The Pennsylvania State University

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MALE MOLDING FABRICATION PROCESS DEVELOPMENT WITH THE USE OF COMPOSITE MATERIALS

A Thesis in

Aerospace Engineering

by

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ABSTRACT

Processes used to fabricate thick composite beams were developed. The advantage of female molding, which is typically used, is that it provides a smooth outer molded surface. However, the lay-up process is labor intensive, and the two halves need to be joined in a secondary operation. Male molding is generally less labor intensive, and allows the beam to be fabricated as a single part, thus eliminates the need to join separately fabricated sections. In the work described herein, a male molding beam fabrication process was developed that results in a smooth outer surface. This was achieved through the use of caul (external) tooling. De-bulk cycles were used to consolidate the laminate and reduce the degree of wrinkling on the surface of the male molded part. This paper also provides examples of innovative methods currently and formerly used in industry to both contrast and compare the methods to be used during experimentation. Trials were done on a tapered male foam mandrel using lay-ups of 10 ply increments (about 0.25" thick). About 100 plys of composite prepreg material were used during the process trials, which involved innovative in-situ gap fillers implemented between caul sections. In this way, the entire surface can be tooled. It was found that this was necessary to eliminate the occurrence of wrinkles and ridges during de-bulk of the laminate. Results showed that thick beams can be male molded to achieve a smooth outer surface with the use of corner and flat caul blocks accompanied by in-situ caul gap fillers.

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Chapter 1 :

Introduction

Composite materials have been around for over 2000 years since the days of the straw and mud mixtures, and have continued to evolve ever since they were created. The use of modern composite materials allows for the application of different molding processes to achieve the desired part. These molding processes can be created out of a variety of material and can be made to produce very complex surfaces including doubly curved surfaces. Surfaces similar to these are required in some applications such as boat hulls, yardarms, and structural spars. With the use of molding comes a variety of molding techniques such as male and female molding. Each has advantages and disadvantages when it comes to making a part quickly and effectively at an affordable price for the consumer. (Johnson, 2012)

Female molding is a concave mold that is often CNC machined after a Computer Aided Design (CAD) file has been created to model the desired tooling. The composite material is then laid inside this mold to be cured. This process excels in creating a smooth outside surface due to the smooth surface of the tooling contacting the outside of the material of the fabricated part. The tooling is much more expensive than if the part were to be male molded. Maintenance of the female mold is also very important because the slightest imperfection in the mold will display on the outside surface of the material.

Male molding is the process of creating a mold that will be built upon or “grow” as materials are added to its outer surface. This, opposed to the female molding process, results in a lower tooling cost for the product. Cost is an important factor in almost every application and tooling can be a deciding factor in whether a project is a success or not. Although tooling costs are reduced with the use of male molding, there are a few disadvantages to this molding technique. Since the composite material is fabricated on the outside of the tooling, as opposed to inside the mold with female molding, the surface finish of the material does suffer. After fabrication is complete, the resulting rough outer surface requires a labor intensive finishing process. This method also requires creating the mold to be a calculated dimension smaller than the final part to accommodate for the laminate to be laid up. (Rayplex Composite Technology, 2012)

1.1: Fabrication methods

There are several methods available to fabricate composite materials. Fabrication methods entail the details of fabricating composites. Specifically in the spar manufacturing industry there are a few methods that are more common for specific reasons. Some of the advantages and disadvantages will be discussed here. Current fabrication processes will be discussed in detail in this section.

1.1.1: Wet Lay-up

Wet Lay-up fabrication refers to the method of using dry fibers, such as fiberglass or carbon fiber, along with liquid resin to “wet out” the fibers. The fibers are cutout and placed by hand into or on top of the mold. After the fibers are laid down, the resin is applied on top of the fibers and evenly distributed across the mold using brushes or rollers. This process can be utilized in both male and female molding. The initial capital investment of this process is much less than other fabrication processes. The mold, fibers, and resin along with a brush or roller are the only materials needed to utilize the wet lay-up process. Although this process has low material costs, it is quite labor intensive compared to other fabrication methods. Particularly on larger scale items, the cost of labor can become a concern. Another disadvantage is the quality of the product. The final weight and uniformity of resin distribution varies after the lay-up has been completed. The use of a vacuum to apply pressure to the wet lay-up in the mold can help with the uniform distribution of the resin across the mold. The wet lay-up process is not recommended or suitable for tight tolerance or high strength requirement applications. One of the principle reasons the current industry has been shying away from this process is that the fumes that the resin gives off after an extended exposure to the substance can be harmful to the human body. This method can cure at ambient temperature. (Smithers Rapra, 2012)

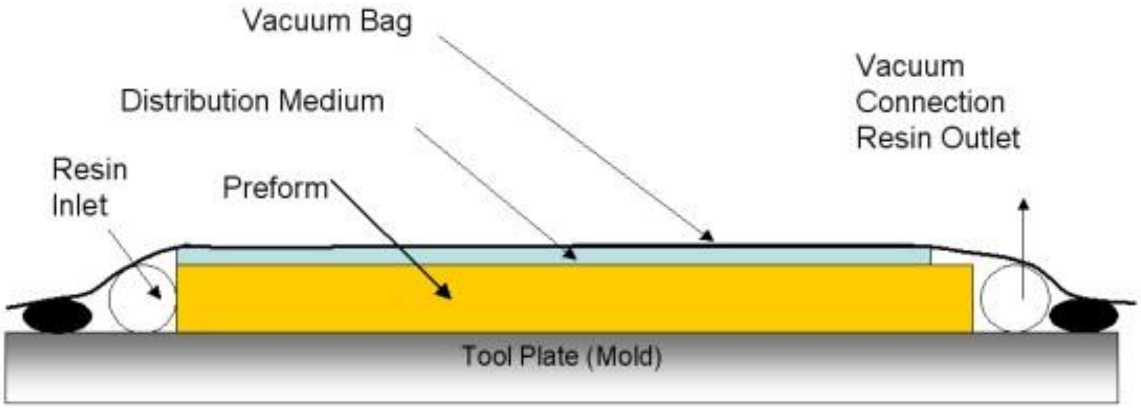


Figure 1-1. Image of Vacuum Assisted Resin Transfer Molding (VARTM) (Northwestern Engineering, 2006)

1.1.2: Resin Infusion

Resin infusion technology is another process often found in industry has many slightly varying sub-methods such as Vacuum Assisted Resin Transfer Molding (VARTM), Resin Transfer

Molding (RTM), Vacuum Infusion Processing (VIP), Seemann Composite Resin Infusion Mold Process (SCRIMP), and Resin Film Infusion (RFI). Similar to the wet lay-up process, resin infusion technology does use dry fibers along with epoxy resin to create a part but that is where the similarities end. In VARTM specifically, after the fibers have been placed inside the mold, a material called a distribution medium is placed down on top of the precut fibers. A tube is then placed on top of the distribution medium and the part is put under the vacuum as seen in Figure 1-1. This tube has holes or open sections along the tube to allow the resin to wet-out the entire part. The resin then flows through the part while under vacuum. The distribution medium allows the resin to be evenly distributed across the part while the pressure from the vacuum allows the resin to wet out the entire area of the part evenly. With this method it is possible to control the flow of the resin. Resin infusion technology allows for a high quality part by increasing the speed of the resin's infiltration of the part as well as the amount of infiltration thereby decreasing the void content. VARTM in particular is low both intensity of labor and difficulty which decreases cost in some applications. One of the disadvantages of VARTM is that the choice of resin is limited to low viscosity resins. Compared to other resin infusion technology methods, VARTM achieves lower fiber volumes by roughly 10%. This method cures at ambient temperature or the use of an oven. (Beckwith, 2007), (Northwestern Engineering, 2006), (Hall, 2012)

1.1.3: Prepreg

Prepreg refers to fibers such as fiberglass or carbon fiber pre-impregnated with resin. This material is most commonly fully wet-out with resin. Recently, material forms have been developed that allow oven vacuum bag (OVB) consolidation with low void contents. In this form, the prepreg has one "dry" side and one "wet" side. The dry side refers to the fibers and the wet side refers to the side that has been infused with the resin. An example of which can be seen below in Figure 1-2. The side with resin is tacky and allows the prepreg material to adhere to a mold surface. Due to the pre-impregnated resin, no additional resin is required to be applied to the fiber before it is applied onto or into the mold. This material is manufactured by the roll and can be ordered from a large selection of vendors. Prior to the development of OVB materials, prepreg was usually cured in an autoclave. To use this method, one simply pulls out the amount of prepreg needed from the roll and cuts the material based on the shape of the mold. The prepreg is then removed from the paper film and applied to the mold. After being applied to the mold, the part is then sealed, put under vacuum, and placed into an autoclave. The heat in an autoclave reduces the viscosity of the resin, while the pressure of the autoclave aids in the compaction of the material and allowing the resin to completely wet-out the fibers. As long as the vacuum is sufficient, multiple parts can be fabricated within very tight weight tolerances. Another advantage is very low labor intensity and difficulty of the application of this material. This prepreg technology can make very high performance parts that can stand up to larger loads than its wet lay-up counterpart. There is a large capital investment with prepreg given that the resin is already infused into the material.

Another large cost investment and requirement of the autoclave based prepreg material is the requirement of an autoclave. Purchase and operation of an autoclave can increase the production costs of a project. Depending on the size of the part, the use of this material may not be possible. Companies often must pay for time using an autoclave that is adequate to cure the part or parts. This can be troublesome and expensive and is often one of the main reasons this material is avoided in manufacturing processes.

Figure 1-2. Example of Prepreg material (Aero Consultants AG, 2012)

Oven Vacuum Bag (OVB) prepreg is a composite material that cures under vacuum bag inside of an oven without the addition of pressure as would be seen with material that requires an autoclave to cure. One of the largest disadvantages of the autoclave prepreg is that it an autoclave is needed for the cure stage. Between the time required in the autoclave and the cost of owning and/or operating an autoclave, prepreg material could not previously be used in a variety of applications. In the early development stages, OVB prepreg only saw uses in applications such as prototypes and secondary structures such as flaps and fairings. With the development in OVB prepreg to be on par with autoclave in terms of very low void content (1%) and high strength applications, OVB prepreg is technology that will revolutionize the way composites will be fabricated and manufactured. (Gardiner, 2011)

1.2: Objective

For the application of male molding with the following experiments to be seen in Chapter 3, OVB prepreg will be used to achieve the goals of male molding a tapered part seen below in Figure 1-4 that results in the best possible surface post-cure without wrinkles in the corners. After the part has been place under a vacuum bag, the suction from the vacuum often pinches the corners of parts causing bunching and wrinkling seen below in Figure 1-3. This phenomenon is unacceptable in nearly every application. One of the goals is to eliminate all wrinkling and grouping of the prepreg material in the corner sections. The dimensions of the part can be seen in Figure 1-5 and Appendix C. As discussed earlier, one of the large issues with male molding is the final surface of the part. Successful results of this research means minimizing the machining that needs to be done post-cure as well as reducing the amount of cure stages as a whole. Minimizing the time, difficulty, and cost of the fabrication process as a whole is also a goal.

Figure 1-3. Post-vacuum bag compaction of prepreg material (Gurit, 2012)

1.2.1: De-Bulk

In both male and female molding, a stage called de-bulking can be required for compaction of the prepreg material onto the mold in cases where excessive plys must be applied to the mold. The de-bulking is done to compact the prepreg material, which prevents fiber distortion and wrinkling during cure. In some cases, heat is also required to allow the resin to flow throughout the plys. In male-molded parts, de-bulking can cause wrinkles on the part requiring a cure and labor intensive machining to fix. Another goal of this research is to improve the de-bulking process and limit the number of cure cycles needed during fabrication.

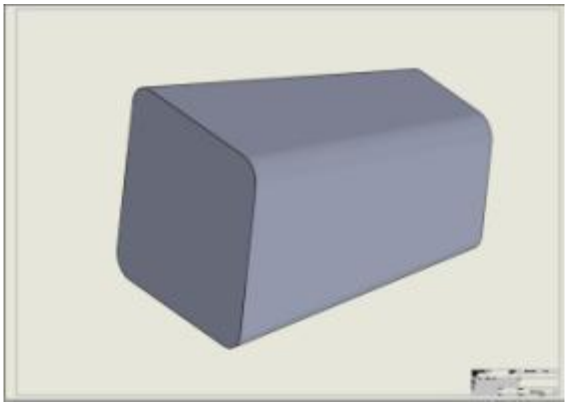


Figure 1-4. CAD drawing of tapered spar section – isometric view

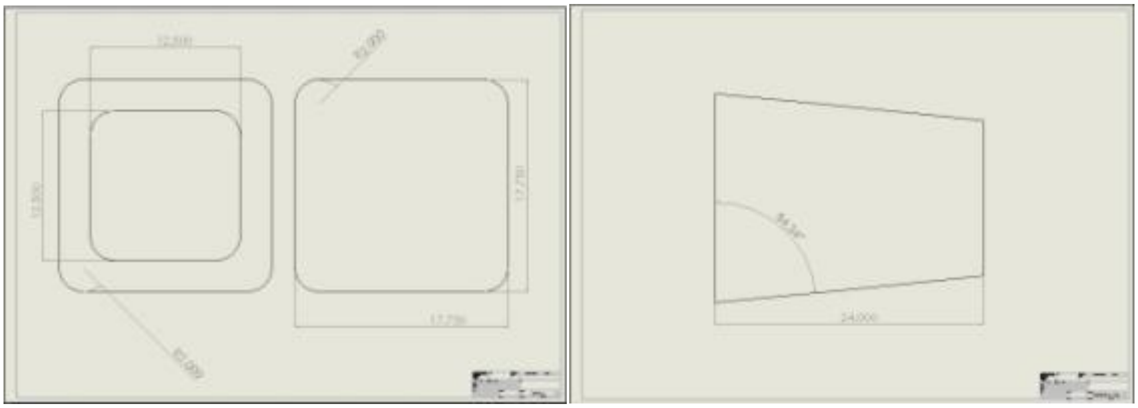


Figure 1-5. CAD drawing of tapered spar section with dimensions (Appendix C)

To reiterate, the goals are:

- To develop the best methods to fabricate a male molded part by
    - Reducing wrinkling about all faces of the tapered spar as well as the corners
    - Reducing surface roughness of the male molding
    - Limit the number of cure cycles overall during the fabrication process by improving a specific de-bulking process
    - Experiment with new and existing de-bulking processes that exist to save time and money of fabrication
    - Reduce the cost involved to fix errors that arise from male molding issues
    - Reduce the overall time involved with fabricating a male molded part

1.3: Motivation

The motivation behind this research is that male molding exists and is used in industry, but is often excluded as an option because of its particular disadvantages such as wrinkling and surface roughness. With the development of male molding fabrication methods, male molding may become more viable and produce more affordable parts from vendors to the consumers. In applications such as turbine spars and yardarms where only a few spars need to be made at a time, male molding is the perfect method to manufacture these products.

Chapter 2 :

Literature Review

This chapter will provide evidence of methods both formerly and currently used in industry to fabricate composite materials emphasizing detail on their fabrication methods and processes. Specifically spars that use male mold tooling for their fabrication processes will be assessed along with the evidence to support the appropriate choice in materials has been made for similar applications. Examples that use female mold tooling will also be used to compare and contrast development decisions made in Chapter 3. Although materials were found to compare process developments, much of the industry's techniques and method used to fabricate and manufacture composite materials is kept a secret. In (Griffin, 2004) this specific subject is mentioned. Quote:

> "The research and development efforts of each manufacturer are usually kept proprietary until a new product or innovation is ready to be marketed. Also, both the size and manufacturing technologies of MW-scale blades are rapidly evolving. As a result, any attempt at reporting the "current" status of the industry is bound to be at least slightly outdated by the time it is published. The current data should then be considered as a snapshot of this rapidly changing technology, summarizing the best non-proprietary data available at the time of the writing."

2.1: U Shaped Mold

A process was developed by Cole H. Beadon to fabricate a mold for the purposes laminating spars, masts, and/or columns using composite materials. His patented concept uses neither a female or male mold but instead a U shaped mold with a cap to close the concave female mold as seen below in Figure 2-1. The uniquely shaped 2-part mold has a cavity similar to female molding where fibers are applied along with a cap for the mold where additional fibers are laid. (Beadon, 2003)

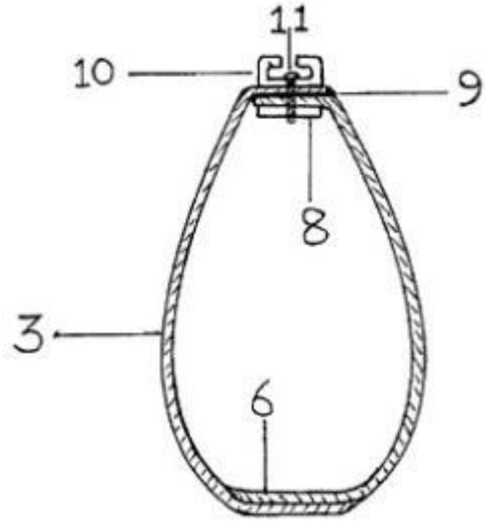


Figure 2-1. U-shaped Mold (reference 10)

Beadon discusses the surface roughness issues, mentioned in Chapter 1, and how they plague the mast and spar male mold sailboat industry. This method is recognized as able to vary thickness without affecting the outside dimensions of the part. (Beadon, 2003)

He also discusses the female mold issue regarding edge bonding. Edge bonding is stated to be both expensive and time consuming, driving up production costs. Although the edge bonding is a problem, the female mold method of fabrication is much more similar in comparison to Beadon's method. The geometry of the female section of this mold can be calculated with minimal difficulty keeping in mind the top section and amount of plys to be applied. One of the important benefits mentioned is that clamping together the mold pre-stresses the walls, increasing the resistance to buckling. There are also a few variations to Beadon's mold that would ease the fabrication process depending on the fabrication method desired. (Beadon, 2003)

2.2: Gurit Blade Manufacturing Process

Gurit believes that the only two viable options for fabricating composites in industry are resin infusion and prepreg. Some of the advantages and disadvantages of each process are discussed. Resin infusion has a cheaper investment cost whereas prepreg is more consistent and can produce parts with higher resin properties resulting in lighter parts. Gurit specializes in all materials and fabrication processes concerning blade fabrication. (Gurit, 2012)

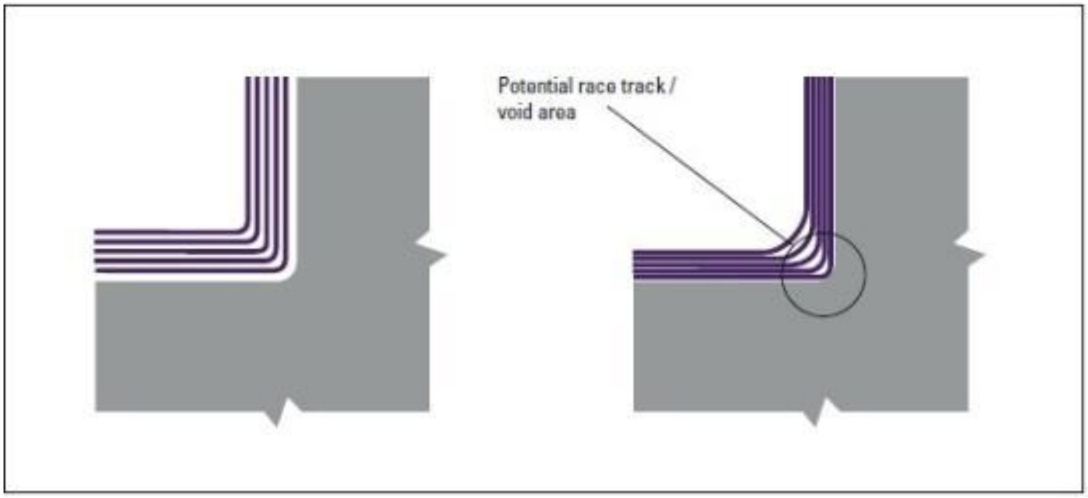


Figure 2-2. Female mold race track phenomena (Gurit, 2012)

In the above Figure 2-2, an issue with the bridging of dry fibers into a female mold can be seen. When the fibers in Figure 2-2 bridge, this causes areas of high permeability and "race track" the resin in the corners of the female mold. This means the resin does not wet-out the material as intended. Although this phenomenon is not a concern in male molding, there is an issue with the growth of "ears" in the corners of male molds after vacuum bagging is applied. Below in Figure 2-3, the "ears" can be seen on the right hand side. These can be prevented by proper application of fabric, staggering joints, and overlapping. (Gurit, 2012)

