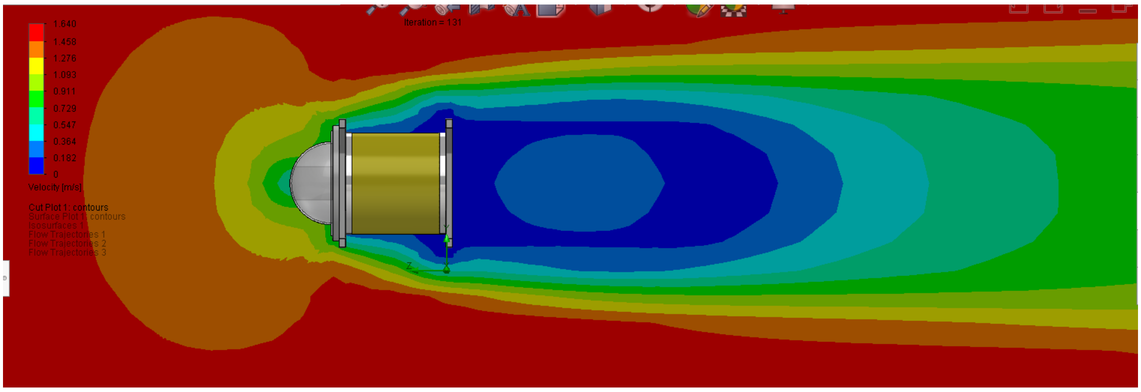

Figure 22 Cut plot velocity Orca II

The cut velocity plots show us that Orca II has a stagnation area in the back of its design. This is a problem because the stagnation in the back causes vacuum effect that affects the movement of the submarine at the moment of the movement. In the other hand, Stingray has its biggest velocity values in the top and bottom part of the faces, which makes it move in water easily. Stingray does not have any stagnation points as you can see in the simulation.

Drag calculation.

Using the force resulting from the CFD analysis of both submarines, it could be determined which design is better based on their drag coefficient, which implies how much friction the body has when moving through a fluid (Gerhart, Gerhart, & Hochstein, 2016). For this, the force experienced by the Orca II is Fd = 63.19N and for the Stingray is Fd = 55.49N, both at 1.5 m/s. Using the cross-section area of both submarines (0.0711 m^2 for Orca, and 0.0927 m^2 for Stingray) and the formula:

$$C_d = \frac{F_d}{\frac{1}{2}\rho v^2 A_c}$$ (Gerhart, Gerhart, & Hochstein, 2016)

Where Ac is the cross-section area, ρ is the density of water and v is the velocity, the drag coefficients are 0.73 for Orca II and 0.27 for Stingray. Meaning the Stingray is better hydrodynamically than the Orca II.

Hydrostatic pressure simulation.

The hydrostatic simulation was done applying a pressure border condition equal to the 0.98 MPa that the submarine will be facing at 100 meters. The analysis was done in one half of the submarine lid since it is symmetrical. The bottom flange was applied a fixed condition and the simulation was ran. The following results were obtained:

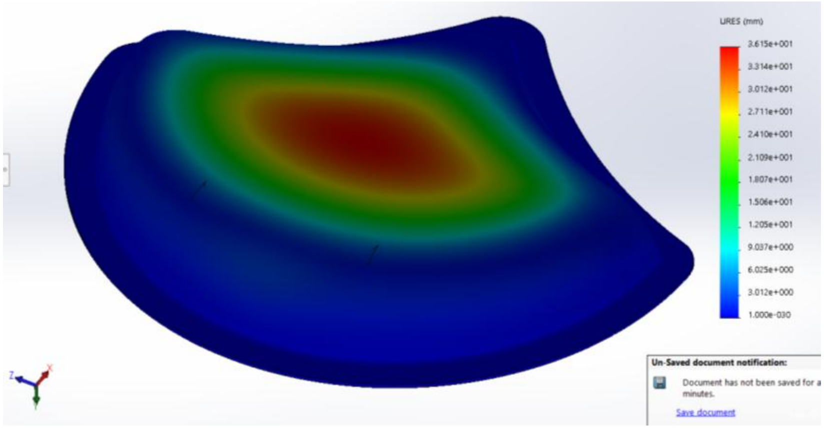

Figure 23 Deformation plot

The following results were plotted: deformation, strain, principal stress 1, principal stress 3 and shear stress in the XY plane. By doing this the following things can be said from the simulations. Since Stingray has a flat part near the tail, the hydrostatic pressure affects deeply in this area and therefore the largest deformation is in this point.

The strain plot shows that the weak spots are in the wings side, however it is not that significant because of the high resistance this area has.

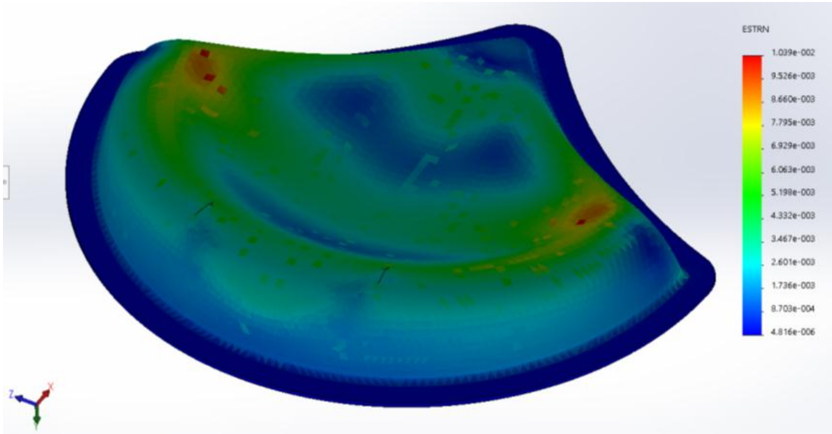

Figure 24 Strain plot

The principal stresses 1 and 3 show that there are some weak areas along the surface, however since this is the most resistant area it is not that significant.

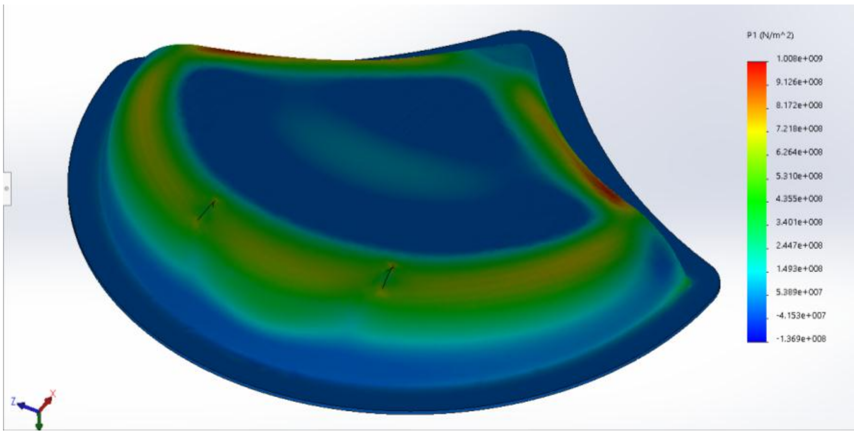

Figure 25 Principal stress 1

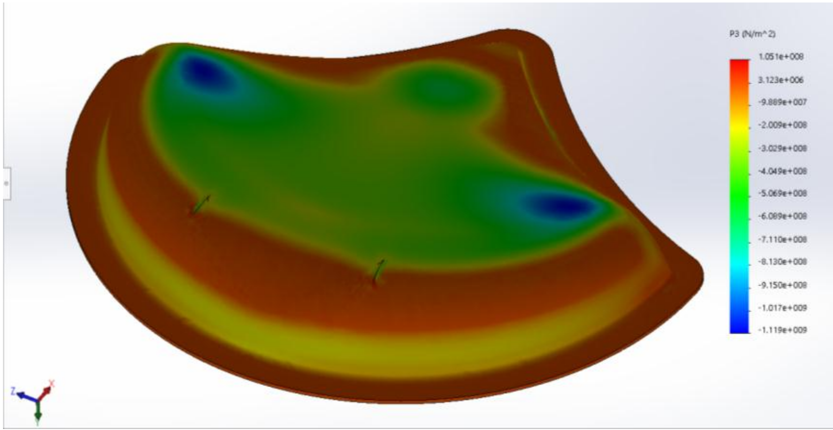

Figure 26 Principal stress 3

The safety factor is a feature Solidworks offers here that can validate that the design has a safety factor of minimum 2.3 which is good for a simulation a guarantee that the design is working in a safe zone. Finally, the shear stress simulation shows that there is a shear stress concentrator along the front hull surface.

