MANUFACTURING REPORT: FUSELAGE

Following the design report, the manufacturing report aims to present a comprehensive study and review of the manufacturing methods considered to produce the fuselage structure. Various manufacturing techniques were analyzed based on their merits and demerits. After a detailed discussion, it was concluded that vacuum bagging with the E-Glass prepreg followed by autoclave curing was selected as the primary manufacturing process. This was due to its superior process control, final laminate quality and adherence to the SAMPE 2025 guidelines. The report outlines a detailed manufacturing methodology, risk assessment, alternate manufacturing plans (if necessary) and finishing techniques employed to ensure that the final product complies with satisfactory quality and manufacturing standards and is optimized for performance and manufacturability.

1. Materials

Prepregs are formations of resin and fibers preform with enhancement in the ease of handling without any requirements of further treatments other than the curing cycles, hence acting as precursors to manufacture composites used in a high-performance setting. Prepregs have a characteristic of providing desirable tack and drape to allow the formation of structures with complicated shapes. Prepregs based on thermosetting matrices are generally formed when the fiber tow is impregnated with the resin under elevated temperatures and pressure, further quenched and stored in a cool condition so as not to initiate the reaction(curing) mechanism. [1]

Prepregs are significant in manufacturing high-performance, high-stress, enduring composites [2]. Prepregs are mostly selected because of their ability to form void-free composite structures, which could be manufactured in a rapid process, and which would help in reducing the constraints of handling and the possibility of varied accumulation of resin (in case of resin infusion technique). Therefore, for the manufacturing of a fuselage, which is idealized as a cylinder, using a prepreg is the best choice to achieve high structural durability as well as maintain geometrical characteristics [3].

Since the SAMPE bending test requires a continuous loading condition until the cylinder breaks, the plies undergo tension in the bottom but compression at the top; therefore, it is imperative to look at the properties of the fibers due to fibers being the maximum load-bearing constituent in the axial direction. The table below shows the superior properties of S-Glass which offers several distinct benefits over E-Glass for aerospace applications. Its 5.2% elongation, compared to E-Glass's 4.7%, improves impact resistance in multidirectional laminates, while its higher fiber toughness reduces the risk of delamination during manufacturing. Additionally, its 30% greater compressive strength contributes to enhanced structural integrity around door openings and other high-stress areas.

Property	S-Glass	E-Glass
Tensile Strength	4600 MPa	3400 MPa
Elastic Modulus	89 Gpa	72 Gpa
Density	2.53 g/cm^3	2.54 g/cm^3
Impact Resistance	High	Moderate

Table 1: Properties of Different types of glass fibers

Within prepregs, the choice of fiber matrix system for the prepreg, which also adheres to the regulations of the SAMPE design competition, brings down the choice of fiber to glass fibers. Ideally, S glass fibers with epoxy resin system would have been the optimum choice as the S-glass fiber composites have high stiffness modulus which is required to withstand the 1000 lbf load and less than 1” deflection. But the ABAQUS simulation as seen from the figure below shows a respectable deflection of less than 0.5” in case of E-glass fiber which has modest modulus as compared to S-glass fiber allowing for room adjustment without taking a cost penalty. The ABAQUS calculations in the design report had been done using the effective Young’s modulus of the composite, wherein the resin system was opted as epoxy-based and the fiber as the S/E glass fiber.

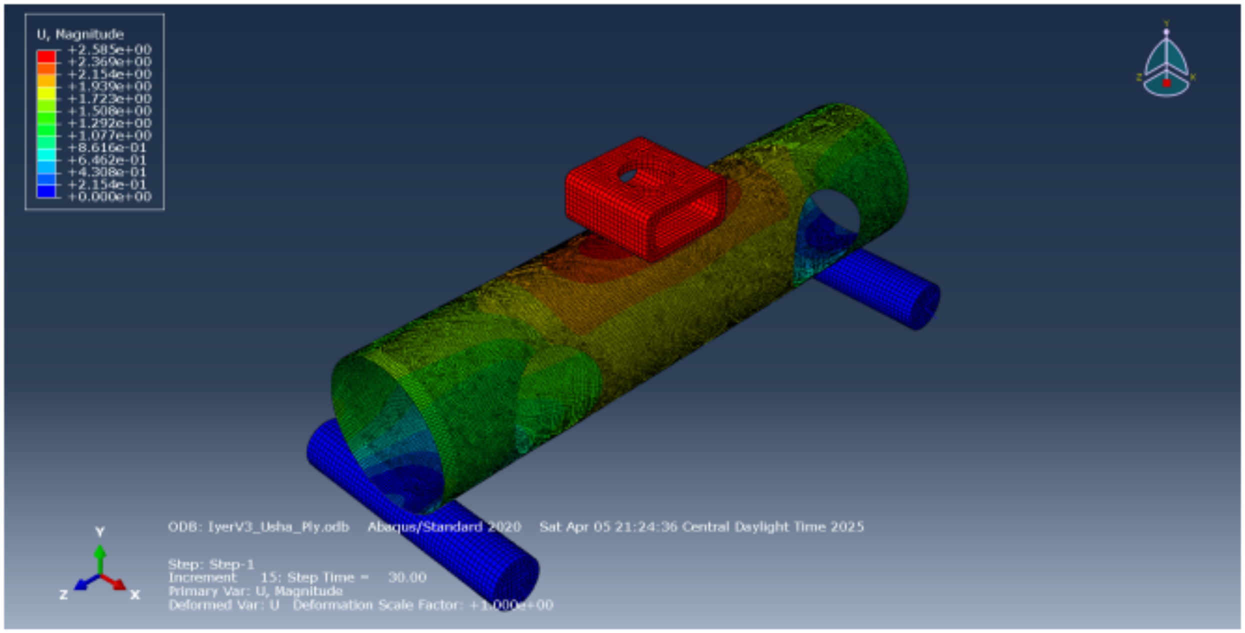

Fig 1: ABAQUS simulation of E-glass fiber composite with cutouts.