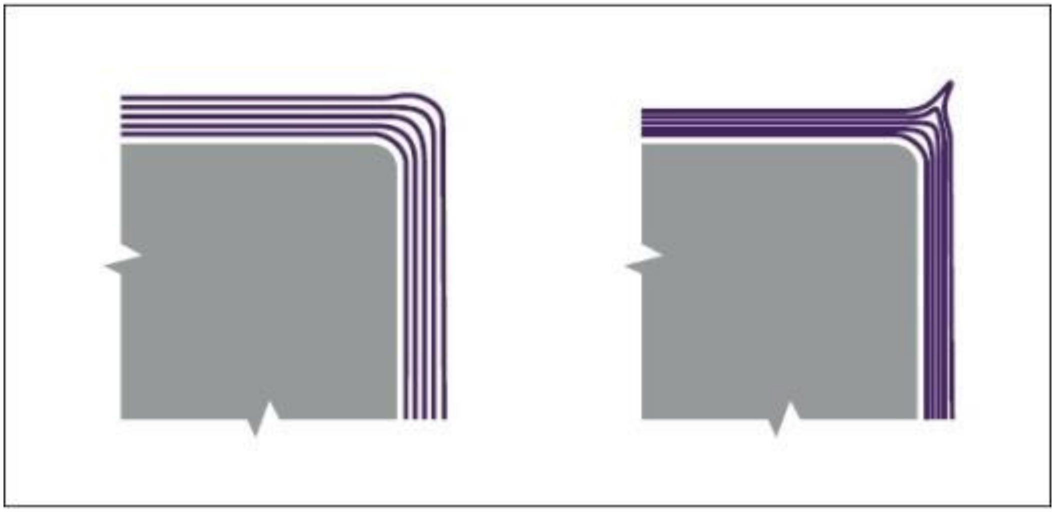
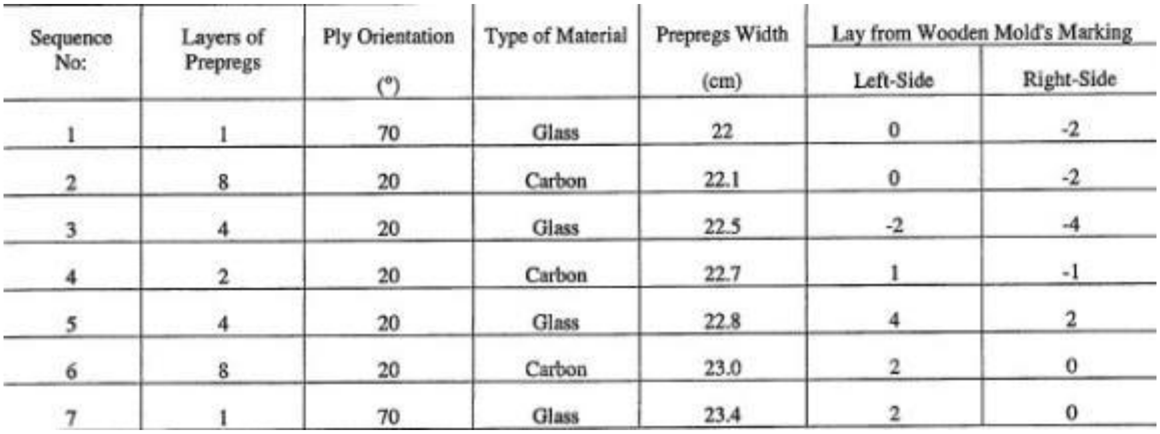


Figure 2-3. Male molding growth of ears (Gurit, 2012)

2.3: D-Spar

The goal of the D-Spar research was to fabricate a spar using composite materials and achieve maximum bend-twist coupling while still maintaining desirable structural properties. Two spars were fabricated with prepreg material out of both fiberglass and carbon fiber. A bladder process was used to fabricate the two spars. (Ong and Tsai, 1999)

The bladder process uses an inflatable balloon in the place of a male mold, inside a female mold to create a smooth outer surface. The fabrication of the D-spar begins with cutting prepreg material to the appropriate geometry. The width of some of the cutouts varied based on the lay-up schedule of the staggering joints seen below in Figure 2-4. (Ong and Tsai, 1999)



Sequence No:	Layers of Prepregs	Ply Orientation (°)	Type of Material	Prepregs Width (cm)	Lay from Wooden Mold's Marking	
					Left-Side	Right-Side
1	1	70	Glass	22	0	-2
2	8	20	Carbon	22.1	0	-2
3	4	20	Glass	22.5	-2	-4
4	2	20	Carbon	22.7	1	-1
5	4	20	Glass	22.8	4	2
6	8	20	Carbon	23.0	2	0
7	1	70	Glass	23.4	2	0

Figure 2-4. Lay-up scheme of D-Spar (Ong and Tsai, 1999)

A peel ply was applied to the wooden male mold for the purpose of releasing the material with the intention of taking out the wooden mold before the assembly of the female mold. Using the lay-up scheme, the prepreg material was then applied to the wooden mold. The purpose of the wooden mold is to lay-up the prepreg material based on its overlapping and staggering scheme before it is transferred to the closed female mold. After the lay-up on top of the wooden mold has been completed, the female mold is then prepared. The female mold can be seen below in Figure 2-5. (Ong and Tsai, 1999)

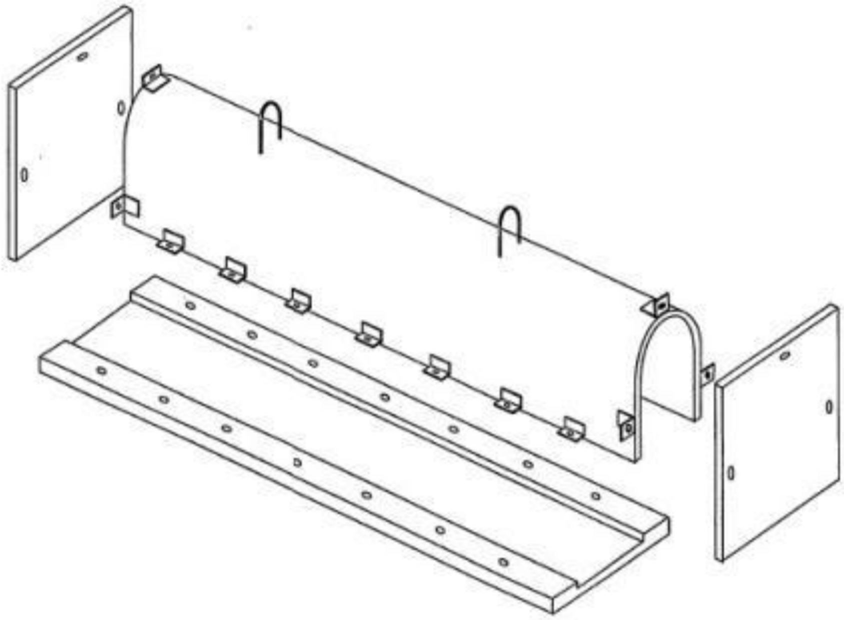


Figure 2-5. Female mold tooling (Ong and Tsai, 1999)

The female mold tooling was made up of two end plates, one base plate, and one U-shaped plate as can be seen in the above Figure 2-5. After releasing the inner surfaces of the female mold, the U-shaped plate was turned upside down and the wooden mold was flipped upside down inside to the female mold. The wooden mold was then removed from the mold and the inflatable bag was placed in the void left by the wooden mold. Next, the base plate and end plates were then assembled onto the U-shaped plate. Finally the bag was inflated and the part was cured. One of the critical aspects of the D-spar design is the overlap and butt joint design which can be seen below in Figure 2-6. After trial and error, the staggered joint lay-up method was chosen as the final method for fabrication of the D-spar. The disadvantage of the overlap joint is the doubly thick laminate located at the overlap location and the weakness introduced by the distribution of the change in thickness. The disadvantages of the butt joint were said to be the same as the overlap joint but required more ply steps during its lay-up. The staggered joint hybrid design can be seen in the far right of the Figure 2-6. The main advantages of this design are that both the step-change in skin thickness has been minimized and the joint have been strengthened. (Ong and Tsai, 1999)

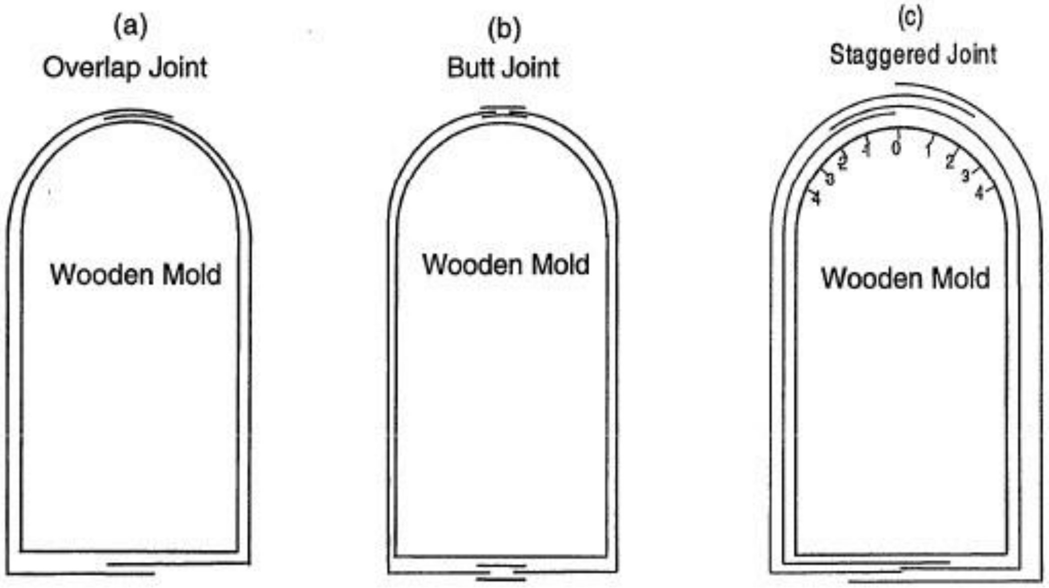


Figure 2-6. Joint design for D-Spar (Ong and Tsai, 1999)

2.4: Custom Sailing Yacht Design and Manufacture

This article discussed in depth the materials and methods used in manufacturing different components of a boat including the hull, deck, mast, and rudders. Each of the components are fabricated with different methods and materials but all involve the use of composite materials. This article discusses the steps used to manufacture a one-off or low production amount of yachts.

Due to the difference in tolerances between the aerospace industry and the boat building industry, the “clean rooms” in the boat building industry are not maintained as well. This is in regards to the lack of control of the ambient temperature which, in these environments, have a direct effect on the lay-up process of composite fabrications. The choice in materials for fabrication also has a substantial effect on the lay-up process for the yacht. The growth in low-temperature prepreg with a long out life has a substantial effect on the growth and development of the manufacture process. The author of the article states the advantages of working with prepreg material as very clean working conditions and longer working times with the materials. These two advantages allow for smaller working teams which save on labor expenses. Another advantage of prepreg is increased control over the weight as opposed to its wet-lay-up counterpart. The prepreg rolls can be tracked and recorded to aid in weight traceability of produced parts. One of the disadvantages is that more care is necessary in the tooling design and construction to ensure dimensional stability at high cure temperatures. The article goes on to state that de-bulking is required during the lamination process which does drive up the cost of both materials and labor. (Downs-Honey et al, 2003)

Figure 2-7. Male mold of yacht hull with prepreg applied (Downs-Honey et al, 2003)

Low cost is one of the guidelines for the tooling of hull and deck fabrication. When creating molds for a low number of production items, high durability tooling is not necessary since it will not used numerous times. The ultimate goal of tooling is to provide a low-cost method to fabricate a part while being able to withstand high cure temperatures without distortion. Cracks in the mold can also cause loss of vacuum when the mold has been put under vacuum bag. Tooling for the hull is most commonly made as a male mold from particle board as seen above in Figure 2-7. The male mold allows for a higher quality faired surface of the hull shape. Fairings can often be much cheaper and lighter than gel coats and their equivalents. Spars manufactured with prepreg are often cured in an autoclave which requires even more precision and care when creating the mold to maintain thermal stability. The thermal stability of the mold is also affected by the number of cures that take place which makes it desirable to have only one cure take place. This makes the de-bulking stages vital. With de-bulking, it is possible to avoid prelease or de-molding of the laminate. Unfortunately, the de-bulking cycles introduce increased durations of the prepreg's exposure to the ambient environment. (Downs-Honey et al, 2003)

Curing can be a difficult task for large parts such as is the case with boatbuilding. For the yacht, the first step taken when curing is removing the air from under the vacuum bag after the bag has been secured to the mold. Several workers aid in this step while taking great care to prevent wrinkling and small bridges on the surface of the mold along with voids in the corners. After the oven is created around the part and the part has been cured, the vacuum bag is removed and a thin layer of fairing compound is applied to the surface of the mold to fill and gaps that had developed during the curing stage. This process can be iterative, time consuming, difficult labor but eventually, an evenly distributed smooth surface will be acquired. The article goes on to mention the repercussions of a mistake during the laminating or de-bulking stage as being very costly. Man hours, money, and materials will all be wasted and have to be reinvested in to rectify these errors from the previous stages ultimately driving up costs that were intended to be avoided. (Downs-Honey et al, 2003)

2.5: Male Molding with Oven Vacuum Bag Prepreg

This paper goes into detail discussing the use of Oven Vacuum Bag (OVB) prepreg identical to the material discussed in Chapter 1 and the innovations being made at the Applied Research Laboratory (ARL) in Penn State. The cost efficiency of male molding and the benefits of using caul blocks are also discussed for a few applications.

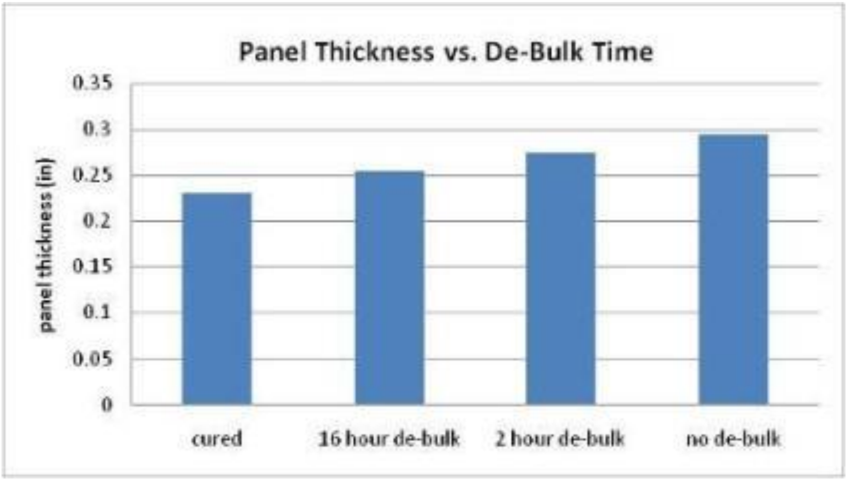


Figure 2-8. Graph of post de-bulk thickness (Juska et al, 2012)

Some of the goals of this research were to use methods to fabricate low cost, low void content (between 0% and 1%) parts by saving money on labor costs. This can be done by developing methods to create male molded parts with a surface finish similar to that achieved by female molding. With the use of OVB prepreg room temperature de-bulks are used. These de-bulk cycles compact the laid up plys to reduce the wrinkling of thick parts in areas of high curvature. Tests were done to assess the effectiveness of a de-bulk at 2 and 16 hours as compared to the thickness obtained before a de-bulk and after a cure. Elevated temperature de-bulks are used when full compaction, full compaction of the material is desired. It is noted that no increase of void content was shown post-cure with the use of de-bulk stages during the lay-up stages. A part with a thickness of 5.5”, through inspection, showed no signs of increased void content after the use of a de-bulk stage. No string breathers were used during the de-bulk stage of any of the applications to be discussed below. (Juska et al, 2012)

2.5.1: Navy Cover Plate Application

The first application discussed in the article was the Navy cover plate with given specifications that must be satisfied similar to the goals discussed for this paper. The intent of this application was to fabricate a cover plate using low cost composite fabrication. OVB prepreg was selected in conjunction with male molding derived from a “splash” pulled from the ship’s structure. A splash is made by laying up composite materials on existing geometry to essential “steal” that geometry for use elsewhere. The original surface is released beforehand to allow the laid up material to be removed after its cure. This method is used commonly for applications with Navy ships due to the varying geometry from ship to ship. (Juska et al, 2012)

Figure 2-9. Navy cover plate (Juska et al, 2012)

In the above Figure 2-9, the Navy cover plate with a length of 10’ and thickness of 1” can be seen. Also as seen in the above figure, the prepreg material has been laid up to the edges of the part because the material will not be machined post-cure. The author notes the major difficulty with the male molded approach to this application as the areas with high curvature. The issue is rectified with darting the prepreg in these areas to allow the prepreg to conform. One intermediate de-bulk cycle takes place at 20 plys for the parts 40 ply laminate. A large oven with a propane heater was created to cure this part which was made out of plywood. Similar to other boat building applications, this part does not use the high temperature cure prepreg as used in the aerospace industry due to lack of necessity. Post-cure, slight wrinkling was seen after inspection that was corrected using a palm sander. (Juska et al, 2012)

2.5.2: Cusp Fairing

After the success of the cover plate, another application for low cost composite fabrication appeared known as the cusp fairing for a submarine. For these parts in particular, machining a complex doubly curved surface from steel is substantially higher than its composite counterpart. Male molding with OVB prepreg was selected as a fabrication method for the cusp fairing fabrication. Before the full scale part was created, a half scale cusp was fabricated at ARL Penn State. Wood tooling was used for the base and syntactic foam was poured into the shape from a Styrofoam plug. Although care was taken during the pour of the syntactic foam, there was some shrinkage and spring back after the foam cure. The cusp can be seen before and after the syntactic foam had been poured below in Figure 2-10. (Juska et al, 2012)

Figure 2-10. Cusp inner skin and Syntactic Foam pour (Juska et al, 2012)

Lay-up of the laminate was done across the surface of the foam in 6” wide strips with the selected OVB prepreg material. The plys were oriented at 0^{o}, $+45^{o}$, -45^{o}, and 90^{o} ply direction and the ply butts were staggered every four plys. This means that after the previously mentioned orientation had been laid upon the part, the ply butts would then be moved meaning the initial lay-up of the first 0^{o} strip would begin at a different location. The change in direction of the ply orientation can be seen below in Figure 2-11. Due to the complex curvature, some of the prepreg material was occasionally darted during its lay-up. (Juska et al, 2012)

Figure 2-11. Cusp fairing lay-up change in direction of ply lay-up (Juska et al, 2012)

For this part, de-bulk cycles took place after every 2 plys had been laid on the part. The thickness of each ply of the material used for the fairing was .058” as compared to a normal ply thickness of roughly .02”. The complex curvature must also be considered when deciding on the number of de-bulks to take place during lay-up. After cure, the cusp fairing was nearly wrinkle-free and the full scale part was then fabricated afterwards. (Juska et al, 2012)

2.5.3: Doubly curved structure with smooth surface

For this application the main goal was to use the male mold made of low cost foam tooling below in Figure 2-12 to fabricate a part with smooth surface as if there were two molded surfaces with the use of caul blocks and OVB prepreg. Caul blocks are successful because there is generally no need to bleed resin so the laminate quality is not affected with the blocks on the part. A caul block was fabricated on this mold using VARTM along with two plys of carbon fabric Style 94-117 and Derakane 510A vinyl ester. 36 plys were to be laid upon the mold with two de-bulk stages and one cure stage for the lay-up scheme of this part. Each stage took place every 12 plys and the de-bulk stages took place before the final cure stage. The de-bulk stages made use of the caul block as well. Unfortunately the fabricated caul block was not rigid enough to prevent edge distortion. This can be explained by the selection of the number of carbon plys for the caul blocks. The edge distortion can be seen below in Figure 2-13. (Juska et al, 2012)

Figure 2-12. Male mold for doubly curved structure (Juska et al, 2012)

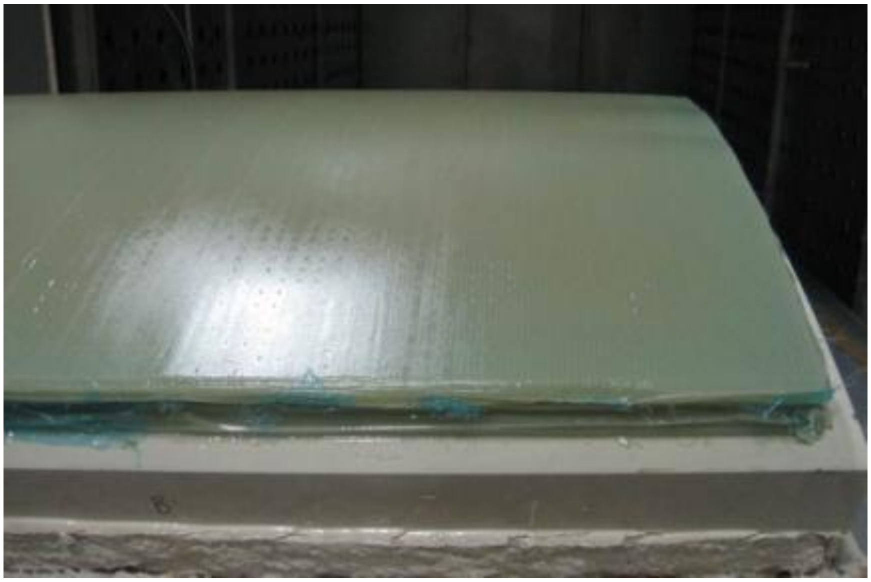


Figure 2-13. Edge distortion of doubly curved surface (Juska et al, 2012)