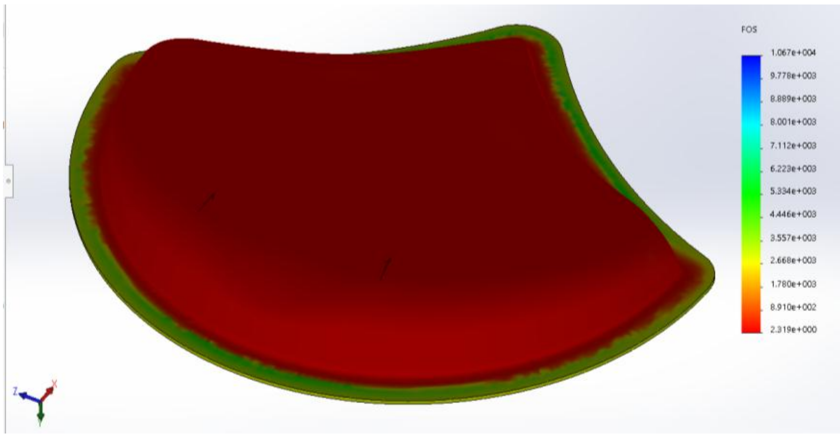

Figure 27 Safety factor

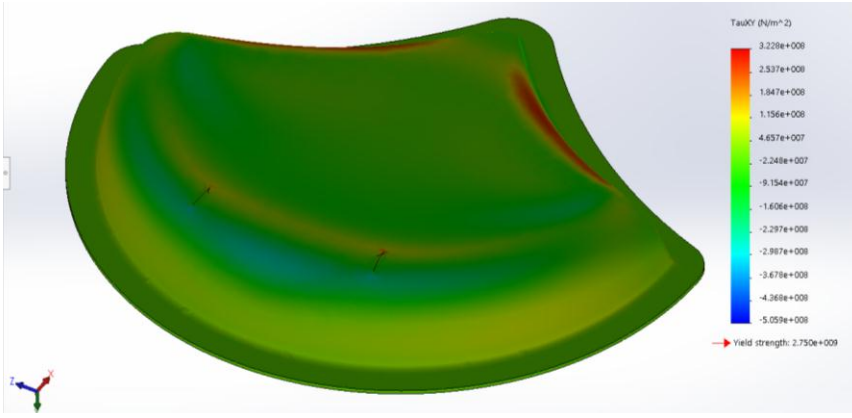

Figure 28 Shear stress in XY plane

Real size model Cast design and construction

After the test on the prototype were finished, and the design was validated for the characteristics it was being tested. The design of the real size model began. For this, the same design was used, with some minor changes in order to be able to print this real size model. For this, the limitation is the volumetric capacity of the 3D printer being used. In order to be able to print the whole hull, and that it maintains structural integrity when assembled, the design will be fragmented into puzzle-like pieces that will fit together and which, after the fiberglass coating will be permanently joined. This will be made using 3mm PLA as material for the 3D printer, and the width of the printed shell has been decided it will be 3 mm. The division had to be made because the 3D printer used has a printing volume of 280x280x250 mm, and the submarine is considerably bigger. Considering the volume limitation, the submarine was divided into 13 pieces, all of them with dimensions that can fit in the 3D printer used for the project.

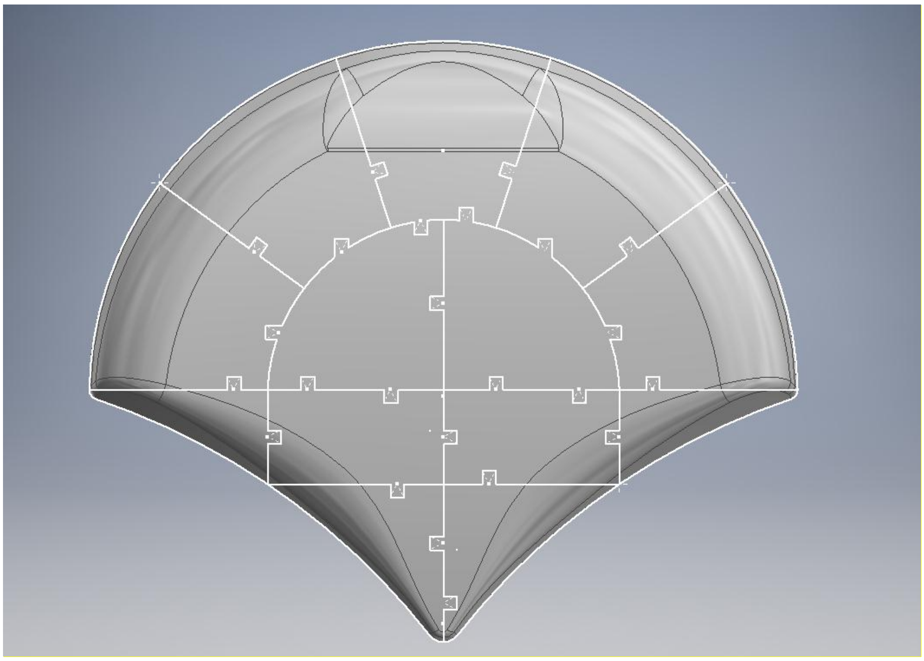

Figure 29 Puzzle pieces design

Preparation of the mold.

Once all the pieces were printed the supports of some of the pieces needed to be eliminated, since they were not part of the design but were needed to print some of the pieces. After eliminating all the supports the edges were polished so that all the faces could fit without any loose edges. The pieces were joined using super glue and duct tape until a uniform and structurally stable hull 3D design was produced.

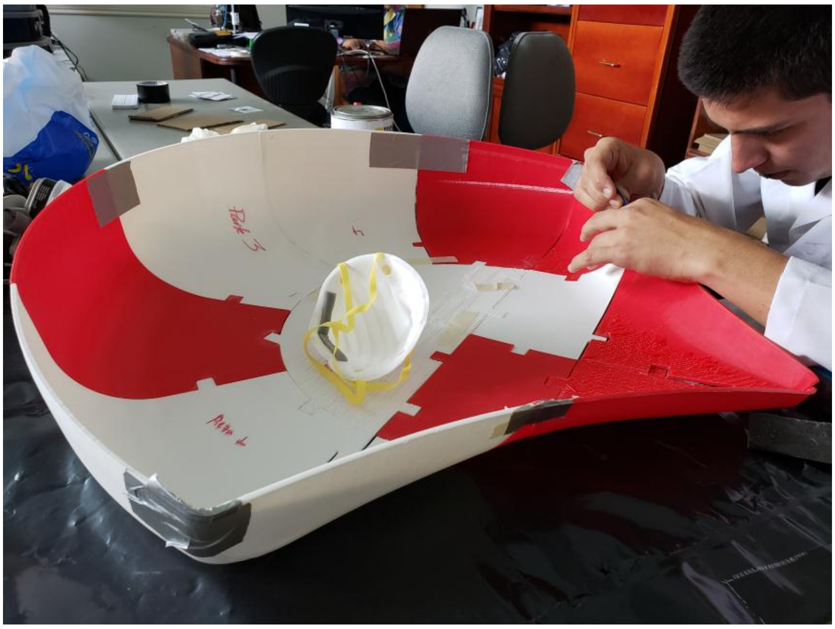

Figure 30 Assembling of the 3D printed mold

Figure 31 Finished assembly

Since the surface of the PLA hull design had some small gaps between some of the pieces, due to the fact of 3D printing errors such as excess of material or uneven edges, Wesco polyester body filler was used. The car body filler gives a small layer of polyester to even the surface and to fill the gaps between the PLA pieces. A small layer was applied in all the PLA design surface. Since the layer surface is not perfectly uniform a polishing process needed to be made to even the surface.