A second process trial of the previous experiment was done using a more rigid caul block in hopes of eliminating the edge distortion using two plys of ST94/QE1203. The thickness of this caul block was 80 mils (.08”). Two other changes were introduced including the use of a surfacing film and allowance of the caul block to be placed directly against the lay-up. The newly created caul block can be seen below in Figure 2-14. (Juska et al, 2012)

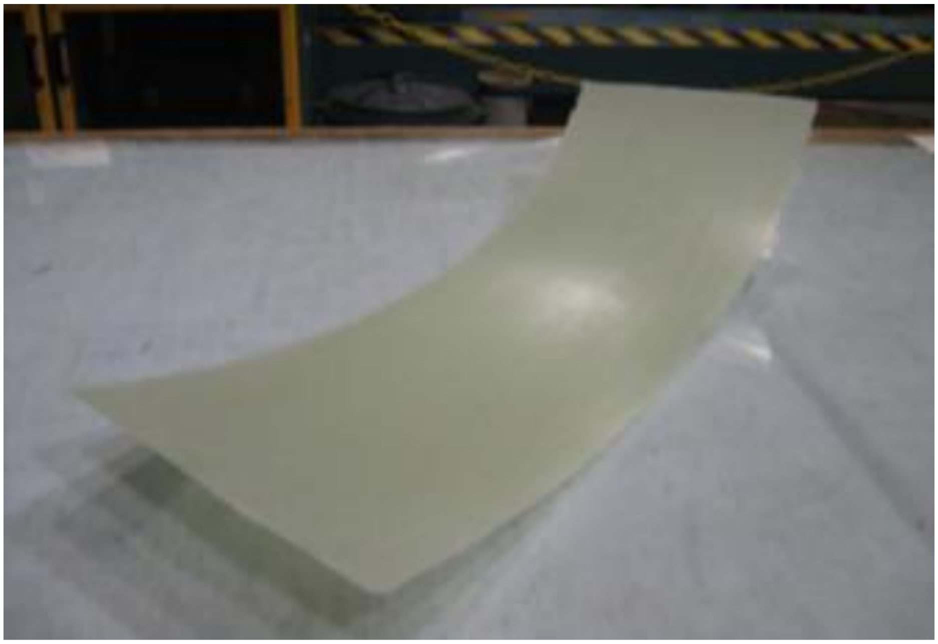


Figure 2-14. Second trial caul block (Juska et al, 2012)

The surfacing film chosen was Gurit SF 95 PF that is a pigmented resin film in-between two light scrim fabrics. One of the scrims allows for breathing between the surface film and the mold while the other allows for an evacuation path for the air trapped between the lay-up and the film. For this trial, the de-bulk stages again utilized the caul blocks on the surface of the laminate. Due to the surface finish of laminate directly depending on finish of the caul blocks, close attention was paid to the inner surface of the caul blocks. The inner surface was faired, sanded, and then released to achieve a better finish. Post-cure, the finish of the surface of the part appeared as if there were two molded surfaces as seen below in Figure 2-15. (Juska et al, 2012)

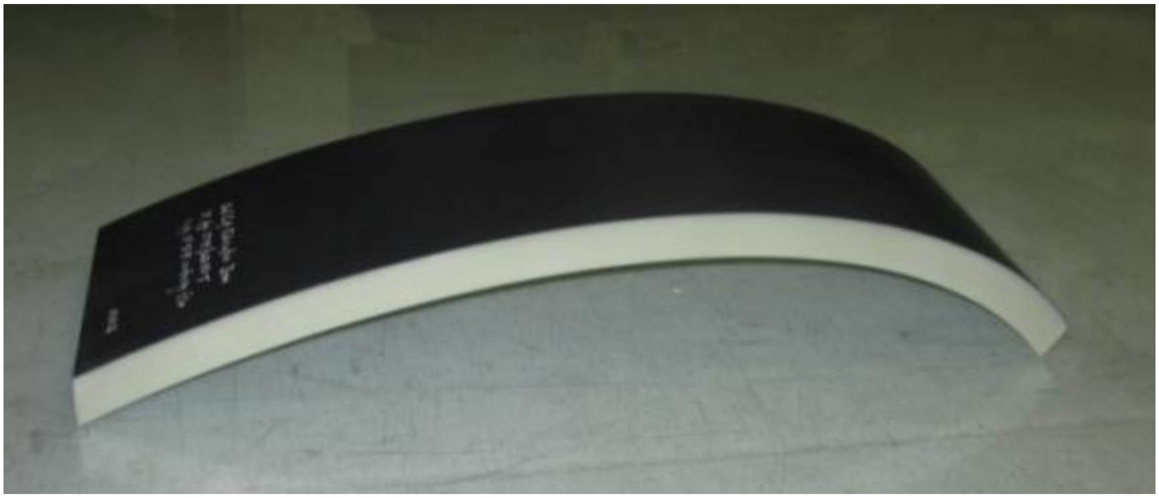


Figure 2-15. Second trial male molded w/ surfacing film (Juska et al, 2012)

Also after the cure, a Federal Pocket Surf Surface Gage was used to measure the Roughness Averages (Ra). The gage uses stylus transducers to determine the smoothness of the surface. The roughness of a typical female molded composite surface has a value of 15-20 micro-inches. The typical roughness of a conventional vacuum bag (peel ply) surface is 220-230 micro-inches. The measured surface of the fabricated part and caul block inner surface for the second trial was 30-35 micro-inches. The author noted that the Pocket Surf was not effective at measuring the Ra of wavy surfaces. (Juska et al, 2012)

The third trial was made using integrated steel framing for the mold. The low cost foam in conjunction with the frame limited the expenses for the mold. A CAD file along with the frame seen below in Figure 2-16 was used to create the mold also seen below in the figure. (Juska et al, 2012)

Figure 2-16. Male mold with steel frame for third trial of doubly curved surface (Juska et al, 2012)

A caul block was again fabricated before the laminate was laid using the same material as the second trial due to its adequate properties of stiffness and rigidity. For both the caul block and the laminate, transverse prepreg sections alternated with longitudinal sections for 36 plys. The laminate did stagger the ply butts using the same method as previously discussed in this paper. De-bulk stages also took place at 12 and 24 plys applied with a cure stage after the laminate was completely laid up. Due to the thickness of this lay-up, an extension was added to the caul block as seen below in Figure 2-17. (Juska et al, 2012)

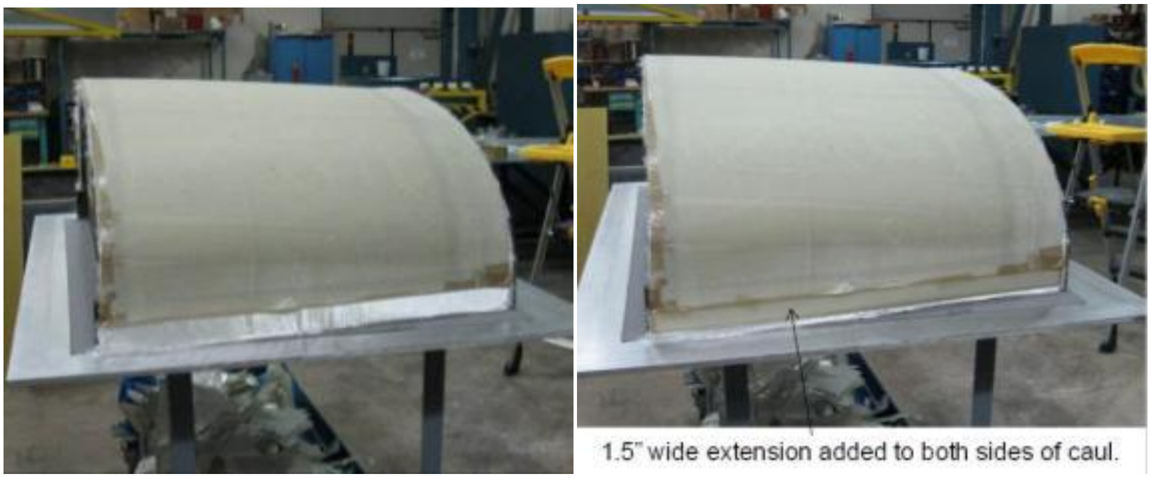


Figure 2-17. Third trial caul block extension (Juska et al, 2012)

Similar to the second trial, the caul blocks were prepared by fairing, sanding, and releasing the inner surface of the caul block. The part was cured by holding vacuum at room temperature for 16 hours, elevating the temperature in the oven to 120 ^{o}F for 12 hours, then to 160 ^{o}F for 10 hours, then a final 185 ^{o}F for 4 hours. After the cure, there was an apparent mark off from the caul block extensions that were made during the lay-up stage. To avoid the mark off as seen below in Figure 2-18, an alteration to the fabrication process must be made. (Juska et al, 2012)

Figure 2-18. Mark off on third trial of doubly curved surface post-cure (Juska et al, 2012)

2.6: Low-Cost Design and Fabrication of Composite Ship Structures

The Navy discusses in this paper the details of a VARTM method use to fabricate high-performance structures for ships. These methods were developed for such as monocoque, single-skin stiffened, and sandwich configurations. The author claims that the result of these methods is on par with those fabricated by both wet lay-up and prepreg autoclave cure. Structural performance tests were also done on prototypes and were successful according to the paper. Composite materials were seen as a viable option for Navy over metal due to very specific reasons that have a large impact on the operational performance of their ship structures. Composites can reduce weight, cost, noise transmission, corrosion, and fatigue cracking. They also provide the ability to increase fire containment and shock resistance. The chance to improve performance in all of these areas warranted further development of methods involving composite fabrication. After research and experimentation RTM and VARTM were seen by the author's department of the Navy to be the most versatile and efficient way to produce their composite materials. Filament winding and pultrusion were also considered as viable low cost options for ship structures but did not fit the requirements for the difference between all of the ship structures to be created. Pultrusion is not seen as suitable for non-uniform or tapered structures while filament winding generally has difficulty with complex geometry and the application of stiffeners. RTM is considered for manufacturing medium to large sized parts with a closed mold process while VARTM can be either or open or closed allowing for more customization. The author mentions that the Navy has been very successful with open mold VARTM fabrication processes for deckhouse, mast, and foundation structures. The type of VARTM used is called SCRIMP. The Seemann Composites Resin Injection Molding Process (SCRIMP) as mentioned and described briefly in Chapter 1 utilizes its patented distribution medium to achieve aerospace quality composites with high fiber content and low void content. The SCRIMP process was selected because of the cost estimates being less than other similar methods. (Critchfield and Judy, 1994)

The main reason for the Navy's interest and choice of the SCRIMP process was its ability to fabricate parts that were previously made by other means much more affordable. In 1989, with the use of the SCRIMP process; the Navy was able to remake their largest high-performance composite panel much more affordable than its wet lay-up autoclave cure counterpart. In addition, the new panel used a vinyl ester resin instead of the previously used isophtalic polyester resin to increase the toughness of the panel under dynamic loading. The deckhouse for a ship is another application where the switch to composite materials made a difference by decreasing the overall weight by 45% and eliminating corrosion and fatigue capacity along with an increase in fire containment. The use of sandwich construction increased the weight reduction by an additional 10% or more. The cores were tested with a variety of materials but balsa was determined to be the most efficient. The outside panels were made using the SCRIMP process along with a vinyl ester resin. After testing, it was determined that the panel showed no signs of delamination with inspection after air blast testing had been done. The composite mast was the next application assessed to be integrated into composite materials and after a design study it was determined that 20% to 50% of the weight could be saved. A half scale model was created for an applied research fabrication test. After the half scale model was created it was determined 20% of the weight was saved. Construction of composite foundations actually showed that smaller scale models were more costly and difficult to create then their larger scale models due to the difficulty of placing the fabric in the corners. (Critchfield and Judy, 1994)

Overall, the Navy showed great interest in the switch to composite materials due various advantages including the extremely important aspects of weight and cost reduction. The SCRIMP process was chosen due to its particular advantages for the navy as compared to other methods available at the time of publication. (Critchfield and Judy, 1994)

2.7: Process Development Issues of Glass-Carbon Hybrid-reinforced Polymer Composite Wind Turbine Blades

This article uses VARTM as its process to fabricate wind turbine blades due to the relatively low cost and repeatability for numerous blades. The authors label VARTM as the preferred method even though several methods are applicable. Although methods like VARTM are preferred, they do pose concerns regarding permeability of large tow sizes. Selection of tow size of material is a large concern as it directly impacts the permeability of the resin across the part as well as the choice in materials available. Larger tow size decreases the amount of permeability through the fabric and also increases the fill time of the resin through the fabric. The resin flow and port locations for the VARTM process were all determined through simulation tools. (Sharma and Wetzel, 2010)

The reduced scale of the blade at 3.2m as compared to their 10m counterparts seemed to cause some issues that would not appear on a larger scale. Molds often have a network of pipes through them which can help with the heating of the fabric contacting the surface of the mold. Due to the smaller scale of the experiment and only a few blades to be made from the mold, a plaster tool with a limited life expectancy is deemed appropriate for the purposes of this application. Unfortunately, these tools are later noted to lack effective thermal conductivity making heat blankets the only viable option. The heat blankets introduced another problem. They had to be vacuum bagged in addition to the laminate to ensure appropriate heat distribution across the entire part. The female tooling was created from a CNC machined male mandrel. There are two separate female halves that are intended be brought together using a clamshell method. A fixture or jig as seen below in Figure 2-19 holds the respective pressure and suction halves of the blades. (Sharma and Wetzel, 2010)

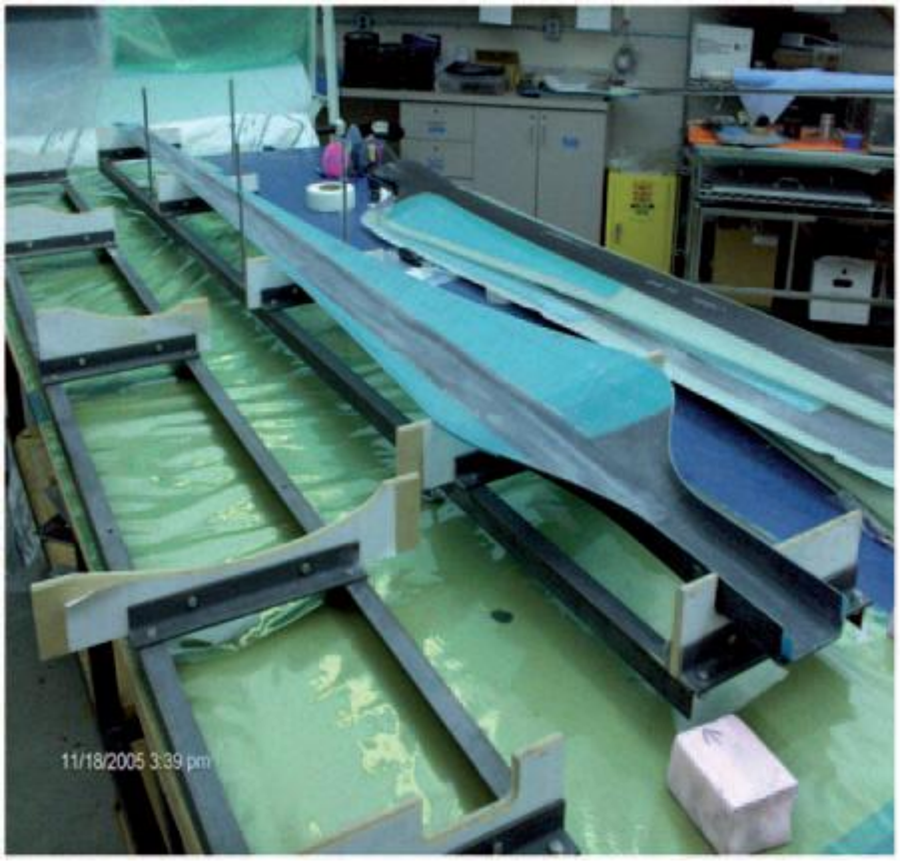


Figure 2-19. Blade fixture/jig in preparation of clamshell method (Sharma and Wetzel, 2010)

A foam mandrel is then machined to the appropriate dimensions of the inside of the blade and acts as a shear web core. The shear web is bonded after one half of the blade has been placed in the fixture and the second blade skin is secured on top of the shear web with paste adhesive bonding the leading and trailing edges together. Clamps are put in place to assure nothing moves out of place and the composition is left to cure for 24 hours at room temperature. (Sharma and Wetzel, 2010)

Chapter 3 :

Applied Research on Tapered Spar

3.1: Design

Many of the innovative approaches to fabrication discussed in this chapter were made while fabrication was taking place. Some decisions had to be made in the design stages before fabrication. Refer to Appendix A for the lay-up scheme of the laminate.

Based on the materials available for the research of this project and ease of fabrication, the ply scheme did change slightly due to material availability and ease of fabrication. In addition, each of the four horizontal faces of the spar was given a letter corresponding to their location on the spar, enabling easy reference to specific surfaces of the mandrel. This is especially helpful later on in the fabrication process when slight changes in the surfaces post-cure cause each of the surfaces to vary slightly. These four surfaces were assigned A, B, C, or D. A being the surface that is most commonly facing upwards and C being the face that pointed towards the ground. A depiction of this can be seen below in Figure 3-1. Each of the corners were also labeled using numbers 1 through 4. It is important to note that the face in Figure 3-1 is the larger of the two vertical faces of the spar. Labeling the surfaces and corners also aided in description of the ply staggering described in the section below.

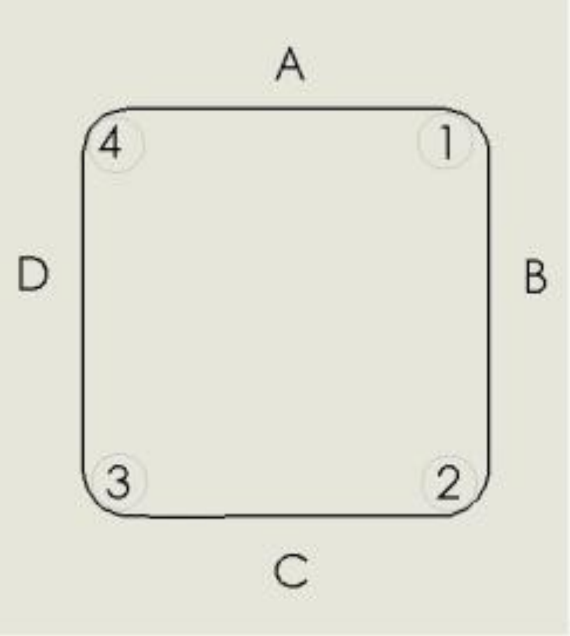


Figure 3-1. Spar labeling of corners and flat surfaces – Front view

3.1.1: Lay-up Scheme

The design stated that for the first ply of the lay-up and all of the odd numbered plys between plys 1 through 10 ST70-1/WRE850, a 29 mil (.0029”) thickness woven fiberglass prepreg material, would be used. For the second ply of the lay-up and all even numbered plys between plys 1 through 10, two different prepreg materials were used. On the B and D faces 2 plys of a uni-directional carbon fiber Sparpreg material with a thickness of 10 mils (.001”) each were used. On the A and C faces, one ply of a fiberglass material called ST94/XE603 with a thickness of 20 mils (.002”) that is stitched in the 45^{o}/45^{o} direction was used. The Sparpreg material had a set width making the ST94/XE603 occupy some of space of surfaces A and C as seen below in Figure 3-2 and Figure 3-3. To summarize, plys 1, 3, 5, 7, and 9 all used the ST70-1/WRE850 material. Plys 2, 4, 6, 8, and 10 all used both Sparpreg and ST94/XE603 material. A depiction of the second ply can be seen below in Figure 3-2. A layout of the laminate scheme for **all** plys applied to the mandrel can be seen in the Appendix A.

Figure 3-2. Second ply lay-up on mandrel

3.1.2: Ply Staggering

During the design stages, it was decided that the part would be de-bulked at roughly every .25”, or 10 plys as noted in Appendix A. It was also decided that there would be a stagger of odd numbered ply butts. The purpose of staggering the ply butting is to reduce any stress concentrations and avoid de-lamination of the laminate. The ply butts of the ST70-1/WRE850 material were staggered in different areas as the lay-ups went on, resetting after each de-bulk stage of 10 plys. If all butts of the spar were left in one location, it would cause a drastic weakness in the spar. This method was developed to produce a stronger spar. This concept can be seen below in Figure 3-3. Marks were made on the released surface of the foam mandrel that was untouched by the laminate to denote staggering locations.

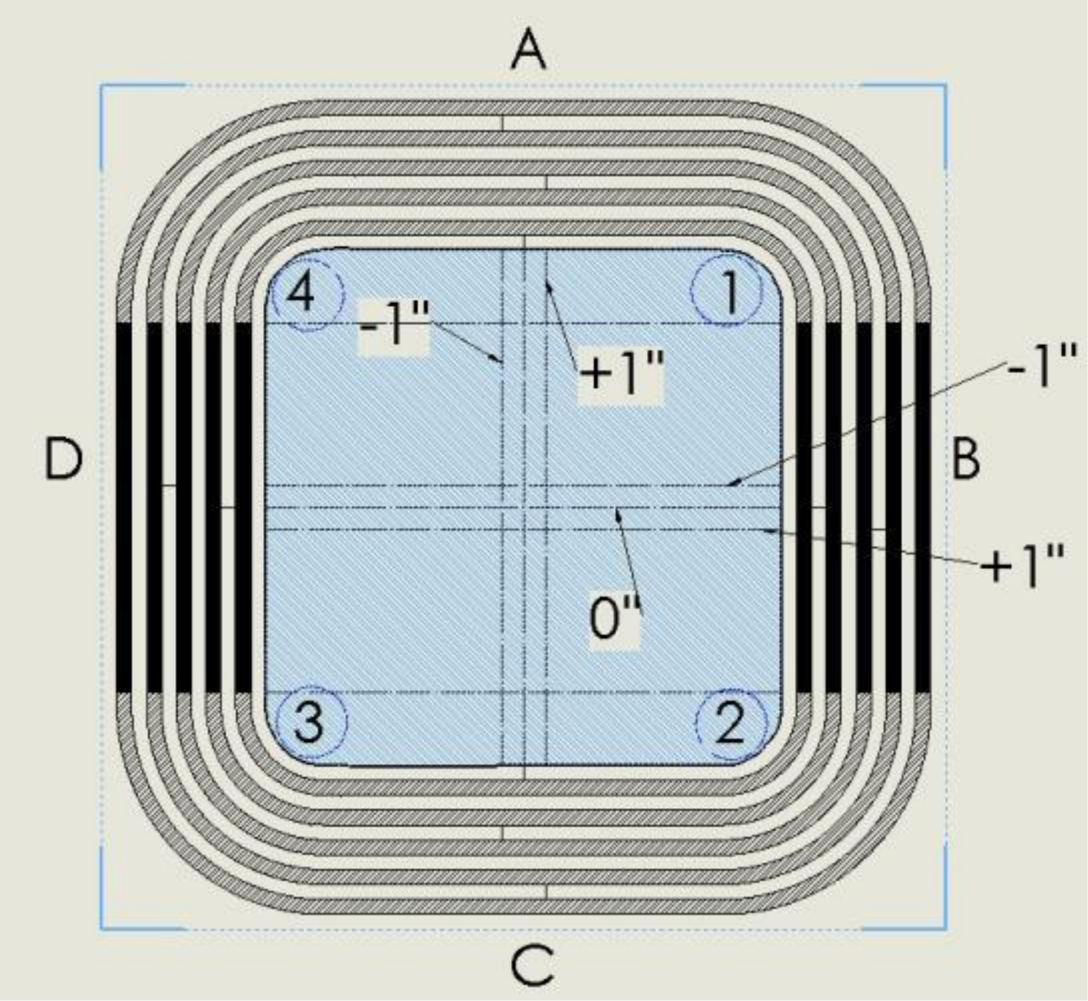


Figure 3-3. Ply staggering implementation

These marks were labeled as +1”, 0”, and -1” as seen above in Figure 3-3. Before an explanation is made, note the pattern between the even numbered plys and odd numbered plys. The pattern of the even numbered plys is completely independent from the pattern of the odd numbered plys. The very first ply application was placed on surfaces B and D. Due to the template shape modeling only half of the shape of the mandrel to be cutout at a time, each ply required two separate cutouts butted together to create one ply as was mentioned previously. It takes two cutouts to create one ply. Since each cutout from the template is applied to the surface, they meet at two different opposing positions on the mandrel. This is called the ply butt locations. The ply butts for the first ply application were located on surfaces A and C at 0”. The third ply lay-up was made so that the middle of the ply was on the 0” surfaces of faces A and C. So this means that the ply butts were located on faces B and D for this particular ply. Next the 5th ply lay-up shifts the middle of the ply to the +1” section of face B and continues to stagger these plys so that no butt ends in the same place between each de-bulk stage. The stagger process is documented for future reference. The new ply lay-up scheme that was created for ease of fabrication is depicted in Appendix B.

3.1.3: Template Design

Prior to applying the first ply upon the male mold, a Computer Aided Design (CAD) model of the spar was made using the recorded dimensions of the spar. Since the spar is vertically and horizontally symmetric about the two opposing vertical faces seen in Figure 3-4, the spar was cut in half and the surface was flattened using a composite ply flattening program called FiberSim. This file allowed for the design of full scale templates for the spar lay-ups. During the fabrication process it was discovered that with respect to the particular spar to be used, the template was only accurate for roughly 10 plys of lay-up or .25”. This is due to the buildup of the laminate of the spar in all directions. As plys are laid up, the spar essentially “outgrows” the template and a new template must be made.

In Figure 3-4 below, some of the first steps of the CAD drawing can be seen. As was mentioned previously, the dimensions of the spar were recorded and these documented measurements were used to create a model of the part in Solidworks. The model began by first creating the larger of the square faces and then filleting the sides with the known equal radius in each of the corners. The opposing smaller surface was then created 24”away to denote the length of the spar.

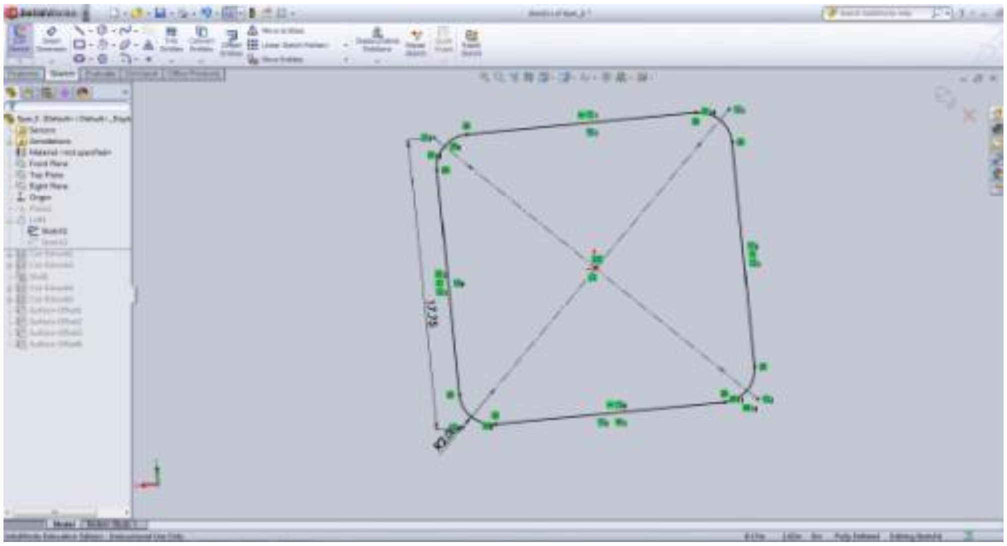


Figure 3-4. CAD drawing part 1

The two faces of the spar were then drafted together, using the “draft” feature, to make a solid part with the exact dimensions of the existing spar as can be seen below in Figure 3-5. After the solid surface had been made, the surface that the template would be made from was created. Due to the part being symmetric down its span, one template is used for both halves of the spar. This is the reason for cutting the spar in half as discussed previously.

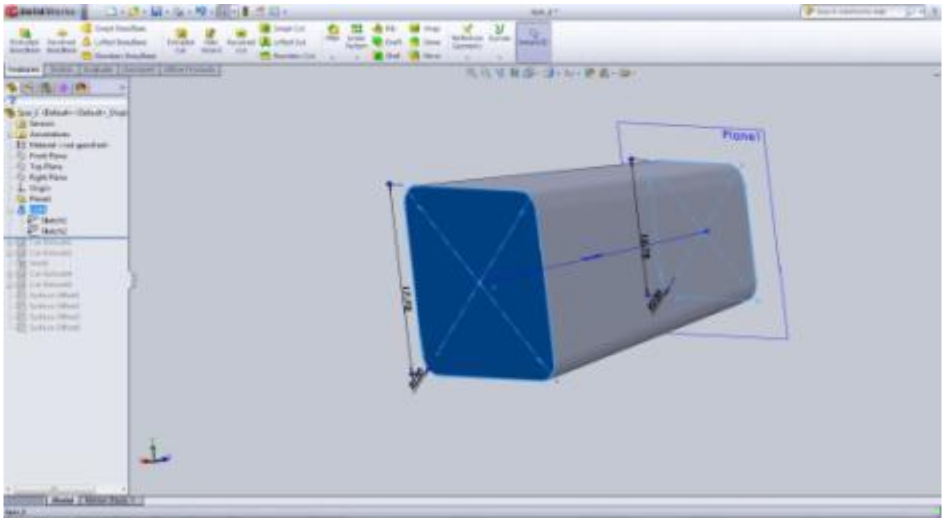


Figure 3-5. CAD drawing part 2

The model was then hollowed out using a function called “shell” within Solidworks changing the part from an entirely solid model to one with a uniformly thin surface. This allows the model to be flattened for the purpose of the template. The “flatten” feature in FiberSim does not operate with a thick part. The new surface was saved as an IGES file and imported into NX, another type of CAD software, to allow for the use of FiberSim. An IGES file is a file format that allows a part to be saved in one type of CAD software and imported into a different one, in this case from Solidworks to NX. For future templates, the surface saved into Solidworks was referred back to and offset based on the geometry of the lay-up to follow. For example, plys 1-10 had a thickness of .25”. To create a template for plys 11-20 the initial CAD file was opened and the surface was offset by .25” outwards from the spar. Several created surfaces can be seen below in Figure 3-6.

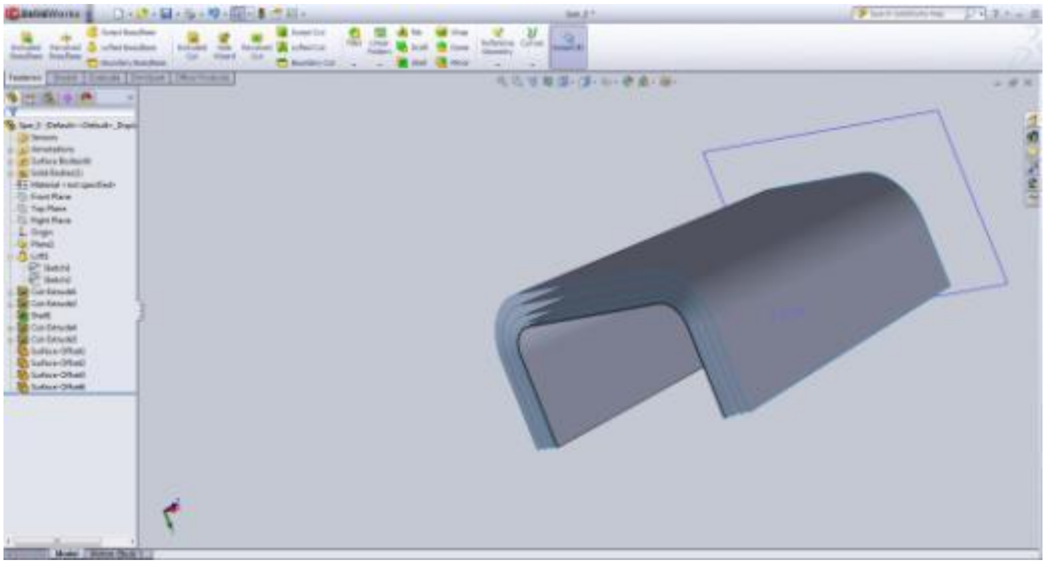


Figure 3-6. CAD drawing part 3

Each of the surfaces seen in Figure 3-6 represents a different template that was created for the purposes of lay-up onto the spar. Each of the preceding surfaces was hidden using the “hide” function within Solidworks allowing appropriate offset surface to be flattened after the IGES file had been created.

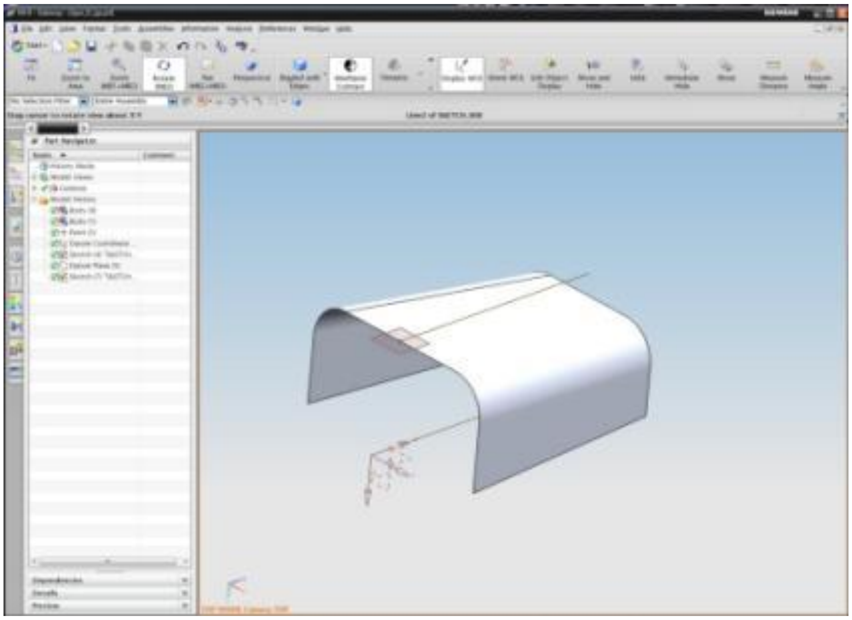


Figure 3-7. IGES file import into NX – Plane and Axis creation

After the IGES file was imported into NX, a plane was created on the top of the surface. This plane was used to create an axis and point as a basis for the ply flattening to begin. The resulting plane and point on the model can be seen above in Figure 3-7. There are 3 main functions after opening FiberSim that the user must input before a surface can be flattened. The functions are "Laminate", "Rosette", and "Ply". After selecting "Laminate", the user must select a "Lay-up Surface" which is the outer surface of model that will be flattened. The next option is to select "Net Boundary" under the "Laminate" function. The "Net Boundary" function is the boundary that encloses the "Lay-up Surface". In other words all of the edges of the model are selected in this case. After the conditions for the "Laminate" function have been satisfied, the "Laminate" was saved and the "Rosette" function was opened. The "Rosette" function required a selection of the "Origin" and "Direction" to complete this function. The origin is the point that was created on the surface of the model previously and the direction was the axis that was created along with it. The purpose of the origin and direction are to inform FiberSim of the center of the ply. Depending on the stitching angle and the type of prepreg material selected, the flattening pattern will be different making the center and direction of the ply important. The "Ply" function is the next function opened. The "Rosette" and "Laminate" were inputted into the "Ply" function to their corresponding locations. The "Net Producibility" button allows FiberSim to calculate the geometry of the material and the location of any slits that need to be made so the prepreg will be applied to the mold appropriately. This button was selected and then the "Generate Flat Pattern" button was selected afterwards to produce the flat pattern. The resulting flat pattern for the spar section can be seen below in Figure 3-8. This pattern was then saved and printed in full scale.

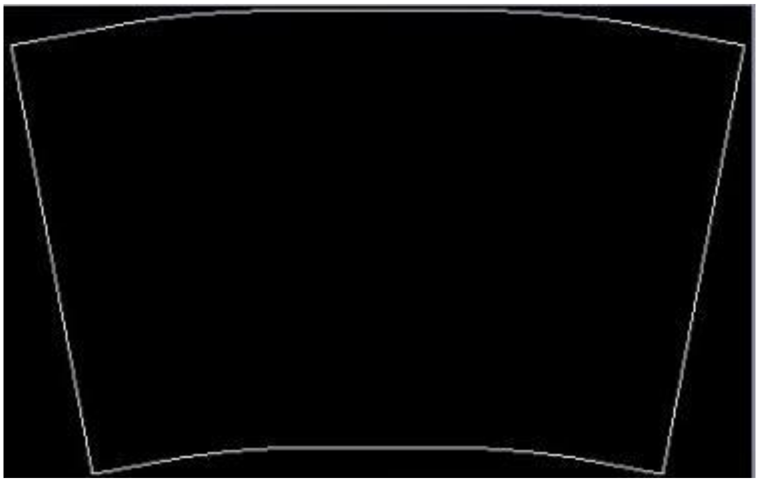


Figure 3-8. Template created in FiberSim

3.2: Fabrication

3.2.1: Vacuum Bagging

One of the most important aspects of fabrication that has not yet been covered in detail is vacuum bagging. Vacuum bagging is the process of applying vacuum to a part, removing all of the air under the sealed bag and applying pressure to the laminate under the bag, consolidating the material. This process requires a vacuum, a hose with a nozzle attachment, released bagging material, breather, and sealant tape. The first step is applying the green sealant tape as seen below in Figure 3-10 and labeled below in Figure 3-9.

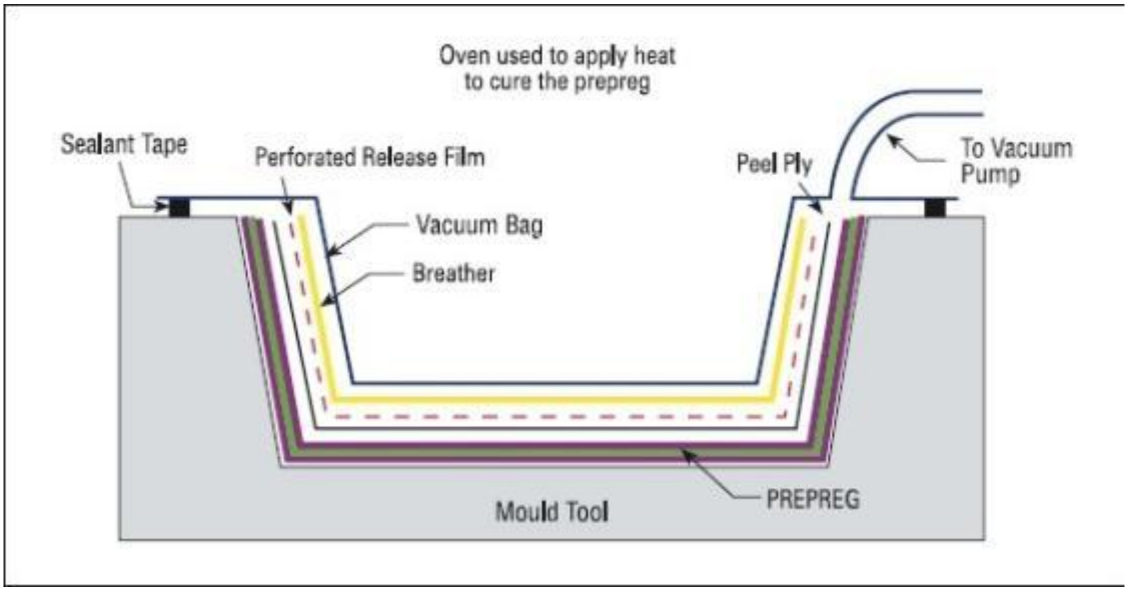


Figure 3-9. Example of prepreg bagging scheme (reference 12)

Figure 3-10. Example of a part under vacuum

The vacuum requires a pathway enabling it to pull air out from under the bagging material. The breather allows for the pathway along where this material contacts. The breather covers the surface of the laminate on the mandrel. The released bagging material is then applied by placing the bag around the part, sticking the bag to the sealant tape, and using the tape to seal the bag and prevent any air from escaping. During the bag placement process the hose with the nozzle attachment has part of the hose wrapped in sealant tape so that no air escapes over the tube. The hose wrapped with sealant tape is then placed on the sealant tape that is on the edge of the mandrel. The hose is also secured to the part with Teflon tape to assure that it does not fall off. The released bagging material is then placed over the rest of the mandrel and sealed. The vacuum is then turned on and any leaks between the sealant tape and bag must be found before cure or de-bulk cycles can take place.

3.2.2: Foam Mandrel Fabrication

Figure 3-11. (a)Foam mandrel mold (b) Foam pour into mold

As seen above in Figure 3-11 and below in Figure 3-12, the project began with a foam mandrel as a base for the spar with the intent to male mold the spar section. The female mold in Figure 3-11 was used to create the foam mandrel seen below in Figure 3-12. Before the foam was poured, a metal rod was centered in the mandrel to allow rotation about this axis. This allowed for ease of access to each of the surfaces of the mandrel.

Figure 3-12. Foam core mandrel

The surface of the foam was coated with epoxy for surface preparation. Surface preparation is a very important step when fabricating composites ensuring that the laminate adheres to the surface.