Figure 32 application of filler over the cast

The surface was polished using sandpaper with grain size 100, 220 and 400. The grain size 100 was used to eliminate body filler excess and generate an even surface, 220 and 400 were used to give a smooth finish to the design. The final result was a perfectly even surface that could be used to cast the desired shape for the design using the fiberglass layers.

Figure 33 preparation of cast

Figure 34 finished cast

After the assembly and preparation of the puzzle-like mold, the integration with fiberglass can begin. To do this, the 3D printed model must be prepared, eliminating all support structures created by the 3D printer. For this activity, roving unidirectional fiberglass was bought, that through a couple of coats will provide the submarine with the structural strength to withstand the high pressures, and a couple coats of multidirectional fiberglass mat to further strengthen the hull in other directions. These five coats of fiberglass in different directions will be strongly held together through the properties of the resin being used (Arias, 2018). For this purpose, pre-activated vinyl ester resin will be used, that does not require mixing it with other components and will harden enough to give the fiberglass coatings uniformity and strength.

Fiberglass coating.

Once the cast was ready, the fiberglass coating process could begin. The process followed for the coating of the fiberglass in the cast was the same one used in the scaled prototype. First, the cast was covered with unmolding grease. This greasy substance is going to prevent the cast to stick together with the fiberglass layers on top.

Figure 35 covering of mold with grease

After this the fiberglass coating was applied using the same 5 layers used in the prototype and the same order of layers (unidirectional Roving, multidirectional mat, unidirectional roving, multidirectional mat and unidirectional roving) all joined together using Vinyl ester resin.

Figure 36 Application of fiberglass

Figure 37 Application of vinyl ester resin

The final result was a fiberglass hull with the desired form of the cast. The process was repeated exactly the same to create two symmetrical halves that will be assembled into the submarine hull casing.

Figure 38 hull result

Fiber Glass Hermeticity Test.

To validate that both halves constructed from fiberglass were fully hermetical a simple experiment was made, in which both halves were submerged separately into water and applied pressure in different parts of the hull to see if water drops got through. Surprisingly, there were some spots in the fiberglass shell in which water passed through. This was highly unusual since the combination of fiberglass layers and the vinyl ester resin should have given a perfectly hermetic surface. The conclusion was reached, that water passed through because of some reasons: First, the vinyl ester resin may not have spread evenly in some parts of the surface, causing some pores in the fiberglass from which water may get through. Second, since the cast stuck together with the fiberglass casing because of the adhesion of the polyester car filler and the vinyl ester resin some stresses were generated in the hull at the moment of separating both parts. This stress may have produced small cracks or pores between layers allowing water to pass.

Figure 39 first hermeticity tests

To solve this water filtration problem, 2 layers of vinyl ester resin were added in the inner part of each case and 2 layers in the outer surface. These new layers should solve the problems of water filtration by generating a uniform permeable layer in both parts.

After applying the 2 extra resin layers the test was repeated. As it was expected both parts were fully impermeable and there were not any other spots with water filtration in both parts. Once both parts of the casing passed this test, the team could start working in joining them and sealing them so that is fully hermetic.

Figure 40 application extra layer vinyl Esther resin

Assembly of two halves.

In order to assemble the two halves, the assurance was needed, that both parts were symmetrical. First, the excess of the fiberglass needed to be cut off. This process was done using a manual saw leaving a plane border so that there is a surface in which bolts can be attached to join both halves. The border was left at a dimension of 40 mm, this dimension allows us enough space to drill the holes for the bolts without compromising the designed hermeticity.

After the two halves are fully symmetrical the bolts distribution was calculated. To determine how many bolts were needed to keep the two halves joined at a force that will not compromise the design a calculation needed to be made. For this calculation, Chapter 8 of Shrigley's Mechanical Design was used as a reference. This Chapter guided us as a good example of how to calculate the number of bolts to join two surfaces (Budynas & Nisbett, 2011). This was used as a base for the calculation.

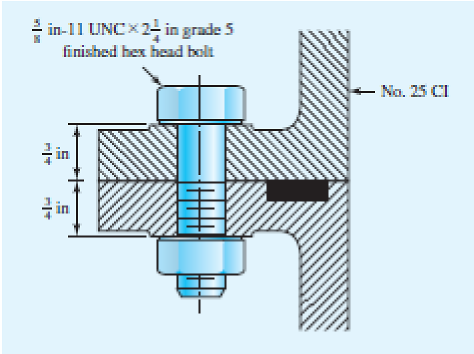

Figure 41 Design screws (example) (Budynas & Nisbett, 2011)

In order to solve this problem some formulas described in Shrigley's Mechanical Design were used. In the next steps the process will be explained including the explanation of the value of every constant.

The following values were used, for the values that have a maximum and minimum value the minimum was used to consider the worst-case scenario.

Table 2 Constant values used for bolt determination

Constant	Description	Description Values Used	Value
d	Bolt diameter	M10 bolts were used, meaning a diameter of 10 mm	10 mm
E_1	Youngs modulus for the material of the bolts	Stainless Steel grade 70. Has a young modulus of 27.5572 and 29.032 MPSI	27.5572 MPSI*
E_2	Youngs modulus for the base material	E-Glass Fiber has a young modulus between 10.4427 and 12.3282 MPSI	10.4427 MPSI **
l	Grip longitudinal adjustment	Both joined halves have a thickness of 10 mm	0.3937 in

t	Nut thickness	Found in table A-31	31/64 in
z	Thread beyond the nut	Measured how much of the thread is beyond the nut	1/11 in
S_p	Load factor	Load factor depending on number of cycles	85 KPSI
n_l	Safety Factor	A factor of safety of 4 was used	4
A_t		Determined from table 8-2	0.226
* (Atlas Steels, 2013) * (AZoM, 2001)			

The first step is to calculate the bolt length. Equation 1 was used to do so.

$$L = t + l + z \tag{1}$$

$$L = \frac{35}{64}\text{ in} + 0.3937\text{ in } + \frac{2}{11}\text{ in} = 1.1224\ in$$

Then the thread length was determined using equation 2

$$L_T = 2(d) + \frac{1}{4} \tag{2}$$

$$L_T = 2(0.3937\ in) + 1/4\ in = 1.0374\ in$$

The length of the unthreaded portion in the grip is obtained by replacing in equation 3.

$$l_d = L - L_T \tag{3}$$

$$l_d = 1.1224\ in - 1.0374\ in = 0.085\ in$$

The threaded length in the grip can be calculated in equation 4.

$$l_t = l - L_d \tag{4}$$

$$l_t = 0.3937\ in - 0.085\ in = 0.3087\ in$$

The major-diameter area is calculated using equation 5.

$$A_d = \frac{\pi}{4}(d^2) \tag{5}$$

$$A_d = \frac{\pi}{4}(0.3937\ in)^2 = 0.1217\ in^2$$

The bolt stiffness is then

$$K_b = \frac{A_d A_t E}{A_d l_t + A_t l_d} \tag{6}$$

$$K_b = \frac{(0.1217\ in^2)(0.226\ in^2)(29\ MPSI)}{(0.1217\ in^2)(0.3868\ in) + (0.226\ in^2)(0.0069\ in)} = 16.40\ Mlbf/in$$

The stiffness of the members is then

$$K_m = \frac{0.5774\pi E d}{2\ ln\left(5\frac{0.5774l + 0.5d}{0.5774l + 2.5d}\right)} \tag{7}$$

$$K_m = \frac{0.5774\pi(10.4427MPSI)(0.3937in)}{2\ ln\left(5\frac{0.5774(0.3937\ in) + 0.5(0.3937in)}{0.5774(0.3937\ in) + 2.5(0.3937in)}\right)} = 6.6598\ Mlbf/in$$

The result in equation 6 and 7 was used to obtain the stiffness constant.

$$C = \frac{K_b}{K_b + K_m} \tag{8}$$

$$C = \frac{16.40\ Mlbf/in}{16.40\ Mlbf/in + 6.6598\ Mlbf/in} = 0.6858$$

Finally, based on the load force of the submarine and the area in which the bolts will be applied, the number of bolts is calculated with the following equation.

$$N = \frac{Cn_L P_{total}}{S_p A_t - F_i} \tag{9}$$

$$N = \frac{(0.6858)(4)(48\ Kip)}{(85\ Kip)(0.2260\ in^2) - 0.75(0.2260\ in^2)(85\ Kip)}$$

After the determination of the number of bolts needed to hold the two pieces together, the holes 28 needed could be drilled in the flat section of the flange. A 10mm high speed steel drill was used to make the holes. They were uniformly distributed and at regular intervals so that the pressure distribution in all the border is as equal as possible. First, the most critic points of the surface were set. These were at the front, one in each wing and at the tail. Based on the position of these holes, the remaining space was evenly divided according to the total number of bolts.