3.2.3: Corner Caul Block Fabrication

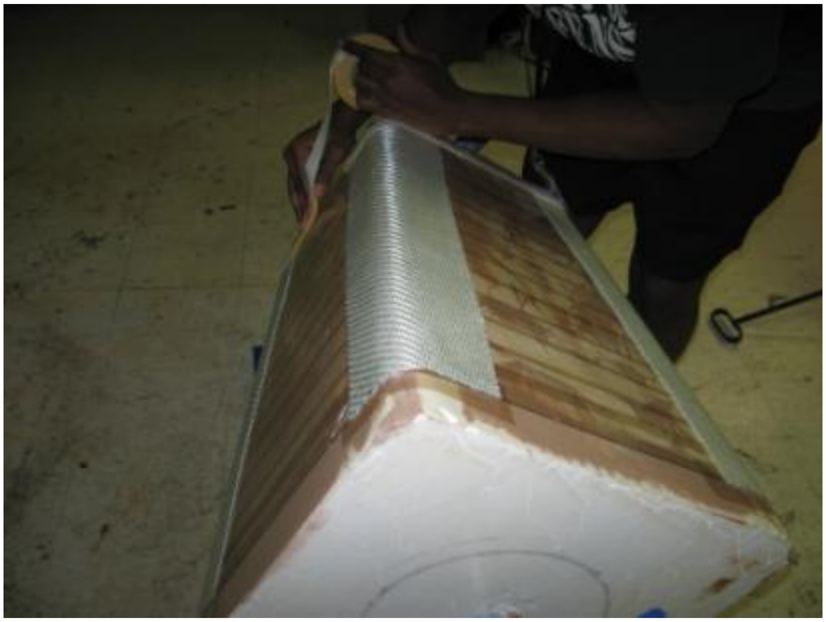


Figure 3-13. Corner caul block lay-up

After the surface of the foam mandrel had been prepared, the process of fabricating the “corner caul blocks” began. Corner caul blocks serve the purpose of reducing the bunching of material in the corner as well as eliminating the wrinkles in this area during the cure and de-bulking stages. In future figures the corner caul blocks can be seen layered on top of the plys that were directly applied to the foam mandrel. In Figure 3-13 above, fiberglass was the material used in fabrication of the corner cauls. Specifically two plys of the ST70-1/WRE850 material with a thickness of 29 mils (.0029”) each were used. These 22” X 6” wide sections of corner caul blocks were applied to a released spar surface allowing their removal after they had been cured. Teflon tape was used as the release agent. Figure 3-14 below shows corner caul blocks pre-cure. The lines on the mandrel are the overlapping sections of Teflon tape.

Figure 3-14. Corner caul lay-up cont.

The corner caul blocks were vacuum bagged, de-molded, and marked to correspond to each corner that they had been laid upon. This was done solely for precaution considering each corner is geometrically the same. The release tape was removed from the mandrel permitting the first ply to be laid up as seen below in Figure 3-15.

3.2.4: Spar Lay-Up

Figure 3-15. First ply lay-up on mandrel

Above in Figure 3-15, the first lay-up of the first ply can be seen. At this stage, the Teflon release tape had been removed from the spar, allowing the laminate to adhere to the surface of the mandrel.

In Figure 3-16 the spar can be seen after 10 plys have been applied, the corner caul blocks are in place, and the vacuum bag has been sealed in preparation for the de-bulk stage.

Figure 3-16. Spar under vacuum in preparation for de-bulk/cure

Although the original plan was to de-bulk the spar only after every 10 plys of lay-up, it was noticed that the surface of the prepreg material was no longer flat and therefore not ideal to lay-up upon. Any errors on the surface of the spar will be exaggerated as plys are laid upon it if it is not reconciled beforehand. One problem can be seen in the image below Figure 3-17 where the vacuum tube was left on the 10th ply of the spar instead of on one of the corner caul blocks. This causes an indentation in the shape of the vacuum tube as can be seen below in Figure 3-17.

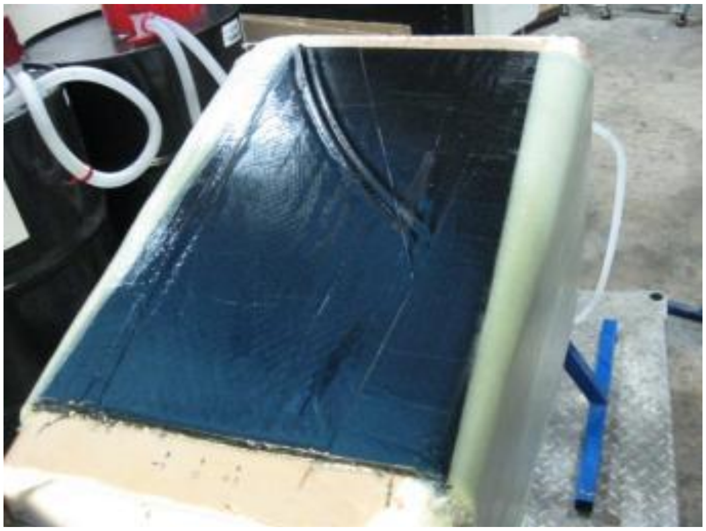


Figure 3-17. Error on part after the first cure

There were also issues with other surfaces of the spar where the vacuum suction had caused wrinkles and ridges. This can be seen through Figure 3-18 below where the material has bunched in the middle of one of the surfaces. Figure 3-17 and Figure 3-18 illustrate some of the drawbacks of male molding. Due to the rough surface after the de-bulk stage, no more plys laid up onto the laminate. Curing and sanding the part is the only way to rectify this complication. In addition, when the material is bunched up as shown in Figure 3-18, some of the materials from plys 1-9 are pulled up along with ply 10. These errors must be avoided or else they will destroy the structural integrity of the laminate.

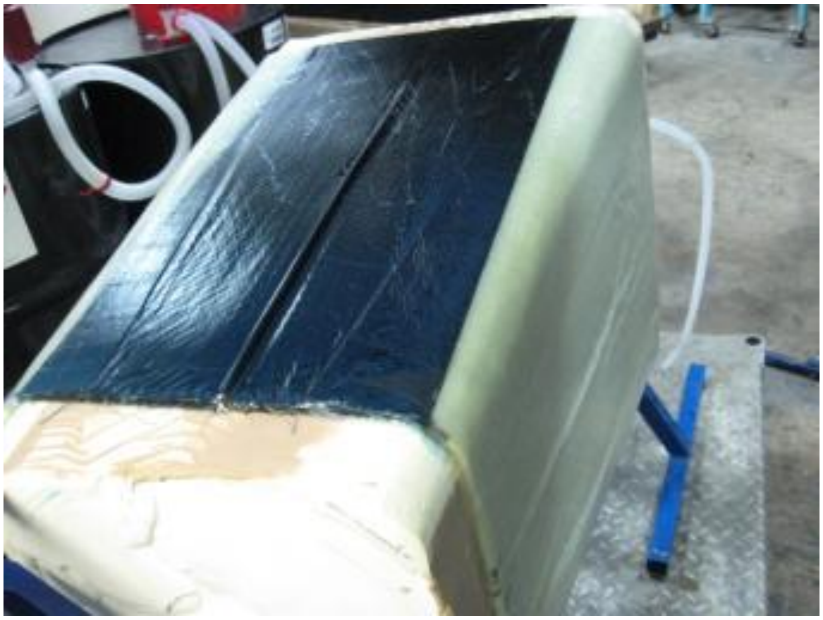


Figure 3-18. Error on part after first cure cont.

As mentioned previously, the only way to repair the surface irregularities was to cure the first 10 plys of lay-up and sand off the extra material that is apparent in Figure 3-18 to give a relatively flat surface to lay-up upon. The spar was cured and sanded before anymore plys were added to spar giving the surface shown in Figure 3-19 below. One of the positive outcomes of this cure and de-bulk stage were the smooth corners. The corners of the laminate cured without wrinkles or any bunching of material.

Figure 3-19. Spar post-cure sanding

With the newly sanded surface, plys 11-20 were ready for application. The lay-up pattern was repeated with plys 11-20 identical to the previous lay-up of plys 1-10. An unusual phenomenon occurred after the lay-up and before the de-bulk stage: there was a bunching together of material in the middle of one of the flat surfaces. Wrinkling is usually associated with male-molding of corners. An attempt was made that was moderately successful at rectifying this error before the de-bulk stage stopping further problems from developing. The plys were then de-bulked and the next set of ply lay-ups began.

After 20 plys of lay-up, the original spar template became unusable. The thickness of the laminate at .5” required a new template to effectively apply the prepreg material. A new CAD model based on the geometry of the spar after two lay-ups had taken place was created and flattened using Solidworks and FiberSim as described earlier in this chapter. The full scale flattened file was printed out and a new updated template was made for the spar fabrication. Ideally, a new template should be made every 10 plys for the most efficient ply application to the spar.

After the second lay-up, it was noticed that the ST70-1/WRE850 material was nearly at its expiration date so a decision was made to make a change to a new material called ST94/WRE850 with the same woven glass fabric but a different epoxy resin. The ply thickness is about 30 mils (.003). This material would take the place of the ST70-1/WRE850 (the odd numbered ply material). It was also decided that the uni-directional carbon fiber Sparpreg was no longer needed for the goals of this project. This decision was made because the spar would not be dynamically tested after fabrication of the spar had concluded. Not including the spar caps also increases the speed and reduces the difficulty of fabrication. For the even numbered plys XE603 was the only material used. To clarify, the XE603 composite material was not staggered similar to the ply butts of the odd numbered plys. This decision was made after plys 21 and 22 had already been laid up so ply 21 was the previous material of ST70-1/WRE850 but ply 22 had already incorporated the change using the XE603 composite material.

It was then decided to cure the part at 22 plys laid upon the spar and start fresh with a flat smooth surface to lay-up upon. There were some slight imperfections on the surfaces of ply 22 post-cure so the surfaces had to be sanded. A blue fairing compound, seen below in Figure 3-20, was used to address surface indentations and imperfections after the initial sanding.

Figure 3-20. Application of blue fairing compound to spar

When applied correctly, the fairing compound can help level the lay-up surface making each of the following surfaces of the laminate parallel to their respective surfaces of the mandrel. The fairing compound has an A and B component that react when mixed. This material has a pot-life of roughly one hour and takes 8 hours to cure. After the fairing compound material was left to cure, the next 8 plys were laid up using the new materials specified earlier, staggering only the ply butts of the odd numbered plys.

After de-bulking plys 23 through 30, errors with the surface of the spar continued to appear. Under the corner caul material, a phenomenon occurred that had not been encountered before, seen in Figure 3-21 below. A ridge of material bunched under the corner caul block. This may be attributed to flexibility of the corner caul blocks. Being too flexible means the caul blocks are not doing their job of maintaining the corner’s dimensions. A caul block that is too stiff will cause the caul block to become irrelevant faster as more plies are laid up.

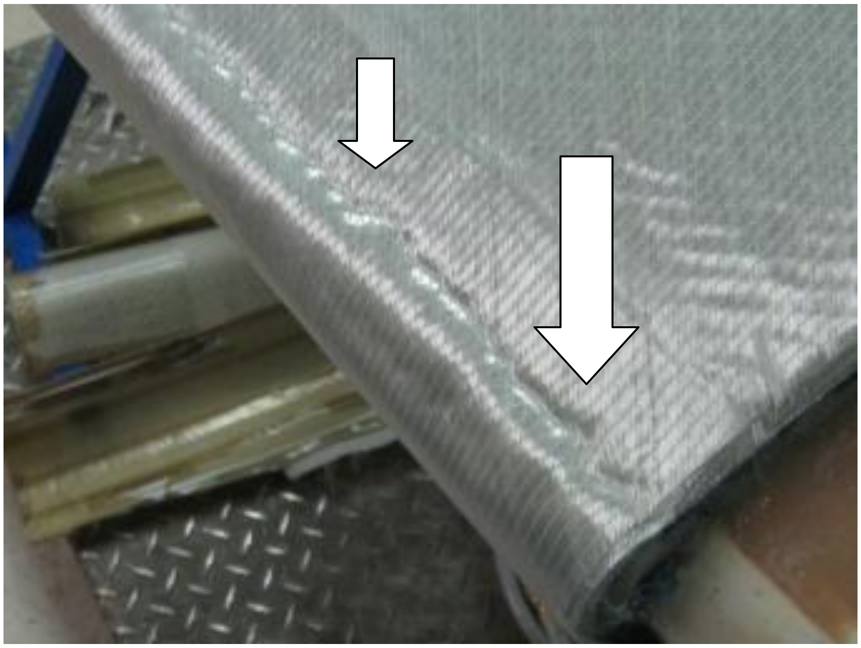


Figure 3-21. Composite fabric bunching under corner caul blocks after de-bulk

3.2.5: Second Set of Caul Blocks, with Flat Cauls

A decision was made to fabricate new corner caul blocks for the spar. In addition to the corner caul blocks, "flat caul blocks" were made for each of the four lay-up surfaces of the spar. The basis for this design decision was to reduce the ridges and voids that had been developing during the de-bulking and curing stages of the spar. As seen in Figure 3-22 and Figure 3-23 below, the composite material bunched again after the part had been put under vacuum. Note that this lay-up was de-bulked before the flat caul blocks had been fabricated.

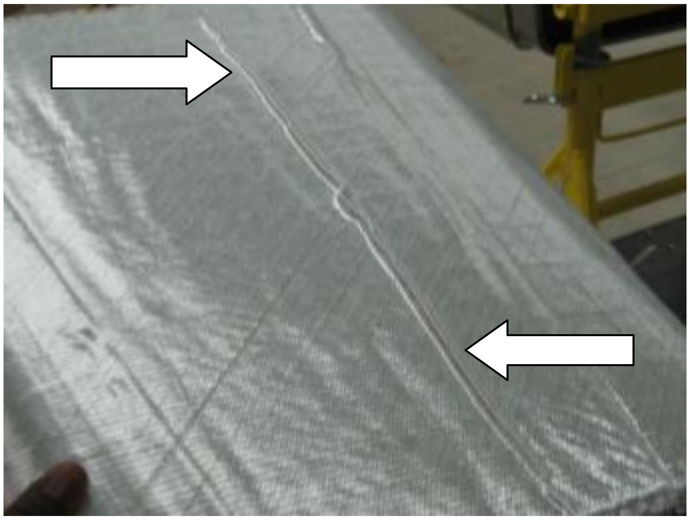


Figure 3-22. Ridge appearance on surface after de-bulk

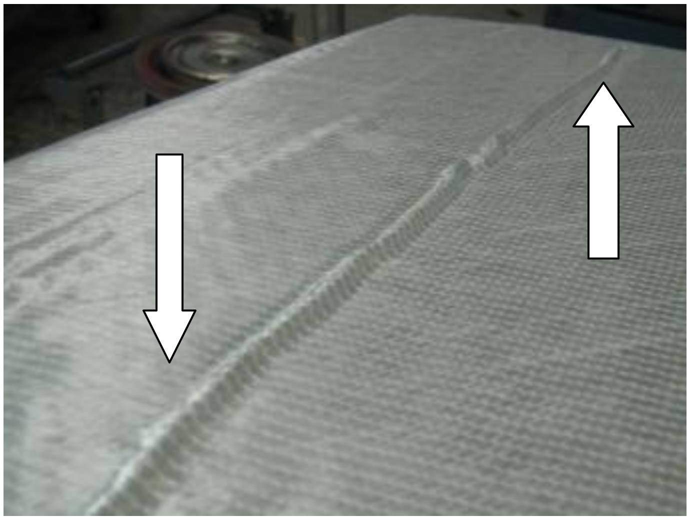


Figure 3-23. Ridge appearance on surface after de-bulk cont.

The surface of the spar below in Figure 3-24 also needed to be level before anymore plys could be laid upon it. The blue fairing compound seen as in earlier figures was used to resolve this issue.

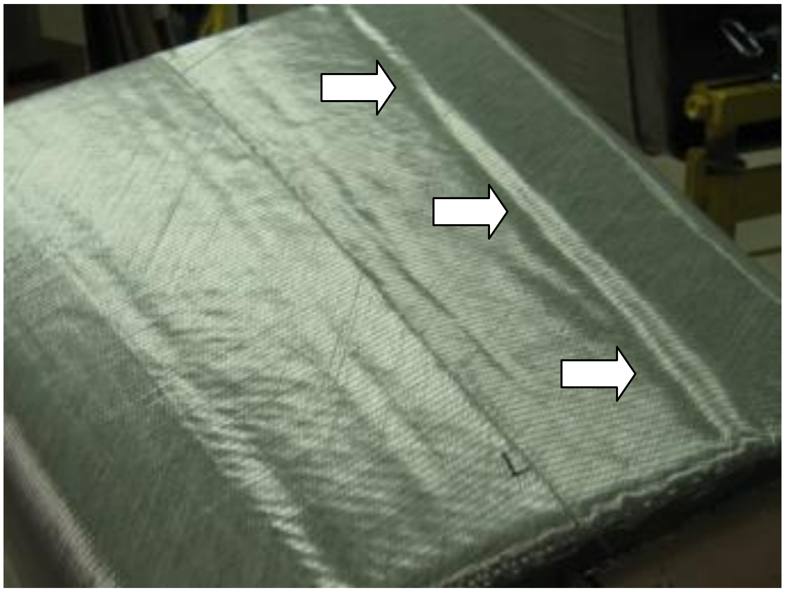


Figure 3-24. Uneven surface after de-bulk

The spar was cured after the de-bulk stage and the blue fairing compound was applied to all of the uneven surfaces to level them out. Below in Figure 3-25, one of the surfaces of the spar can be seen post-cure. The spar was sanded to remove the ridge visible in Figure 3-25. The spar was then released in preparation for the lay-up using both the flat and the corner caul blocks.

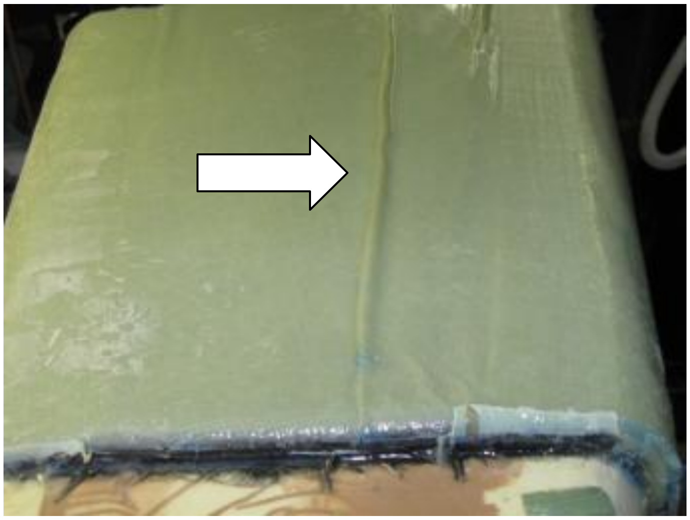


Figure 3-25. .75" of lay-up post-cure (30 plys)

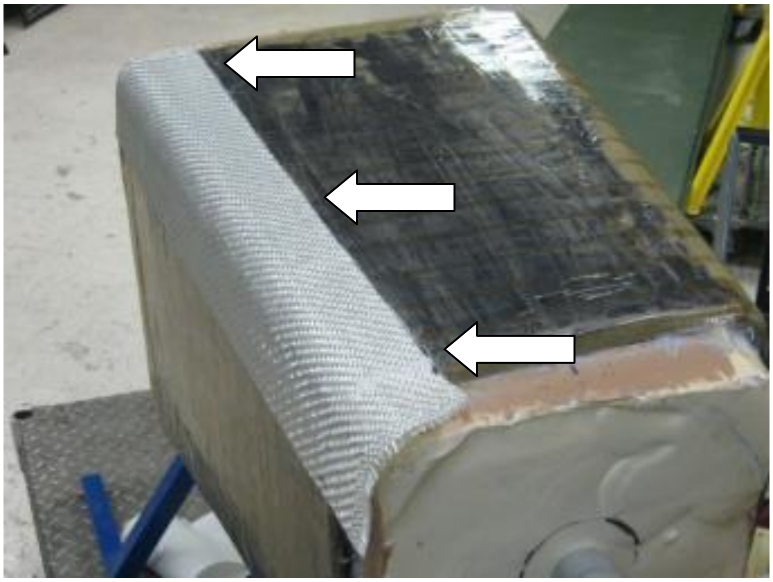


Figure 3-26. Second set of corner caul block lay-up

In Figure 3-26 above, both the Teflon tape release and the first corner caul of the second set of caul blocks can be seen. The blue material (appearing to be black in the figure) under the release tape is the fairing compound discussed earlier. Just like the first set of caul blocks, these corner caul blocks are 22"x 6" using instead 2 plys of the material ST94/WRE850 located on the four corners of the spar. Each ply is 30 mils (.003") so the thickness of each caul is 60 mils (.006").

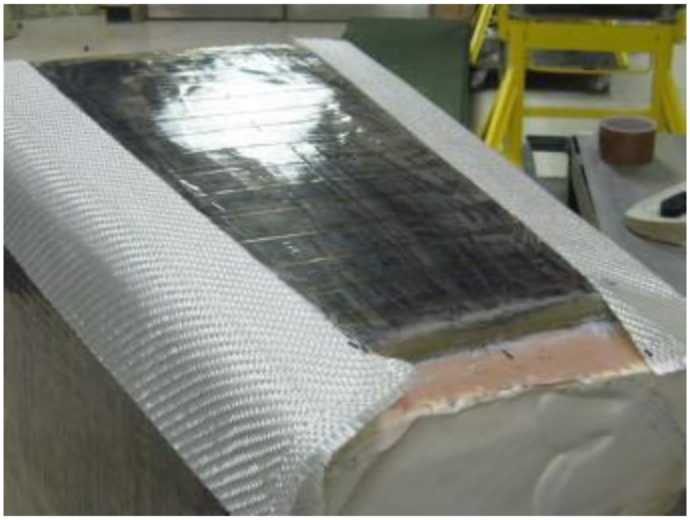


Figure 3-27. Second set of corner cauls lay-up cont.

After all of the corner caul blocks had been laid upon the spar, the 4 trapezoidal areas that remained on each of the surfaces of the spar were measured and recorded. With these measurements, two plys were cut out for each of the corresponding surfaces of the spar. The material used was the same as that used for the corner caul blocks giving the caul blocks a thickness of 60 mils (.006”) with a length of 22”. In the Figure 3-28 and Figure 3-29 below, the flat cauls adjacent to the corner caul blocks on the spar pre-cure can be seen. The numbers and letters in Figure 3-28 and Figure 3-29 correspond to the numbers and letters of the surfaces and corners from Figure 3-1.

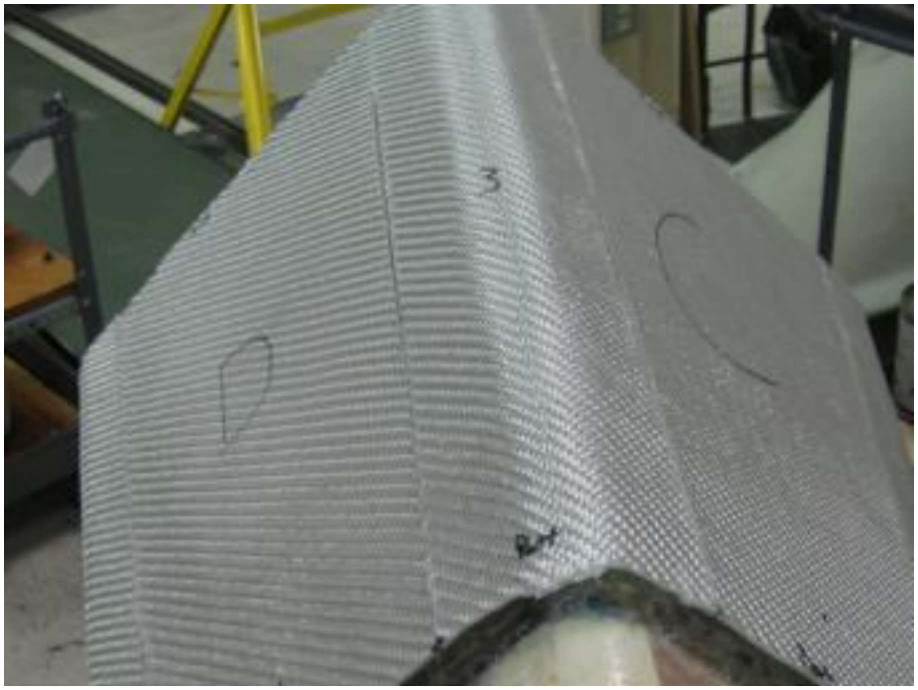


Figure 3-28. Corner caul & Flat caul block lay-up

Figure 3-29. Corner caul & Flat caul block lay-up cont.

The caul blocks were then vacuum bagged and cured to be used during future curing and de-bulking stages. Note that the flat cauls only serve the purpose of eliminating ridges and wrinkles that would develop in the center of the surfaces. As plys are laid upon the spar, the flat caul blocks become less and less useful with helping avoid the development of errors on the surfaces of the spar. One of the large advantages of using these caul blocks is that there will no longer be any surprise as to the location that the ridges shall appear. A predication can be made that the material will bunch at the void between each of the flat caul blocks and each of the corner caul blocks on each surface. The goal is to continue to perfect this method and avoid all of the ridge development completely.

Figure 3-30. Flat and corner caul blocks post-cure (NOT DEMOLDED)

Above in Figure 3-30, the caul blocks before they are de-molded almost appear as one continuous ply which is what was intended. This aids in giving the most desirable results during future de-bulk and cure stages when these caul blocks are applied.

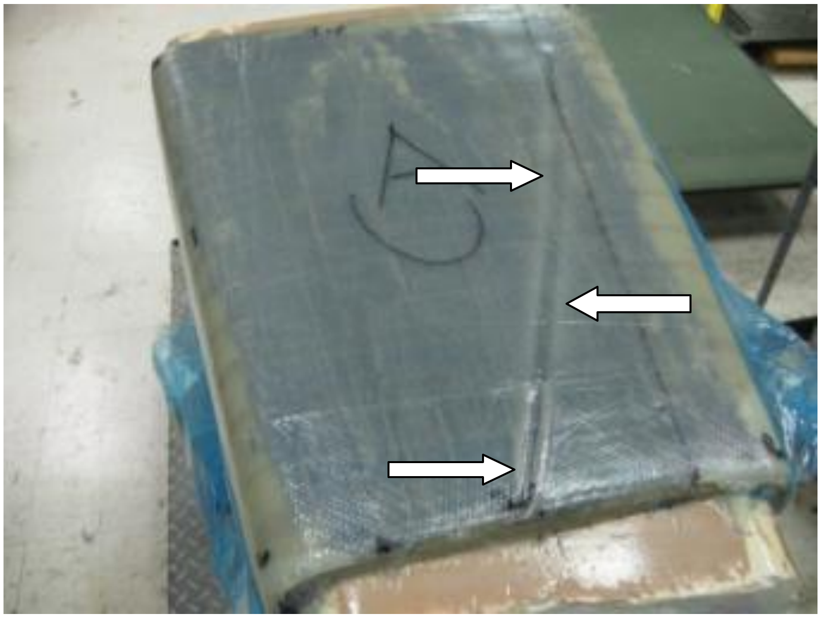


Figure 3-31. Vacuum tube imprint on flat caul block (NOT DEMOLDED)

In Figure 3-31, an imprint of the vacuum tube can be seen on the center caul block. This particular instance of the tube's imprint is not an issue because the integrity of the inner surface of the caul block has not been compromised. Since the duty of the caul block is to achieve a smooth flat surface on the laminate below, the appearance of the caul blocks on the outer surface is irrelevant. Again, the image above in Figure 3-31 is not the laminate but the cured caul blocks before they were de-molded.

The corner and flat caul blocks were de-molded and the release tape was removed allowing for the next lay-up to proceed. The next 10 plys of lay-up used the same process and materials as the previous lay-up. The odd numbered plys were ST94/WRE850 and staggered as discussed earlier. The even numbered plys were XE603 and were not staggered also as discussed earlier.

Figure 3-32. Caul block application pre-vacuum

The preparation for vacuum bagging with the new caul blocks is similar to the previous bagging processes. As seen in Figure 3-32, the center caul blocks are prepared using the same method as corner caul blocks. The bottom surface of the caul blocks is released with Teflon tape and the outer surface of the caul blocks has a breather material applied to it allowing the vacuum to be able to breathe all along the part. The center caul blocks were centered approximately in between the adjacent corner caul blocks allowing for a gap between each of the caul blocks as can be seen in Figure 3-32 above and Figure 3-33 below.

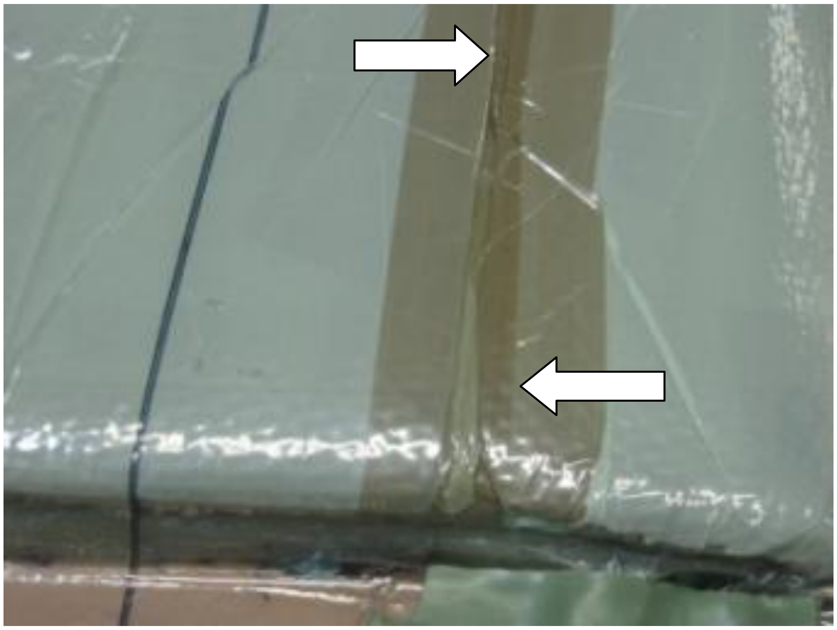


Figure 3-33. Gap between flat caul and corner caul blocks

Figure 3-33 above shows the gap that develops between the caul blocks after 10 plys have been laid upon the spar since the fabrication of this set utilizes caul blocks. It can be assumed, as mentioned earlier, that any possible ridges and or wrinkles that may appear will appear in these areas located on each surfaces of the spar.

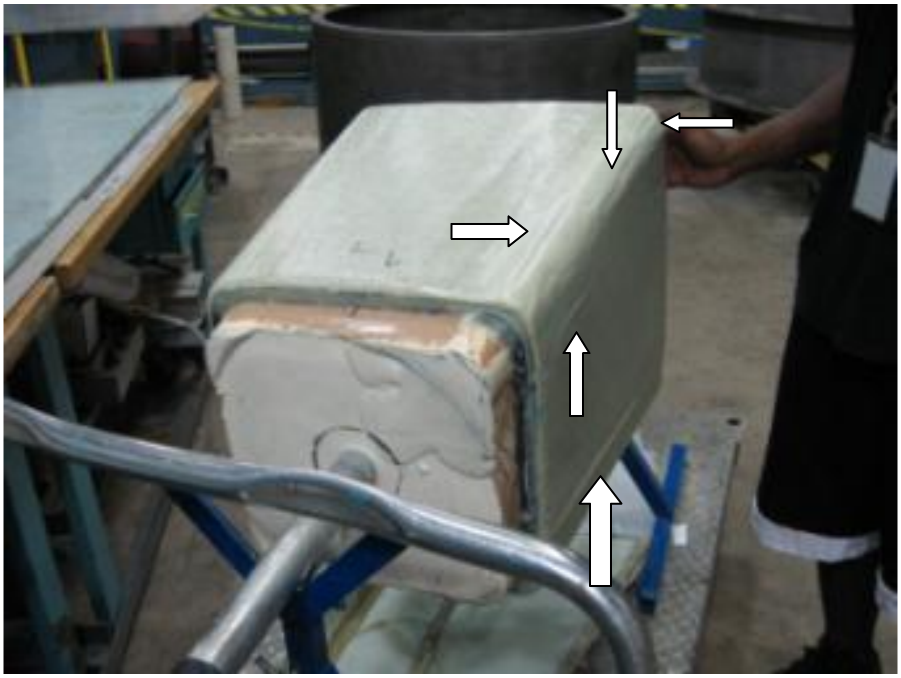


Figure 3-34. Spar post-cure no vacuum

Unfortunately due to a slight error, the spar was cured without being under full vacuum resulting with a surface as seen above in Figure 3-34. This caused some dimpling and ridges all along the part. Despite this error, the surface of the laminate was moderately acceptable. Some of the flat surfaces cured without the occurrence of wrinkles while others showed the development of wrinkles. There was also a moderate amount of dimpling under the corner caul blocks. The dimpling may be attributed to the lack of vacuum, but no conclusions can be made. It may be difficult to see in the above figure but the lack of vacuum caused the resin to cure without wetting out the dry fibers. Since the resin is on the bottom of the plys with prepreg material, without appropriate vacuum to allow the resin to flow throughout the fabric, the resin did not wet out the fibers causing the fibers to be dry and frail. This error stresses the importance of vacuum bagging as well as the importance of a good vacuum. The better the vacuum holds onto the part, the better the chance of the resin fully wetting out the material.

The ridges that were predicted to appear post-vacuum were in the areas anticipated but were not as drastic as expected. This could also be attributed to the lack of vacuum. No definite conclusions can be made after this cure making the effectiveness of the new center caul blocks to to be determined after the next lay-up when the spar is cured under full vacuum. The spar was then sanded and faired using the blue fairing compound. With the use of the newly fabricated set of caul blocks, the amount of fairing required to level out the surfaces of the spar was much less than at any of the other stages that had taken place so far as can be seen in Figure 3-35 below.

Figure 3-35. Fairing compound applied to corner section of spar

The next plys to be added were plys 41-50 which put the spar at rough 1.25” post-lay-up. These plys were added in the same fashion as the previous plys also seen in Appendix B. During this lay-up, one of the causes of the composite material dimpling could be seen after it had been under vacuum and prior to the cure cycle. When the material is applied to the spar and left to sit overnight without being placed under vacuum for a de-bulk cycle, the material begins to detach from the spar and starts to lose the form in which it was applied. The prepreg material does have the ability to stretch. After the material has stretched, it is very difficult and sometimes impossible to put the material back into its original shape. Prepreg material with the orientation +45°/-45° is especially prone to deformation. Several plys are applied at one time, making this occurrence difficult remedy without removing the applied plys and starting the lay-up process over again. To resolve this issue, the part must be de-bulked immediately at the end of each day's lay-up. This method was proven at this stage but seems to be an adequate assessment of the situation.

Figure 3-36. Very slight dimpling on spar corner post-cure

Unfortunately the solution to the problem was discovered during the lay-up of plys 41-50. Before the entire lay-up was completed, the plys were left to sit for an extended period of time and the "ply drop-off" occurred again which may have been the cause of some dimpling under the corner caul blocks as seen in Figure 3-36 above. Despite the lack of overnight de-bulking during the lay-up stage, the results of the surfaces of the spar were almost ideal. The ridges appeared in between the flat and corner cauls as expected and nowhere else. Had the de-bulk cycle stage taken place, there may have been next to no dimpling on the spar.

3.3: In-Situ Caul Block Fillers

3.3.1: Super Ceramic Repair Putty

With the results from plys 41-50, the project proceeded by trying to eliminate the ridges between the flat and corner caul blocks. The best option to solve the ridge appearance was to use a material between the gap of the corner and flat caul blocks to act as filler. This may help prevent the development of any ridges or dimpling on the part. In addition, the filler material must be pliable enough to fit into the gap between the corner and the flat cauls but robust enough to handle the pressure of the vacuum bag without allowing the caul blocks to move from their location after the vacuum has begun. The material must also be able to withstand a temperature of 185° F from the heat of the oven. In addition, cost of the material must be kept in mind since reducing the cost of the male molding process is one of the goals of this research.

Figure 3-37. Super Ceramic Repair Putty – Gap filler material

The first candidate for a material to be applied in between the caul blocks is Super Ceramic Repair Putty. This material was chosen because it meets the requirements of 1) ease of application due to its viscous nature and 2) its ability to occupy all of the space between the caul blocks being a paste instead of a solid material. The repair putty came in two separate containers. One contained the resin and the second contained the hardener. When these two materials are combined at a 7:1 weight ratio of resin to hardener, they begin to react. The repair putty has a pot life of 20 minutes and a cure time of 24 hours. The pot life is the time that the material will be pliable enough to be applied into the gaps between the caul blocks. When the pot life is up, the putty will begin to cure. It will rapidly harden into a single, solid material in the shape it has been molded into. If the resin and hardener were to be combined at an uneven volume ratio it would likely result in an unfavorable result in the composition of the putty material. (ITW Polymer Technologies, 2005)

Figure 3-38. Super Ceramic Repair Putty application.

Before the putty material was applied, the spar surfaces were prepared. Similar to the previous method used, the flat and corner caul blocks were secured to the spar with Teflon release tape. The Teflon tape was also applied in the gaps between the caul blocks, preventing the putty from adhering to the spar skin. The release tape was applied to some areas of the caul blocks for the same reason. Application of the putty combination can be seen above as the grey material in

Figure 3-38. The repair putty material did begin to set-up and become harder to work with roughly 15 minutes after the two compounds were mixed together. After about 2 hours the material still had not reached a solid enough state to apply the pressure of the vacuum bag without the caul blocks squeezing the material out of its current shape. 24 hours was allowed for the super ceramic repair putty to cure before the vacuum bag was applied to the spar. After the de-bulk stage had taken place for plys 51-60, the spar was de-molded by removing the cured repair putty material along with the vacuum bag and caul blocks.

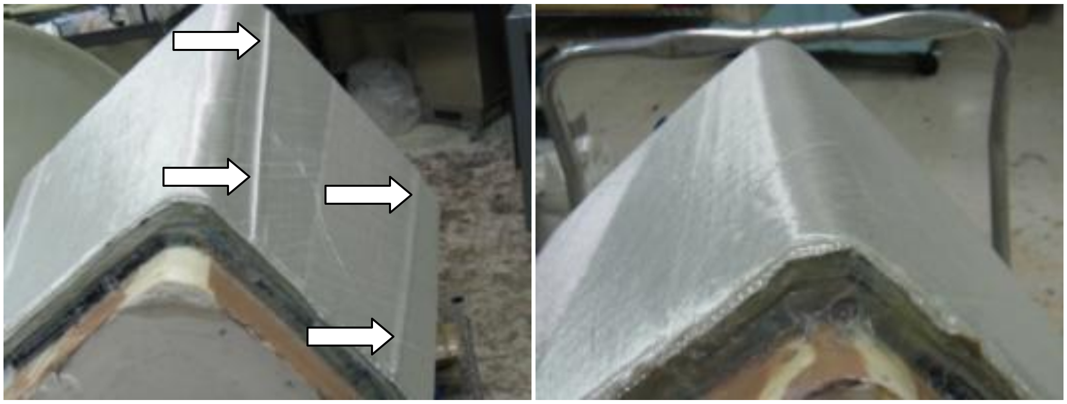


Figure 3-39. Post de-bulk using Super Ceramic Repair Putty

The result of the de-bulk stage can be seen above in Figure 3-39. The result of this lay-up showed ridges between the caul blocks as expected but there were also a few additional irregularities. A small ball of Teflon tape was discovered stuck on the bottom of a flat caul block. This caused an elevation in the caul block, making the caul and prepreg material no longer parallel. The error in the caul block caused the de-bulk stage of that particular surface to be elevated making the surface no longer flat. In addition, the ball of tape was imprinted on the surface of the prepreg material. Despite the occurrence of these errors, the de-bulk stage was still deemed a success. There was no development of wrinkles in the corners and only one surface displayed ridges. It is important to note that the surface with the ridges was surface C. This is the surface that faces towards the ground while the spar is at rest and is most often affected by the force of gravity causing the ply drop-off phenomena.

3.3.2: 2” Glass Reinforced Plastic (GRP) Strips – Wet Lay-up

For plys 61-70, materials in the lab were used as gap fillers as opposed to ordering materials as used in the previous method. The material is a .002’ thick 2” wide strip of dry fiberglass. This dry fiber requires an epoxy resin combined with a hardener to cure. The epoxy resin used is West System 105 and the hardener used is West System 206. The A and B compound is mixed together at a 1:1 pump ratio before being applied to the strips. The strips and West System materials can be seen below in Figure 3-40.

Figure 3-40. 2” Wide GRP strips for caul gap filling

The decision to use two strips per gap increased the stiffness at the gap location. Due to the strips being 2” wide and not having each gap to be 2” wide, the strips did overlap onto the caul blocks a bit. There was an overlap because the width of the GRP strips was greater than each of the individual gaps between the flat and corner caul blocks. The strips were cut to be 22” long, reflecting the length of the laminate on the mandrel. These strips were chosen as a candidate for bridging the gap between the flat and center cauls because of their ease of application and flexibility. After resin is applied to the GRP strips and allowed to wet out the material, they become much less rigid than their initial cloth like state. This allows the strips to take the shape of the gap they are filling. The West System mixture has a pot-life of roughly 30 minutes before the resin becomes difficult to work with. The mixture must be made and applied to the strips quickly before the GRP strips are no longer pliable. Similar to the method mentioned in the previous section, both the flat and corner caul blocks are secured to the spar with Teflon tape. The gaps between the caul blocks are also released with Teflon tape to make sure the strips do not adhere to the spar skin. After the prep work has been completed and the strips have been wet out with resin, the 2” wide strips are inserted within the gaps. Due to the force of gravity and the strips lack of immediate adhesion to the Teflon tape, roughly 2 hours must pass before the spar can be rotated about its axis and another set of strips can be placed. If the strips fall off before they cure in the shape of the gap, they will not be effective at preventing the bunching of the spar skin. After each of the surfaces had a set of strips applied to each gap, the spar was put under the vacuum bag and cured.