Figure 42 Drilling the holes

Once both parts of the casing had the respective holes in the surface, and both are perfectly coincident the process of joining them together could begin.

In order to prevent filtration, a rubber seal was used in between both casing parts. This rubber seal was cut from a 1.20x1 m rubber sheet using one of the halves to generate the same form pattern. A silicon sealing layer was used between the cases and the rubber to prevent water filtration between the gap. For the closing of the submarine, 28 M10X30 hexagonal head stainless steel bolts with their respective nut and a washer at each side were chosen following the calculations made before. Both surfaces were joined together and tightened with the bolts. The submarine silicon was left to dry for a day for the first hermeticity test.

Hermeticity test.

The first hermeticity test was done 20 cm underwater. Weight was placed on top of the submarine hull to guarantee that the joint part was completely underwater. It was left underwater for around 15 minutes and opened it afterwards to see the results.

The first attempt towards reaching full hermeticity failed since water was found inside the casing. However, the conclusions of the problems on first test were reached. First, the bolts were not generating the necessary pressure to join both halves. Some parts of the plane surface were not fully joined, leaving some spaces in joint in which water could have filtrated. Second, the bolts that were used were not efficient. At the moment of tightening the bolts some of them presented some factory issues such as the thread getting damaged, which caused the nuts to lock and prevent them to be disassembled. Nearly 20% of the bolts were damaged and had to be cut away using a saw to be disassemble both parts.

Even though the first test was a failure the team learned that the bolts that were being used were not of a good quality. It was decided to not only change provider, but also to change the bolts that were being used. They were switched to M10X30 Allen bolts and pressure washers were used instead. The process was repeated, and both halves were joined using these new bolts and repeated the test. This time the results were positive, not even a drop of water had filtrated inside the submarine composite hull. This test validated the design and let us move to the next stage; assembling the motors.

Determination of center of gravity.

The first step towards assembling the motors is to calculate the centroid of the bodies, since this is the point in which all the mass of the submarine is going to be concentrated the motors should be aligned with it so that the thrust generated by the motors generates a uniform movement in the submarine. Since the final mass and volume shifted after the addition of the fiberglass, this calculation was done experimentally by tracing a symmetrical axis along each case, then a 2 cm diameter wood stick was used so that the hull could be balanced on top of it. Still, the center of gravity coincided with the one in the CAD design. Since the centroid is the point where all mass is concentrated, there is a point in that symmetrical line that will give perfect equilibrium; this point is the center of gravity. The symmetry lines across the centroid were marked for the later installation of the motors.

Figure 43 Determination center of gravity

Neutral Buoyancy in Sweet Water.

Neutral buoyancy as defined by Munson is the buoyancy effect of a fluid in which the body neither raises nor sinks. Using the help of the CAD design, by determining the volume of the assembly (0.052 m^2) the team was able to calculate the theoretical neutral buoyancy of the Submarine by using Archimedes principle: The force that acts upon a submerged body is equivalent to the weight of the volume of fluid displaced (Gerhart, Gerhart, & Hochstein, 2016). By using the formula $m_f = \rho_{H_2O} * V_f$, where V_f is the volume of fluid displaced (which is equal to the volume of the submarine), and m_f is the mass of the displaced fluid (Gerhart, Gerhart, & Hochstein, 2016). To achieve neutral buoyancy, the mass of the submarine must be equal to m_f. Hence, the theoretical mass needed for the submarine is around 52 Kg.

By doing the two hermeticity tests it was determined experimentally the needs in weight to achieve neutral buoyancy. In order to submerge the whole submarines body underwater 8 sidewalk pavements were used as weight. Each sidewalk pavement weighted around 7 kilograms. Doing this it could be calculated that the approximate weight the submarine needs to achieve neutral buoyancy is around 55 Kg. The reasons the weight is so high is because the volume that is in contact with the fluid is big, the fiberglass cases are light, and the hull stores a considerable amount of air inside.

Figure 44 neutral buoyancy tests

Neutral Buoyancy in Saltwater.

Given that neutral buoyancy depends on the fluid's density, and as such salt water has a higher density than normal water, the weight needed to achieve neutral buoyancy will be bigger (Gerhart, Gerhart, & Hochstein, 2016). Knowing that the density of saltwater is around 1025 Kg/m^3 (Nayar, Sharqawy, Banchik, & Lienhard, 2016), neutral buoyancy could be calculated for the submarine in saltwater with a total weight of around 54 Kg.

Electrical Components Assembly.

Orca II motors (Seabotix BD-150) were attached to upper halve of the Stingray submarine. Since the submarine has to undergo an hermeticity test at a considerable depth (more than 10 meters) the motors will only be assembled to check if the drilled holes in the hull will affect its resistance or if there is water filtration through those holes. Both motors were installed along the horizontal axis of the centroid at a distance of approximately 2/3 from the symmetry line in the middle to the edge. They were installed using M3X40 were fixed to the hull using two layers of Vinyl ester resin to seal them from water filtration.

The holes for the motors power cable had to be drilled in the upper lid as well. In order to seal the joint part between the cables and the upper lid cable glands were used. The cable glands used could tighten any cable between 4 and 8 mm of diameter. Two 15 mm Holes for the cable glands were drilled, and the parameters used to know where to drill the holes were: they need to be drilled in an area that is flat and they need to be as close to the motors as possible. Holes were drilled at 20 mm of horizontally from the motors. The cable glands are threaded so they were installed as bolts. In order to fix them and avoid water filtration they were reinforced using Vinyl ester resin and gasket sealer. Once fixed to the submarine upper shell the cables passed through the cable glands, a layer of sealing silicon was put inside it to guarantee water does not filtrate from inside the glands. Finally, they were tightened so that they strangle the cables as tight as possible.

As the other holes made in the case, these were also tested at a low depth to see if there was evidence of water filtration. Since by applying some pressure there was no water filtration in any of the holes made then it could be concluded that there has no evident filtration of water through the holes.

Figure 45 hole hermeticity tests

The final low depth hermeticity test was done by assembling both halves of the submarine using silicon sealer. The results resulted positive, without any filtration of water. This meant that the final test at water depth could began.

Figure 46 low depth hermeticity test

Hermeticity Test in San Pablo Lake

The final hermeticity test was done in lake San Pablo. San Pablo is at a close traveling distance to transport the submarine shell with all the weight inside and it has a maximum depth of approximately 50 m which in for the final test is enough to prove the hermeticity of the design. Since the motors will not be doing any propulsion the only way to move the submarine out of the water is by pulling it. In order to do this some adjustments had to be done to the submarine hull so that it resists the tension forces applied through steel cables. First, 4 rope clips of a diameter of 3/16 inch made of Carbon Steel were installed. They were drilled and installed in 4 points along the centroid. The height of the clips was regulated in order that there is enough space for a quick link to be attached in the upper halve.