Figure 3-41. Post-Cure of GRP strip stage

The results of the of cure of the GRP strips as a gap filler were not ideal with the occurrence of the ridges as seen above in Figure 3-41 but otherwise allowed for a smooth surface across the part. There were some issues with the strips staying in place and occupying the entire gap between the flat and corner caul blocks which could be addressed in the future.

3.3.3: Syntho-Glass

A material called Syntho-Glass was acquired from Neptune Research Inc. in several individual hermetically sealed foil pouches. The individual pouches contained the rolled up Syntho-Glass that were each 2”X5’. These pouches were hermetically sealed because of the effect of moisture on the material. The unique Syntho-Glass material contains a moisture activated pre-impregnated polyurethane resin. The resin is listed as “water-activated” but in fact begins to react as soon as the seal of the pouch has been broken. This material is unique because as opposed to conventional prepreg materials, Syntho-Glass has a working time of 5 minutes and set time of 28 minutes. Conventional prepreg materials have a shelf life of several weeks to months and can only cure with at minimum the addition of pressure and heat. Syntho-Glass is made of fiberglass and is conventionally used for repairing pipes. The packing also comes with rubber gloves and shrink tape to restrict the area of application before the material sets. The shrink tape was not used for the particular application of this experiment. (Neptune Research Inc., 2012)

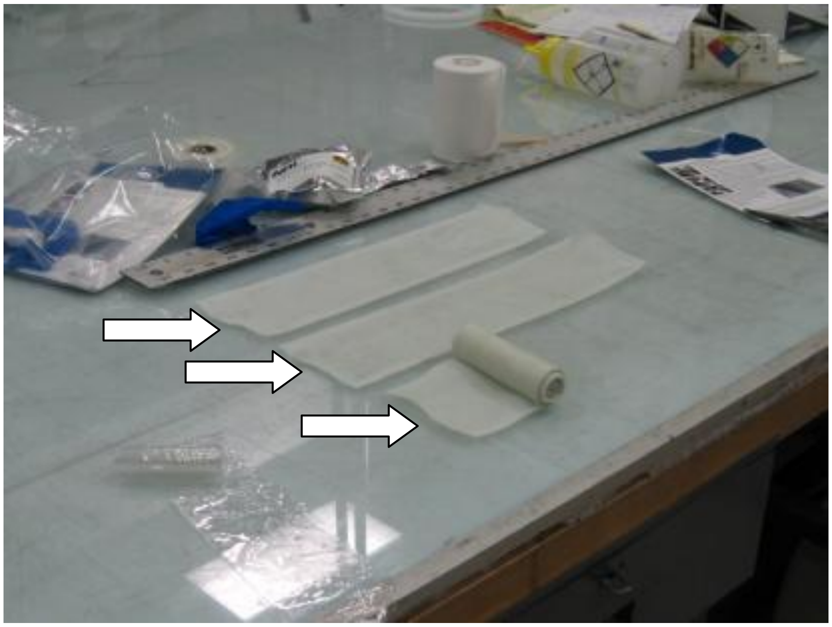


Figure 3-42. Syntho-Glass cutouts

It was decided that instead of using the Syntho-Glass material as filler in between the caul blocks, an attempt would be made to use the material to wrap around the entire spar. The advantage of this method (if successful) is that it would become a one-piece caul that could be rapidly installed. Before the Syntho-Glass was applied to the spar, release material was secured to the spar to prevent the material from adhering to the spar skin. Application of the newly acquired material began by opening the hermetically sealed foil pouch, removing the roll of Syntho-Glass, and submerging the prepreg in water for roughly 10 seconds. The roll of prepreg material was removed from the water and several strips of approximately 12” long were cut and applied to the spar as seen above in Figure 3-42.

Figure 3-43. Syntho-Glass applied to spar

In addition to the strips mentioned previously, a portion of the spar was wrapped in the Syntho-Glass to see if the strength of the material was enough to forgo the use of caul blocks. The wrapping method was used for plys 71-80. Similar to the other previous methods using Super Ceramic Repair Putty and GRP strips, the Syntho-Glass was used as gap filler for plys 81-90. During this trial, the roll of prepreg was cut into 22” long strips, to reflect the length of the laminate, and cut down the length of the roll to make each strip 1”X22”. The reason for this was to maximize the use of the material in between the caul blocks because each of the gaps was less than 2” in width. Material that overlaps onto the top of the caul blocks serves no purpose. The application of the Syntho-Glass to the spar can be seen above in Figure 3-43.

Figure 3-44. Post-Cure first Syntho-Glass trial

As seen above in Figure 3-44, the Syntho-Glass application across the surface of the laminate did not do a good job of acting as a caul block in the corners with the appearance of a large ridge down the length of the corners. It was not rigid enough to prevent wrinkling, thus the surface was not as smooth as when the flat and corner caul blocks were secured to the spar.

For plys 81-90, the Syntho-Glass material was used again but in a different application than the most recently described method. This prepreg material was used as a bridge between the caul blocks. The method of application was similar to the one described in the GRP strip section above, except the cure time is minutes instead of hours. After the corner and flat caul blocks were secured to the spar, the strips were cut to be 22” in length and cut in half to be 1” in width instead of its original width of 2”. The change in width is due to the caul block gap dimensions. None of the caul gaps at this stage were 2” wide and all excess material is wasted otherwise. For ease of application the strips were not wet-out with water until they had been cut and placed inside the gaps. The purpose of this was to increase the amount of working time with these strips to be as long as possible even though they begin to cure with the addition of moisture from the air.

Figure 3-45. Syntho-Glass with Caul Blocks

The result of using the Syntho-Glass as gap filler after the laminate had been cured can be seen below in Figure 3-46 as very desirable. The surface of the laminate was very smooth and the slight ridges were apparent but not overly so. This cure stage was the best to date comparing the result of the ridges from this stage to all of the other stages.

Figure 3-46. Syntho-Glass second trial used as gap filler in conjunction with caul blocks

3.3.4: Shrink Tape

Shrink tape, often referred to as shrink film, is a material that begins to shrink with the application of heat. The tape comes in rolls of various widths and lengths. The film that was ordered for the purposes of the project was one roll of Dunstone HI-TEMP 200HT. The high temperature shrink tape was .002" in thickness with a width of 2" and can continue to operate effectively with temperatures as high as 500^{o} F. The released material has a variety of applications, but for the purposes of the project the tape was intended to simplify and possibly expedite the de-bulking process. Plys 91-100 used the shrink tape method for an attempt to consolidate the laminate similar to the de-bulk stage. (Dunstone, 2010)

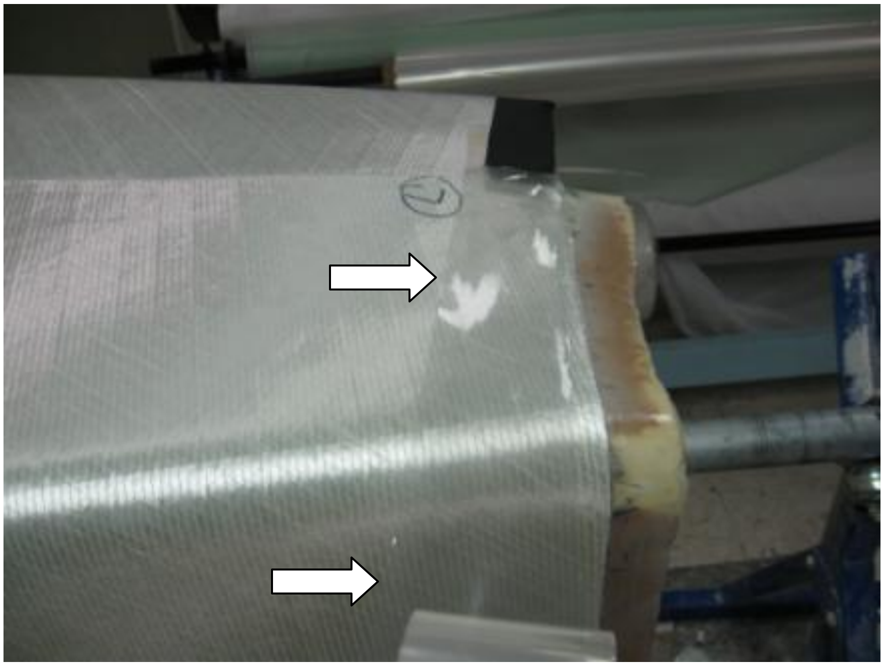


Figure 3-47. Shrink Tape Application

Unlike many of the processes that were discussed previously in this chapter, using the shrink tape theoretically does not require any caul blocks in theory to be successful. The materials needed for this method are the tape, a heat gun, and a small amount of sticky tape to secure the shrink tape to the part due to the lack of tack of the film. After the shrink tape was secured to the part, the spar was spun around its axis and the shrink tape was wrapped around the spar as seen above in Figure 3-47. Each section that wrapped around the spar was overlapped by roughly .5” to assure that shrink tape covered the entire surface of the spar. After the entire surface of the spar had been covered with shrink tape, both ends of the spar were tightly bound with the tape to secure the shrink tape to the spar, preventing the shrink tape from moving. The heat gun was then applied to the shrink tape material on the spar to constrict on the spar. The shrink tape material was said to shrink by roughly 20% in length with 450^o-500^oF of heat application. The spar wrapped in shrink tape can be seen below in Figure 3-48. (Dunstone, 2010)

Figure 3-48. Shrink Tape on spar with heat gun.

The shrink tape had a very drastic effect on the laminate as seen below in Figure 3-49. The shrink tape did a good job applying pressure to the corners, but little pressure was applied to the flat areas. As a result, large areas of poorly compacted prepreg formed between the cured laminate and the uncured. One of these areas can be seen in the right image of the below Figure 3-50. This one surface, surface C, was the only surface that experienced this phenomenon. The other surfaces did experience some ridges as well but they were not as drastic. Another phenomenon that occurred was the pressure of the shrink tape pulling the laminate down towards the smaller of the two vertical faces. To elaborate, the shrink tape's pressure after heat had been applied sheared through the tackiness of the prepreg's resin and pulled the plys down towards the smaller vertical face. It was concluded that although shrink tape might be a useful method of de-bulking cylindrical sections, for applications that have large flat areas, such as the beams in our study, shrink tape was not effective.

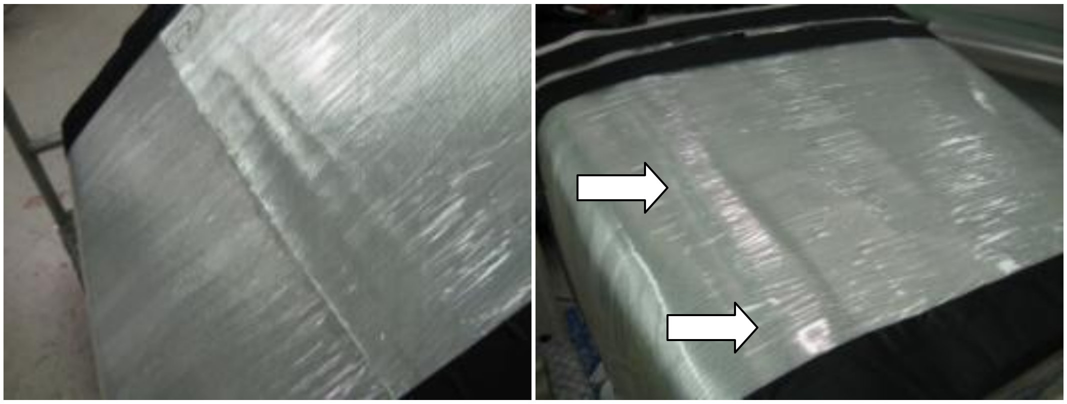


Figure 3-49. Shrink tape trial after heat applied

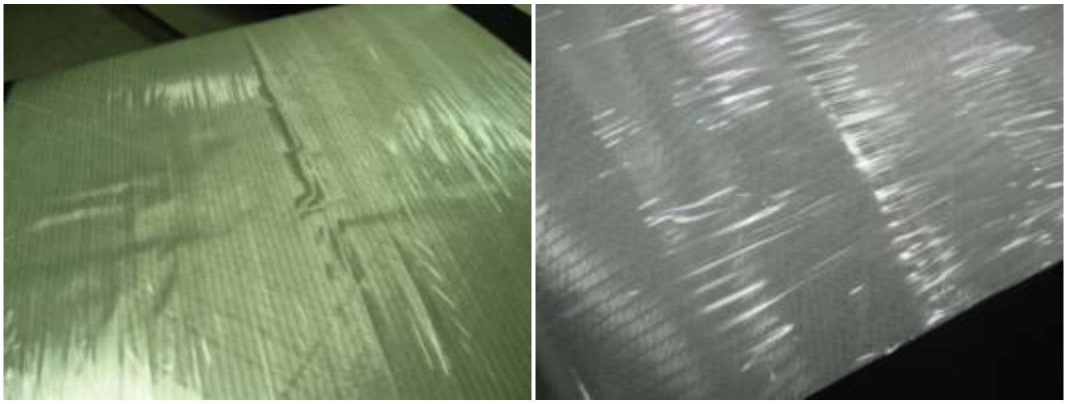


Figure 3-50. Shrink tape trial after heat applied (cont.)

Chapter 4 :

Discussion and Results

4.1: Literature Review Discussion

The 2.1: U Shaped Mold, as seen in Figure 2-1, design is unique in its attempt to use a female mold with a clamp, eliminating issues involving bringing two halves together similar to the clamshell method mentioned in 2.7: Process Development Issues of Glass-Carbon Hybrid-reinforced Polymer Composite Wind Turbine Blades. The method of the U shaped mold is similar to the closed mold method mentioned in 2.3: D-Spar. The difference between the two lies in the D-Spar's method of inflating a balloon to assure adequate application the closed female mold. The closed female mold is desirable due to smooth surface finish along with the previously mentioned advantage of one solid part instead of two halves.

2.2: Gurit Blade Manufacturing Process discusses in detail the advantages and disadvantages of the use of dry fabric or in other words the use of wet lay-up and RTM. The authors of 2.7: Process Development Issues of Glass-Carbon Hybrid-reinforced Polymer Composite Wind Turbine Blades believe that VARTM is the cheapest method to achieve a high quality composite part. The initial investment in materials is cheaper but allows more room for error dealing with wetting all of the dry fabric. Choices must also be made between tow size to achieve maximum permeability and resin viscosity due to its direct effect on the time it takes to wet out an entire part. Both 2.4: Custom Sailing Yacht Design and Manufacture and 2.5: Male Molding with Oven Vacuum Bag Prepreg use prepreg specifically for a few of its advantages. 2.4 lists the advantages of prepreg as having very clean working conditions, longer working time with materials, and more control of the overall weight of their boat structures. The longer working times also lead to smaller working groups saving costs on labor. They list the disadvantage of prepreg as requiring more care with tooling construction due to the higher cure temperature requirements. The prepreg used in 2.5 is OVB prepreg which means no autoclave is necessary, reducing costs of prepreg fabrication drastically. The main goal of the applications discussed in 2.5 is to fabricate parts for the Navy using male molds at a reduced cost. (Gurit, 2012), (Sharma and Wetzel, 2010)

2.5: Male Molding with Oven Vacuum Bag Prepreg went into detail discussing the fabrications processes and approaches taken when male molding composite materials with OVB prepreg. The main goals were to fabricate a one-off part at a low cost and achieve a smooth outer surface, which has been a problem area for the male molding method. For the first application discussed in 2.5.1: Navy Cover Plate Application, a splash was created from existing geometry to be able create the cover plate. For this method and the following Cusp Fairing application, de-bulks were the primary reason limited wrinkling was evident across the surface of the laminate. For 2.5.2: Cusp Fairing there was a de-bulk stage that took place after every two plies had been applied to the part. This resulted in a nearly wrinkle free surface post-cure. 2.4: Custom Sailing Yacht Design and Manufacture also mentioned the use of a required de-bulk to avoid wrinkling but noted that de-bulk stages drive up production costs due to the required materials. The yacht building did require several workers to help during the vacuum bag process to prevent wrinkles across the surface of the male molded part. It can be assumed that caul blocks were not used in this instance. 2.5.3: Doubly curved structure with smooth surface had three separate trials that used caul blocks to attempt to achieve a very smooth surface on the male molded laminate. Trial two was the most successful with its change in material to obtain a more rigid caul block and prevent wrinkle development. Process development such as the change to fabrication methods in

Trial two is what is needed to solidify methods to improve male molding. More research must be done into caul block fabrication and surface preparation to bring male molding surfaces to be on part with the outer surface of female molding. (Juska et al, 2012)

4.2: Design

There were some aspects of fabrication that could in future projects be addressed in the design stages, but were only discovered as experience was gained through trials of ply lay-ups for this research. The first of these was the fabricated templates. Particularly with the spar for the experiments detailed in Chapter 3, new templates were fabricated as a template was no longer deemed to have adequate geometry to aid in lay-ups. It was discovered that creating a template to be used for the geometry of the spar as if it were .25” larger allowed for a new template to be created after 30 plys of lay-up instead of after ever 20 plys of lay-up. To elaborate, similar to the methods mentioned in 3.1.3: Template Design, when offsetting the CAD file to meet the geometry of the current thickness of the laminate the user should offset the laminate by an additional .25” and the template will still be applicable to the desired geometry. During fabrication the cutouts will be slightly larger but with a little effort time can be saved by avoiding additional template fabrication. In addition it may be desirable by fabrication teams to create several templates beforehand of calculated geometry based on the materials to be applied during lay-up.

The staggering of plys, discussed in 3.1.2: Ply Staggering, are also slightly affected by the design of the template. For the given geometry of the spar with the use of the templates, the ply staggering implementation was not an issue. For more complex geometry, there may be issues using one template for both the normal plys and the staggered plys. On a larger scale spar member, there would also likely be more ply butt staggering.

4.3: Details of Fabrication

Some of the results of the lay-ups post-cure and post de-bulk were discussed in Chapter 3 but further insight into these results will take place here in Chapter 4. One aspect of the spar fabrication that was not intended to occur during the design stages was the number of cures that took place after each lay-up. As seen especially during plys 1-10 there was a large amount of extra material that bunched up on one of the surfaces of the laminate that required sanding to rectify. Some of the errors that appeared during the earlier stages had to do with lack of experience in the lay-up room by the fabricator. An example of this can be seen in Figure 3-17 where the vacuum tube was placed on top of the laminate and imprinted upon the part. With every 10 plys, the issues were resolved and surfaces began to improve allowing for the possibility of the de-bulk stage to take place without a cure to follow and smooth the surface. The ply lay-up of 31-40 seemed to be the defining change with the fabrication of the new set of flat and corner caul blocks. The flat caul blocks seemed to prevent any distortion on the flat surfaces provided no debris made its way under these flat caul blocks, such as the Teflon tape found during the Super Ceramic Repair Putty de-bulk stage of plys 41-50. The importance of caul block inner surface smoothness was discussed in detail in 2.5: Male Molding with Oven Vacuum Bag Prepreg. The corner caul blocks did show some issues that were not explained such as the phenomenon seen in Figure 3-21. This error may be attributed to the caul block thickness and or flexibility. More tests must be done with the caul blocks experimenting with different materials and thickness to assess the most appropriate combination of properties for the corner caul blocks. Considering that the laminate final thickness was roughly 2.3”, decisions must be made to decide the lifespan of a caul block keeping in mind that the blocks can be reused for the same de-bulk stage of several other parts. Gurit notes the importance of avoiding the forming of ears with male molding but does not discuss methods to avoid their development.

4.1: In-Situ Caul Block Gap Fillers

As mentioned previously, with the addition of flat caul blocks, the surfaces of the laminate changed drastically. Instead of random wrinkles throughout the different surfaces of the part, the wrinkles and ridges were predictably located in between the flat and corner caul blocks. With these expected ridges, steps were taken to address these errors with the development of the 3.3: In-Situ Caul Block Fillers. The Super Ceramic Repair Putty was the first of the in-situ fillers and did yield very desirable results. The particular lay-up of plys 41-50 was de-bulked and each of the errors, some of which can be seen in Figure 3-39, could be explained by slight fabrication errors. The ball of Teflon tape that was found under the flat caul blocks and the effect of gravity on the laminate were both discussed in 3.3.1. Unfortunately errors such as the elevation of the caul block by the Teflon tape caused changes in the laminate that were increasingly difficult to overcome. Due to the caul block's orientation during the de-bulk and being propped up on one side by the tape, the laminate was no longer level but instead elevated at an angle with respect to the surface. The surface was faired but the fairing compound was not able to fix all evidence of this error and this may have had slight effects on the subsequent lay-ups. The surface C that most often faced towards the ground was infamously error prone due to the effect of gravity on the laminate during the lay-up stages. Surface C was significantly affected by previous complications.

The GRP strips did an adequate job of limiting the ridges in between the caul blocks considering this stage was not de-bulked but instead cured. Figure 2-8 shows the difference in consolidation between a de-bulk and cure stage. It can be assumed that the results would be even more desirable, meaning smaller ridges, if this stage was de-bulked. There were some issues with the use of the GRP strips and experience was gained and passed onto following experimentation. The strips had difficulty staying in place in the very small corners between the laminate and the caul blocks where material such as the repair putty had no difficulty occupying. Instead in future lay-ups such as plys 81-90 with the use of Syntho-Glass, strips were cut into smaller sections to fit only into the gaps instead of overlapping and causing bridging of the strip material. The difference between the strips occupying the gaps can be seen in Figure 4-1 with the GRP strips and Figure 4-2 with the cut Syntho-Glass strips.