After the holes were drilled, the rope clips were installed and were fixed using epoxy resin. In the inner part of the submarine hull a plate was installed in the lower thread of the clips so that the contact area of the clips is larger and thus generate lower shearing stresses in the joint part. The contact area of the plate and the bolted part of the nut was covered with sealing silicon to guarantee hermeticity. Once this process was finished for the four clips the upper lid was tested to see if there is water filtrating in any point.

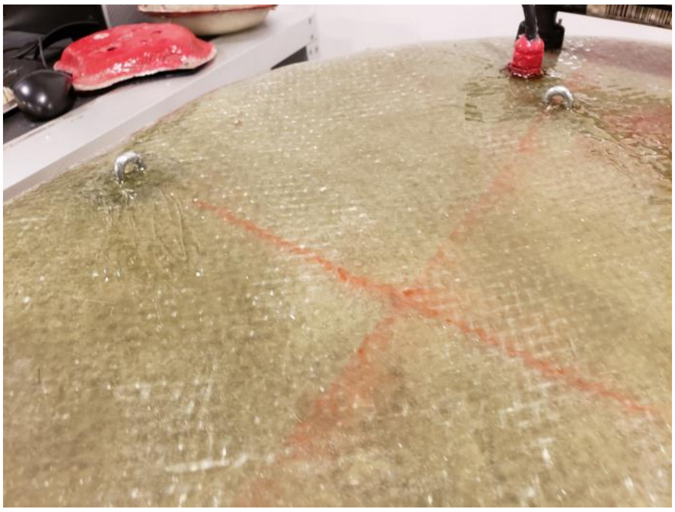

Figure 47 cable anchors on the submarine

Since the upper lid passed the test, the assembly of the two halves could begin. The first step was introducing the calculated weight of neutral buoyancy inside the two halves. Because the motors will not be working in the test, it was needed to achieve a slight negative buoyancy in order that the submarine to sink in water. To achieve this, bags of dry concrete of 5 kilograms each were prepared. They were used because concrete it is heavy, it is cheap, it can be easily distributed along the centroid and the team didn't need to construct any special supports to fix them to the lower inner lid. 10 bags of concrete were distributed, reaching a weight of 40 kilograms, the rest of the weight was introduced in a steel weight plate of 15 kilograms because of the lack of space inside the submarine shell.

Figure 48 neutral buoyancy weight distribution

When the weight inside was set and tested so that they do not move and change the weight distribution of the submarine, the two halves were joined and sealed using silicon as a sealer.

Galvanized steel cable with PVC coating were used to hold the approximately 55 kilograms of weight of the submarine. This cable is designed resist up to 180 kilograms of weight, meaning the team was operating safely in the cable resistance. 4 cables of different dimensions were cut and tied using the quick links to the submarine upper surface, all of them conducting to a 75 meters long cable. The steel cable was labeled after each meter until the first 20 meters and then every 5 meters until the 75 meters in order to know how many meters underwater the submarine is.

Figure 49 quick links and cable

The final test was done in the deepest part of the San Pablo lake which has an approximate depth of 35 meters. The submarine was submerged at a slow descending velocity. Every meter the submarine went underwater it was pulled out a little to see if there is no risk of losing it on the water. Because of the water resistance the more it submerges the more difficult to pull it out of the water. It was submerged 20 meters, this is the distance it could be felt that it could be pulled out of the water safely in case of an emergency, the team did not want to risk the submarine and staying at the bottom of the lake. It was left at 20 meters depth for 30 minutes. After the 30 minutes the team started pulling out the submarine by pulling the steel cable. It was noticed that it was heavier than when it descended, meaning a possible water filtration. After 45 minutes of pulling it out of the water it was noticed that the was a crack in the front part of the upper halve of the submarine hull, but there was only a point in that crack were pressurized water was coming out of.

Figure 50 high depth test

RESULTS

In the following section the possible factors of failure of the upper submarine lid during the final test at a depth of 20 meters will be discussed. The hull experimented 2 different cracks a horizontal and a vertical crack in the front part of the upper hull. The horizontal crack failed due to some factors.

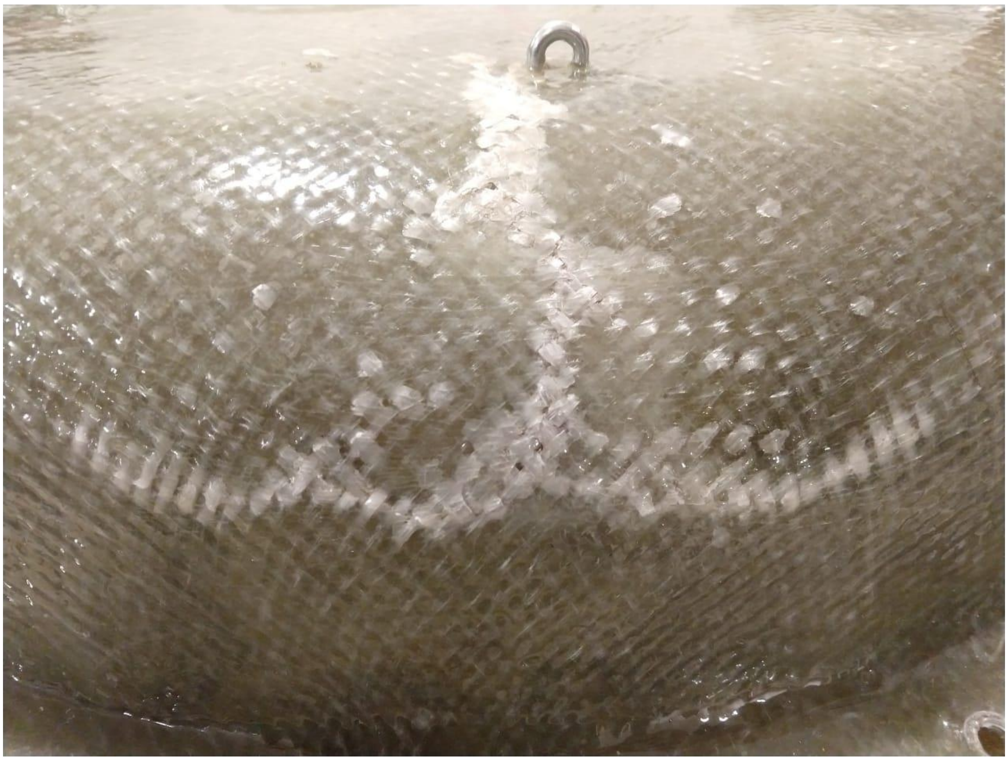

Figure 51 crack in the hull (front)

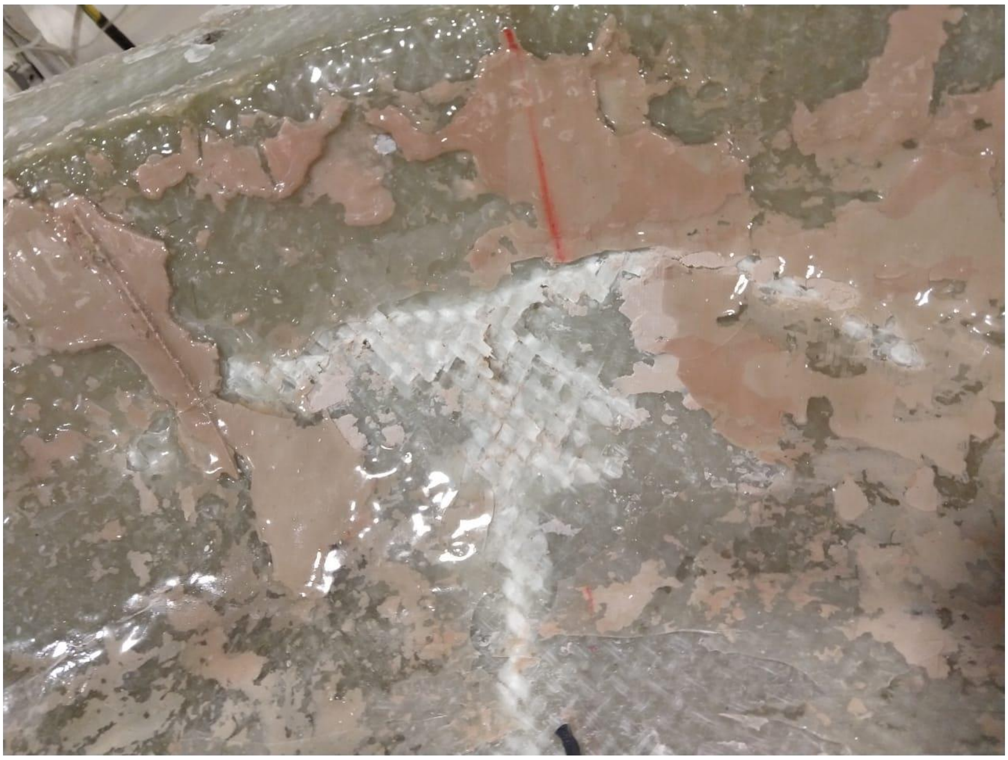

Figure 52 crack in the hull (inside)

First, as it can be seen in the following figures, the section in which the crack can be seen is a section that has a shearing stress caused by the difference in strength between two sections. It was found that this shearing stress by performing a simulation of one of the lids with a hydrostatic pressure load equivalent to 0.98 MPa, which as quoted before is the pressure at 100-meter depth in sweet water. However, this stress concentrator line is present along all the front part of the submarine hull, but it only fails in a specific part of the hull, thus It can be concluded that the crack opening needed to have another factor. By speaking to Marco Leon, a professor in the Mechanical Engineering department it was discussed if in the specific section there could have bubbles between fiberglass layers. These bubbles result in stress concentrators at the moment of loading the material causing that specific section to have a resistance lower than it should. Both of these factors are the most probable reason about how the horizontal crack formed at the moment of the submersion. Even though this crack is bigger than the vertical and you can see the fiberglass delaminated from inside, water did not filtrate through this crack. The team saw that at the moment of opening the two halves of the submarine pressurized water came out only in one point which is approximately 4 cm down from the star of the vertical crack. Which makes us conclude that even though this crack was bigger, caused the fiber to delaminate and is coincident to a stress concentrator.

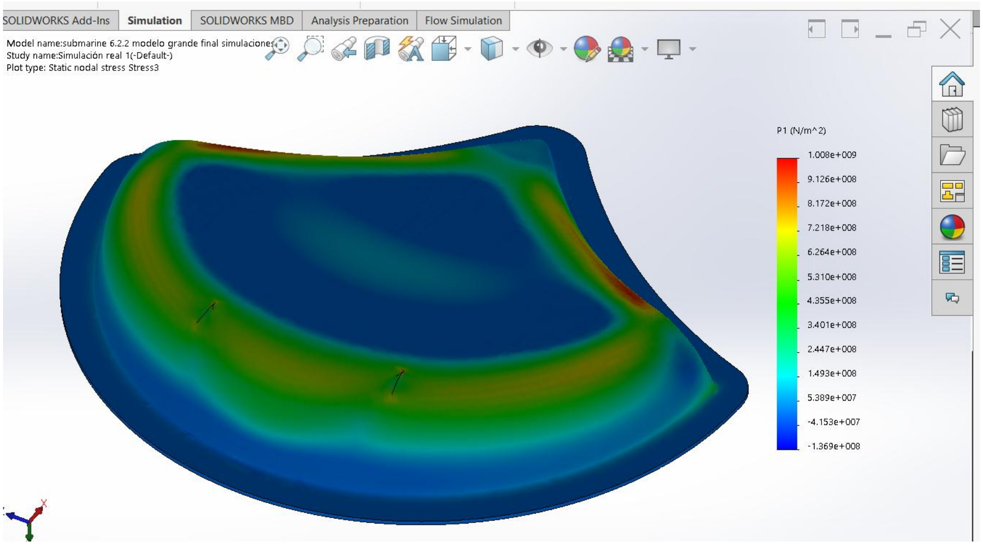

Figure 53 principal stress 1

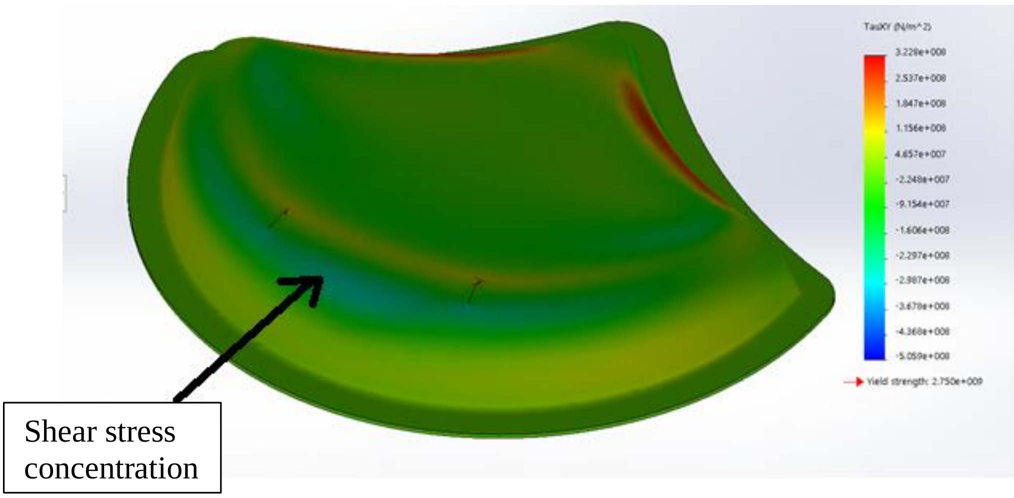

Figure 54 Finite element simulation of stress

The second vertical crack was formed as a result to the stress concentrators in the front and the shearing stress the rope clip transmitted to the submarine hull at the moment of pulling it out of the water. Both of these factors made the crack to propagate from one of the holes of the rope clip to the horizontal crack. As mentioned before at approximately 4 cm from the top of the crack going downwards there is the weakest point of the crack. This point is were pressurized water was coming out at the moment of pulling out the submarine from the water and was the only point in which water was coming out.

Budget

The initial budget that was set for the project was initially around 800 USD which was a rough estimate of the fiberglass, resin and other accessories. Summing all of expenses in the project the project budget is around 664.41 USD which is less than the initial estimation.

Description	Quantity	Unit	Price (in USD)	Total (in USD)
PLA 3mm	3	1 Kg	37	111
Fiberglass mat 450 gr/m2	4	m2	4	16
Fiberglass roving 600 gr/m2	6	m2	4	24
Epoxy resin	4	Kg	7	28
Vinylesther resin	16	Kg	22	352
Bolts and nuts M10x30	28	units	0.97	27
Nitrile rubber 1.5mm	0.5	m2	32	16
Industrial rubber 1.5 mm	1.7	m2	16.50	28
Silicone	3	tubes	3.40	10.20
Steel cable PVC 1/16 in rol 75 m	1	rol	17.41	17.41
Other accesories	-	-	-	31.80
			Total	661.41

Figure 55 Budget used

RECOMENDATIONS

After the test results and the in-depth analysis of the failure, several recommendations can be made for future research on the design of the submarine. First it has to be noted that the design chosen considered in the beginning only hydrodynamic factors, thus the streamlined design that was chosen. This design did not account for the elevated hydrostatic charges on the body on high depths. The flat surfaces of the hull bent when pressure was applied to them, and this brought high shearing charges on the edge where the fracture occurred. To account for this, a rounder body must be designed so that it can withstand the pressure without bending, and thus distributing better the stress along the hull.

Another recommendation related to the design is to make the body slimmer. In the present configuration, the body displaces 52 Kg of water, which makes it very heavy to be operated efficiently. To achieve this, a shape like the one in the B-2 Spirit bomber of Figure 56 B-2 Spirit bomber (https://theaviationist.com). The slimmer body could reduce the volume of displaced water, and further improve the hydrodynamic characteristics of the design.