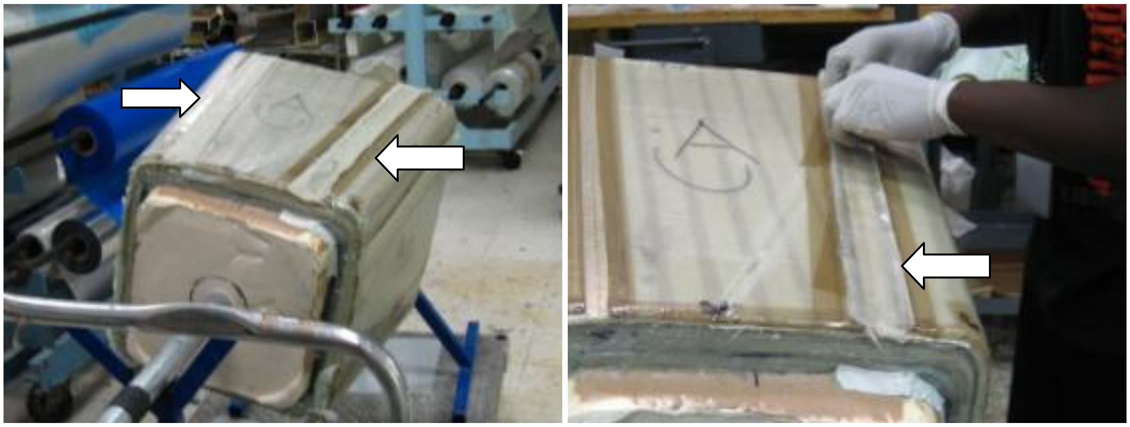


Figure 4-1. GRP strip bridging over caul blocks

Figure 4-2. Syntho-Glass strip cut into smaller sections - No bridging

As expected with the experience gained from the previous GRP strip lay-up, the Syntho-Glass lay-up yielded the most desirable results post-cure of any of the previous lay-ups as seen in Figure 3-46 with very minor ridge appearance. During a de-bulk stage, these results are adequate enough to continue lay-up upon the laminate without the need for a cure and fairing stage. The initial use of the Syntho-Glass was not as desirable as seen in Figure 3-44. This can be attributed to the lack of stiffness of one ply of the Syntho-Glass material. The short working time of this material and the taper of the spar both work against the use of this material to wrap the spar and achieve desirable results. Ideally the Syntho-Glass would be wrapped around a non-tapered member within its 5-minute set-up time and wrapped in shrink tape to aid in compression upon the laminate. The stiffness of the Syntho-Glass material was also an issue that was noted after it had been put under vacuum and after cure as seen below in Figure 4-3. The stiffness of the material must be more on par with the caul blocks fabricated previously. This may be achieved with more application of material but may also not be cost effective as a method to achieve a smooth laminate surface.

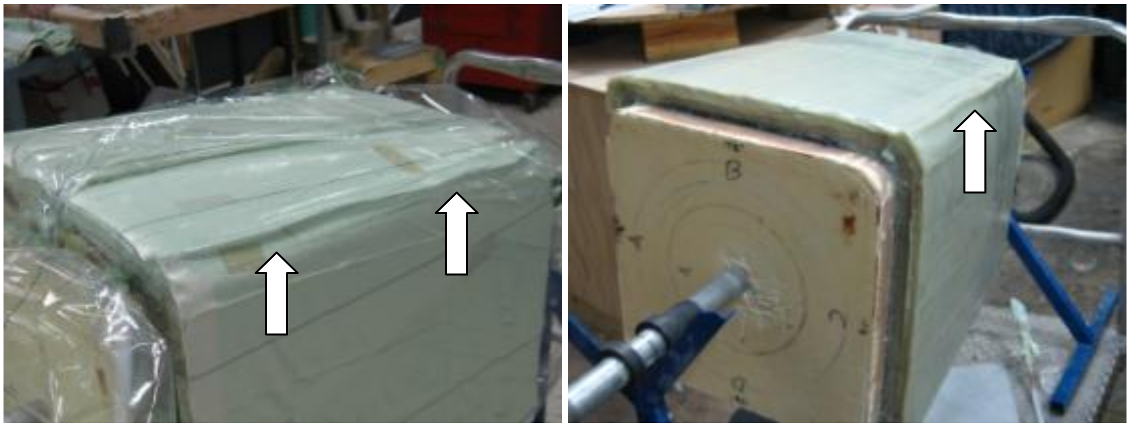


Figure 4-3. Syntho-Glass first trial corner material bunching

The shrink tape was the final method used as an attempt at material compaction. In theory, the shrink tape is a very time effective and simple way to compact material similar to a de-bulk stage. Unfortunately, the use of the shrink tape to compact plys 91-100 did not act as intended. The tape first did not shrink as quickly and as much as predicted with the application of heat at roughly 250 ^{o}F which was the maximum temperature of the initial heat gun acquired. Another heat gun was acquired that output heat over 500 ^{o}F and did provide adequate shrinkage of the shrink tape material. Care had to be taken not to burn through the shrink tape as was discovered through trial and error. Uniform constriction of the material seemed to be hard to achieve without melting some of the tape. It is possible more layers of the material may help with this issue and could possibly aid in compression. Another problem that developed was the shrink tape pulling the uncured layers of prepreg down towards the smaller vertical face at the tapered down end of the spar. This may be attributed to the order at which heat was applied to the shrink tape meaning the constriction of the material at the tapered down end of the spar pulled the prepreg down before heat could be applied to the rest of the shrink tape material. The final issue with the shrink tape is that there is no direct compression of the material perpendicular to the plane of the tape which may be able to be seen by the tension in of the tape below in Figure 4-4. A dome fixture could be devised to allow the compression of the material perpendicular to the plane of the tape after heat has been applied.

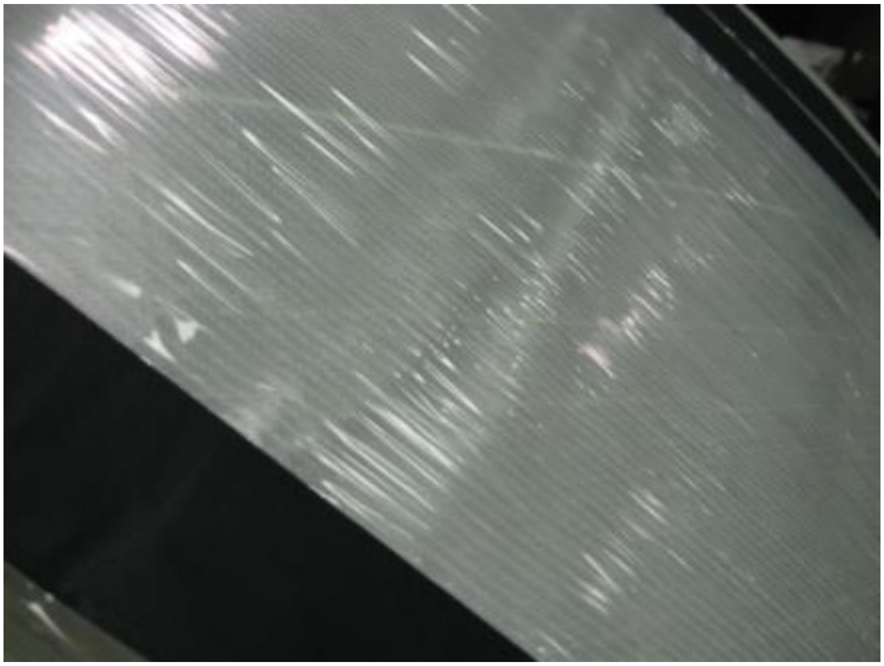


Figure 4-4. Shrink Tape after heat application

Chapter 5

Conclusions

The main advantage of male molding has been clearly stated as a much lower tooling cost than its female tooling counterpart. With the addition of prepreg labor costs are also reduced due to ease of fabrication and cleaner working conditions. OVB prepreg in particular eliminates the need for an autoclave which has been a problem in industry due to the cost of autoclave renting and/or operation. The main disadvantage of male molding is wrinkling due to cure compaction, which requires a significant machining step to remove. The development of caul blocks as proven through the trials detailed in Chapter 3 and the third application 2.5.3: Doubly curved structure with smooth surface, allows for a male molded part to achieve surfaces similar to that of a two molded part for potential use in a variety of applications. Wrinkling was introduced in plys 1-30 on the flat surfaces of the spar and was corrected with the development of flat caul blocks. By localizing the ridges and wrinkles, the next trials were able to predict and eliminate wrinkles allowing for the de-bulk stage to take place.

After 100 plys of lay-up creating a laminate thickness of roughly 2.3” post cure, the in-situ gap fillers seemed to be the most appropriate method to complete a successful de-bulk stage of no wrinkles. In-situ gap filler material in conjunction with caul blocks is the gateway to allowing male molding to develop into a method that is no longer known for laborious and time consuming finishing process to achieve an acceptable surface. Applications such as boat building and Navy submarine structures have already passed the design stage with this method and use it to produce their structural members such as decks, hulls, yardarms, and masts. More research must be done to determine industry standard materials for caul blocks that allow a balance between stiffness and flexibility to achieve the most desirable part.

Chapter 6

Recommendations for Future Work

As mentioned earlier, there was a significant issue throughout most of the fabrication process with gravity pulling the prepreg material off the surface closest to the ground. This problem could be solved by selecting material that is tacky enough to prevent this phenomenon. A disadvantage of this solution is that it may result in a narrow selection of materials for fabrication. The properties of the materials with appropriate tack may not be desirable in all applications. Another disadvantage is that during lay-up, prepreg with tacky resin can be more difficult to work with. Errors are more easily rectified with resins that are not as tacky. Another way to resolve this issue is to apply a device to the spar member fabricated to allow the spar to rotate about its axis. The speed at which the device rotates is irrelevant as long as it is rotating. One of the disadvantages of this is that depending on the size of the part to be rotated, the rotation contraption could be difficult to acquire or create. It is believed that if after several lay-ups one of these methods had been applied, the resulting surfaces of the spar would have been improved. Each of the proposed solutions has their pros and cons but it my belief that the issue must be addressed either way moving forward.

Although the shrink tape method discussed did have several issues, I believe it is a promising technique. The use of shrink tape has many variables such as the temperature to use for the heat gun, the pattern of applying the heat gun to the part, how many layers of shrink tape are needed to efficiently de-bulk the part, as well as other factors that we were unaware of before we used this method. Due to the complexity of this material, the results of this application were not desirable.

Although this material saw compaction as we wanted, it was difficult to discern why we received the reported results. After seeing the shrink tape material pull the plys a quarter inch down from their original position, there was an assumption made that more care involving the use of the shrink tape material was needed. For future work with shrink tape, much time, consideration, and experimentation must be used to make this an efficient de-bulking material.

There were several limitations regarding the research done on the spar member. Several applications had to be considered in a set amount of time with an allotted amount of funds for this project. Materials such as the Super Ceramic Putty had to be purchased for use on the spar. This material specifically showed great promise during the de-bulking stage. Three out of four of the surfaces after the de-bulk stage were very desirable and the fourth had specific avoidable fabrication errors. Recall as mentioned in Chapter 3, there was a small ball of Teflon tape that appeared under one of the flat caul plates as well as the ply drop-off phenomena. Due to the time constraints, the accuracy of the assumptions made could not be confirmed but moving forward it is an aspect of the experiments that should be considered for reassessment.

An aspect of the research that may have made a difference during the de-bulk stage is the thickness of the caul blocks used. For both sets of caul blocks, two plys of the WRE850 fiberglass material was used giving each of the caul blocks roughly 60 mils (.06”). The reason the thickness of the caul blocks is significant is because of the pressure of the vacuum. Thicker caul blocks will not be affected by the pressure of the vacuum as greatly meaning a thicker and stiffer caul block will result in less wrinkles in the corners. The tradeoff of thicker caul blocks is that they are less flexible and must be replaced more often due to the growing dimensions of the radius in the corners of the spar as material is added during lay-ups. If the thicker caul blocks continue to be used, when the pressure of the vacuum is applied to the corner, the caul blocks will begin to push into prepreg material and causes ridges after the de-bulk stage. Thinner and more flexible caul blocks can be replaced less often but run the risk of not being as effective as their thicker counterparts. The caul blocks used worked very well but thicker/thinner caul blocks were not attempted.

With the ongoing development of OVB prepreg to be the industry standard type of composite material that withstands aerospace tolerance void content and strength, costs will continue to be reduced throughout the production process. This development will only continue to open applications where caul blocks will be used for male molding where VARTM may have been used before. It only makes sense to work towards perfecting the methods that will dominate the future and be able to competitively manufacture products. With the largest disadvantage of male molding in sight to be eliminated, along with all of its advantages over female molding, the future seems to point to male molding OVB prepreg.

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Appendix A: Ply Lay-up Details

This appendix documents the procedure in which the ply lay-up took place. The details given include the material used for each ply, the thickness of each ply, and the thickness of the laminate as plies were added.

Ply #	Material	Ply Thickness	**Cumulative Thickness**
1	ST70-1/WRE850	0.029	0.029
2	Sparpreg: ST94/XE603	0.020	0.049
3	ST70-1/WRE850	0.029	0.078
4	Sparpreg: ST94/XE603	0.020	0.098
5	ST70-1/WRE850	0.029	0.127
6	Sparpreg: ST94/XE603	0.020	0.147
7	ST70-1/WRE850	0.029	0.176
8	Sparpreg: ST94/XE603	0.020	0.196
9	ST70-1/WRE850	0.029	0.225
10	Sparpreg: ST94/XE603	0.020	0.245
	de-bulk		
	cure		
11	ST70-1/WRE850	0.029	0.274
12	Sparpreg: ST94/XE603	0.020	0.294
13	ST70-1/WRE850	0.029	0.323
14	Sparpreg: ST94/XE603	0.020	0.343
15	ST70-1/WRE850	0.029	0.372
16	Sparpreg: ST94/XE603	0.020	0.392
17	ST70-1/WRE850	0.029	0.421
18	Sparpreg: ST94/XE603	0.020	0.441
19	ST70-1/WRE850	0.029	0.470
20	Sparpreg: ST94/XE603	0.020	0.490
	de-bulk		
	cure		
21	ST70-1/WRE850	0.029	0.519
22	XE603	0.020	0.539
	de-bulk		

cure

23	ST94/WRE850	0.030	0.569
24	XE603	0.020	0.589
25	ST94/WRE850	0.030	0.619
26	XE603	0.020	0.639
27	ST94/WRE850	0.030	0.669
28	XE603	0.020	0.689
29	ST94/WRE850	0.030	0.719
30	XE603	0.020	0.739

cure

31	ST94/WRE850	0.030	0.769
32	XE603	0.020	0.789
33	ST94/WRE850	0.030	0.819
34	XE603	0.020	0.839
35	ST94/WRE850	0.030	0.869
36	XE603	0.020	0.889
37	ST94/WRE850	0.030	0.919
38	XE603	0.020	0.939
39	ST94/WRE850	0.030	0.969
40	XE603	0.020	0.989

41	ST94/WRE850	0.030	1.019
42	XE603	0.020	1.039
43	ST94/WRE850	0.030	1.069
44	XE603	0.020	1.089
45	ST94/WRE850	0.030	1.119
46	XE603	0.020	1.139
47	ST94/WRE850	0.030	1.169
48	XE603	0.020	1.189
49	ST94/WRE850	0.030	1.219
50	XE603	0.020	1.239

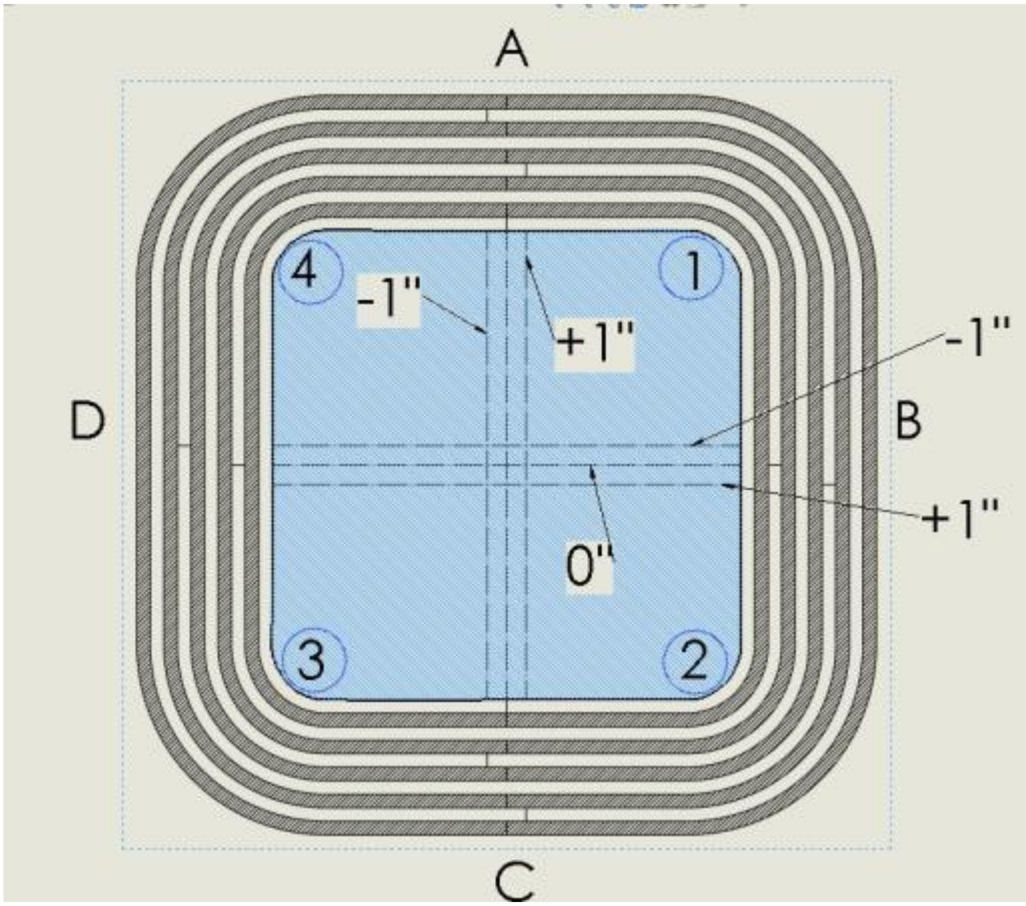
51	ST94/WRE850	0.030	1.269
52	XE603	0.020	1.289
53	ST94/WRE850	0.030	1.319
54	XE603	0.020	1.339
55	ST94/WRE850	0.030	1.369

56	XE603	0.020	1.389
57	ST94/WRE850	0.030	1.419
58	XE603	0.020	1.439
59	ST94/WRE850	0.030	1.469
60	XE603	0.020	1.489
61	ST94/WRE850	0.030	1.519
62	XE603	0.020	1.539
63	ST94/WRE850	0.030	1.569
64	XE603	0.020	1.589
65	ST94/WRE850	0.030	1.619
66	XE603	0.020	1.639
67	ST94/WRE850	0.030	1.669
68	XE603	0.020	1.689
69	ST94/WRE850	0.030	1.719
70	XE603	0.020	1.739
71	ST94/WRE850	0.030	1.769
72	XE603	0.020	1.789
73	ST94/WRE850	0.030	1.819
74	XE603	0.020	1.839
75	ST94/WRE850	0.030	1.869
76	XE603	0.020	1.889
77	ST94/WRE850	0.030	1.919
78	XE603	0.020	1.939
79	XE603	0.020	1.959
80	XE603	0.020	1.979
81	ST70-1/WRE850	0.029	2.008
82	XE603	0.020	2.028
83	ST70-1/WRE850	0.029	2.057
84	XE603	0.020	2.077
85	ST70-1/WRE850	0.029	2.106
86	XE603	0.020	2.126
87	ST70-1/WRE850	0.029	2.155
88	XE603	0.020	2.175
89	ST70-1/WRE850	0.029	2.204

90	XE603	0.020	2.224
91	ST70-1/WRE850	0.029	2.253
92	XE603	0.020	2.273
93	ST70-1/WRE850	0.029	2.302
94	XE603	0.020	2.322
95	ST70-1/WRE850	0.029	2.351
96	XE603	0.020	2.371
97	ST70-1/WRE850	0.029	2.400
98	XE603	0.020	2.420
99	ST70-1/WRE850	0.029	2.449
100	XE603	0.020	2.469

Appendix B: Post Ply #22 Lay-up Scheme

This appendix depicts the scheme of lay-ups after 22 plies had been applied to the foam mandrel.



Appendix C: Spar Foam Mandrel Drawings

This appendix depicts the shape and dimensions of the foam mandrel fabricated before and plies were added. Below a front and side view of the mandrel can be seen.