Figure 56 B-2 Spirit bomber (https://theaviationist.com)

In order to have a better control over the neutral buoyancy, a recommendation can be made of reducing the size of the dry compartment inside de the hull, leaving empty space inside the hull and allowing water to fill those spaces, thus reducing the amount of weight that needs to be added. Additionally, another mechanism that can be suggested is developing a system similar to the naval submarines ballast tanks, in which air or water is introduced into a chamber to control ascension and descension of the submarine. The development of a system like this would reduce the quantity of weight the submarine needs and if there is a good control over the system. In this case it could avoid using the two vertical motors.

Further recommendations include placing the anchor points for the steel cables on the flange of the submarine, where it is sturdier and is not a risk to the integrity of the hull. This would decrease the stress on the hull due to the tension of the cables and avoid any stress concentrators when pressure is applied. Additionally, the process in Fiberglas coating has to be perfected, using better curation methods such as UV lamps to avoid the appearance of bubbles between the layers of fiberglass. In addition, the amount of resin used has to be increased to avoid the existence of porosity in the fiberglass layers once it is curated.

CONCLUSIONS

From the final hermeticity test at San Pablo lake the following can be concluded. The vertical crack, specifically the point at 4 cm from the top downwards was the only point from which water filtrated through the fiber and filled the dry chamber with water. Since there was not any other point were water was coming out at the moment of puling the submarine out of water it can be concluded that the was no water filtration form weak points such as the union of the two submarine halves, all motor drilled holes, both cable glands, all the perforations for the bolts. These means that even though the case structurally failed the weak parts for water filtration were correctly managed.

Additionally, it can be concluded that the seal between the halves worked as expected, by using bolts, silicone and rubber as seal. The cable glands and drilled holes were also hermetic and passed the test by using resin and silicone to seal them when they were installed into the hull of the submarine.

The crack proves that redesign work must be done in the shape of the submarine to make it better at withstanding hydrostatic charges at high depths.

By analyzing the results from the CFD simulation between Orca II and Stingray the team can conclude that Stingray has improve its hydrodynamic behavior considerably from the previous model Orca II. This can be seen in the results of the cut plot velocity, cut plot pressure, surface pressure and drag coefficient obtained from the simulations at 1.5 m/s. It can be seen that a more hydrodynamic design was achieved and validated for Stingray.

The 3D printed casts worked perfectly as a cast for molding the fiberglass. The 3D printing material has three great benefits. First, it replicates with great accuracy complex forms which allows the user to create complex geometries and used them as cast to make pieces that otherwise would require a lot of time in an CNC machine. Secondly, the PLA material is cheap compared to machining process. To machine a block of metal of wood into the shape and size needed for the submarine cast would require a big investment in material and in machining. Considering that few machines have the capacity of handling big blocks of material, 3D printing is the best way to go. Third, the PLA with a small layer of unmolding grease made it easy for the fiberglass to separate when it was already dry. Furthermore, there were no issues of separation at the moment of separating the fiberglass from the PLA. Because of these reasons it can be concludes that 3D printing casts are the best way to go at the moment of using fiberglass.

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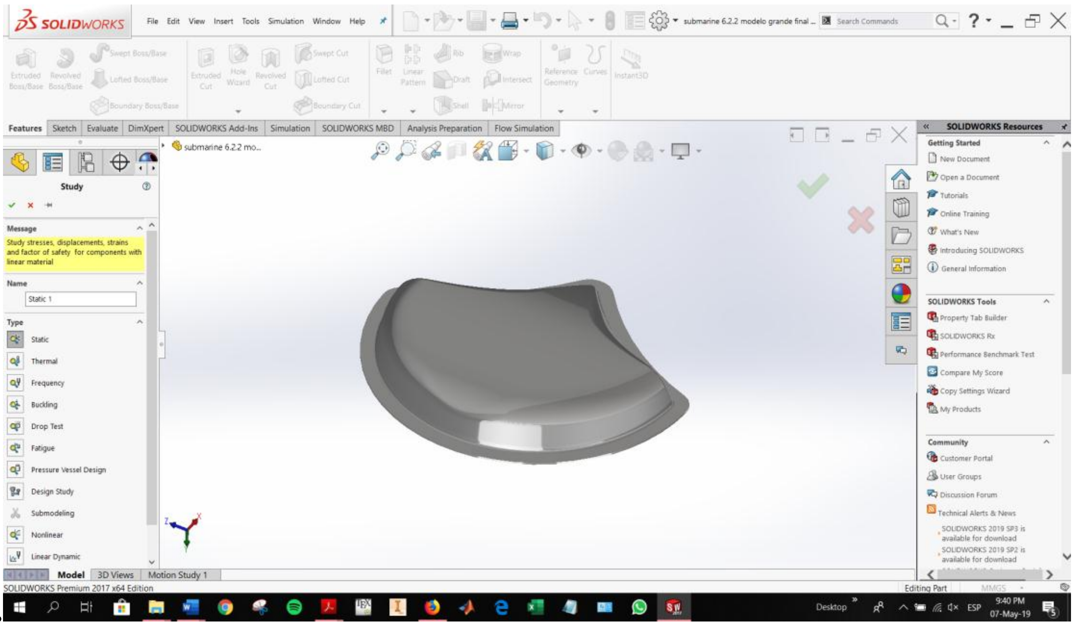
Anex: Process for hydrostatic pressure simulation



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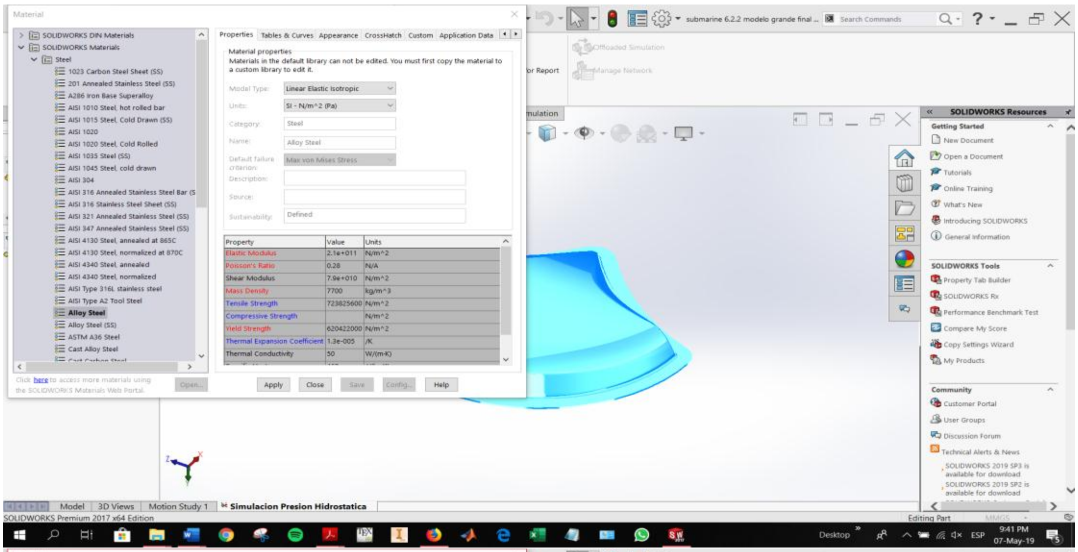

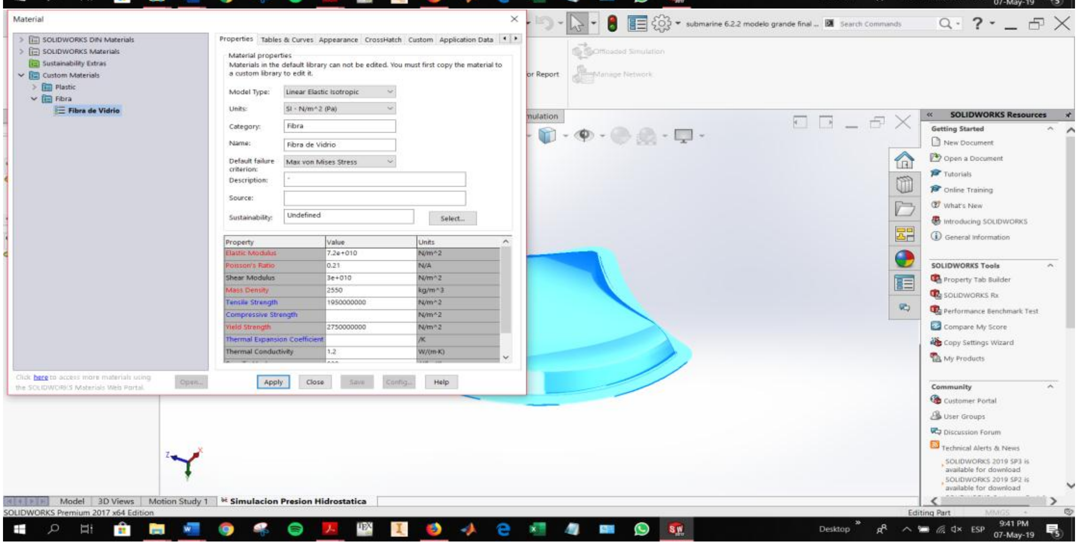

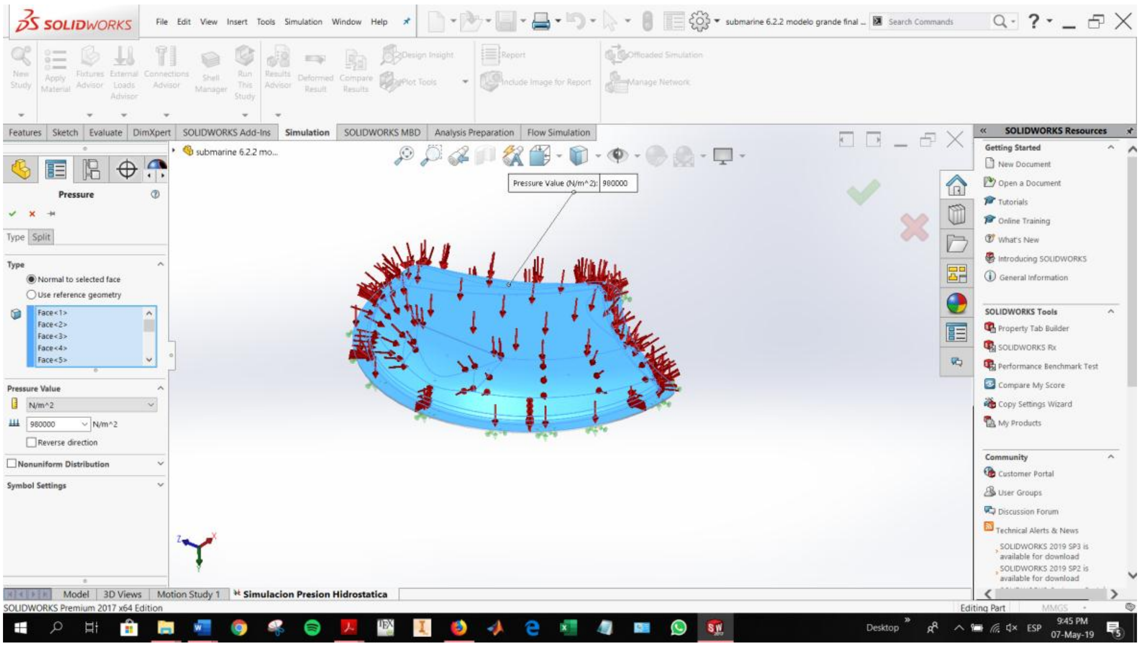

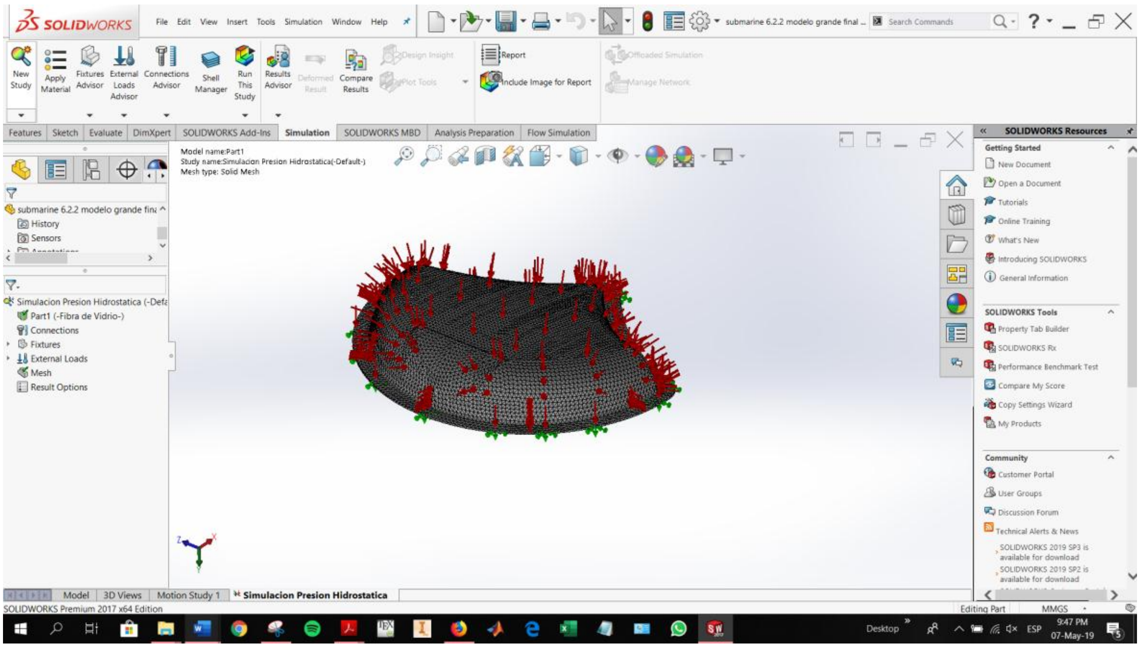

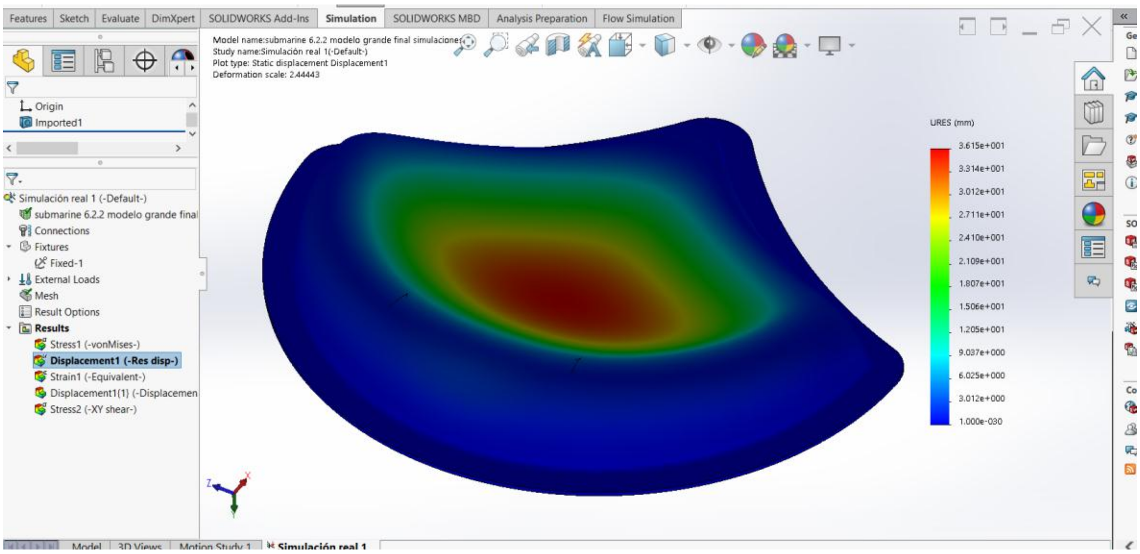
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