Essentially, E glass fibers with epoxy-based resin system are the optimum choice of fiber system because of their lower cost with favorable mechanical properties, as glass fibers have high tensile strength, good impact resistance and ease of processing.

Finally, it is also imperative to discuss the type of weave required for the composite over general unidirectional prepregs. In all the hand calculations and ABAQUS simulations, the composite properties considered are unidirectional, and we had done an optimization study of prepreg orientation using the unidirectional properties.

Unidirectional prepregs are the best candidates for composites which are loaded ideally in the axial direction in case of high tensile strength and stress applications, but since the bending loading conditions are a mixture of tensile stress as well as shear stresses, which adds to the material's resistance to the bending load additionally, due to the cut outs there are stress concentrations which would need to be accounted for and these kinds of complex stress accumulations is best utilized for the woven prepregs wherein a single ply can withstand stresses in multiple directions (warp and weft) with fiber being dominant in both the directions hence providing higher stress and strength capabilities for the final products. Finally, as we are moving forward with a woven prepreg, the type of woven prepreg is also under consideration. The following table shows the advantages and disadvantages of various types of weaves:

Weave Type	Advantages	Disadvantages
Plain Weave	Stable and easy to handle	Poor drapability, high crimp
Twill Weave	High drapability and better strength	Prone to fraying
Satin Weave	Best Drapability and high strength	Low stability
Basket Weave	High strength and impact resistance	Bulky and less stable

Table 2: Various types of weaves with their advantages and disadvantages.

The ease of handling, lead time, and manufacturing cost are the main considerations. Two plain weave prepregs were considered: easy to handle, stable with a lower lead time, and providing the same strength as unidirectional ply. The plain weave offers fiber-dominated strength in both transverse and longitudinal directions, aiding in shear and bending stress. The Prepreg - Fiberglass Woven (7781 E-Glass) - 39.37” Wide x 36” Long x 0.010” Thick - 32% Resin Content w/Black pigment (461 gsm OAW) - 250F Resin is the better choice due to its superior tensile strength and modulus, as discussed above. The mechanical properties of the two prepregs are given below:

Prepreg	Prepreg - Fiberglass Woven (7781 E-Glass) - 39.37" Wide x 36" Long x 0.010" Thick - 32% Resin Content w/Black pigment (461 gsm OAW) - 250F Resin	Prepreg - Fiberglass Woven (120 Glass) Epoxy (Newport 301) - 38" Wide x 0.005" Thick - 40% Resin Content w/out pigment (185 gsm OAW)
Prepreg Overall Weight	440 GSM	185 GSM
Resin Content	32%	40%
Resin System	Propreg 250F	Newport 301
Tensile Modulus	10.5 msi	2.96 msi
Tensile Strength	285 ksi	55.5 ksi
Weight	45812.79 g	13154.168 g

Table 3: Properties of E-glass and epoxy resin prepreg systems.

Core materials play a crucial role in sandwich composite structures, providing a lightweight means of achieving the required strength, stiffness, and energy absorption. When developing high-performance sandwich structures, engineers commonly use materials like aluminum honeycomb cores due to their strength-to-weight ratio and cost-effectiveness. Polymer foam cores such as polymethacrylimide (PMI) foams are also frequently chosen for applications requiring superior mechanical properties, however, the current guidelines constraints limit the choice to Nomex and Kevlar honeycomb cores. Hence are studied further to optimize the fuselage structure effectively. Nomex and Kevlar honeycomb cores are frequently utilized in aerospace applications due to their favorable strength-to-weight ratios, fire resistance, and durability. Each variant presents distinct advantages and limitations, making a detailed comparison essential to identify the most suitable material for specific fuselage sections. Based on the comparative analysis above, Nomex honeycomb cores are well suited for cost-sensitive applications demanding moderate strength and stiffness, making them ideal for fuselage components such as cabin floors and bulkheads. Kevlar honeycomb cores, in contrast, are more appropriate for high-stress regions requiring maximum shear strength and superior compressive performance. Strategic allocation of these materials ensures optimized structural efficiency and performance while complying with relevant design and material constraints

2. Manufacturing Methodology:

Manufacturing of a high-performance composite could be done using various procedures. The methodology selected for this report is the one that has high structural integrity, cost-effectiveness, design and process flexibility.

Vacuum Bagging:

The vacuum bagging process involves sealing layers of fiber under a vacuum bag to ensure uniform pressure during curing. This technique is designed to consolidate the laminate effectively while simultaneously removing excess resin and trapped air. By creating a controlled environment under vacuum pressure, the fibers are compressed uniformly, resulting in a more compact and cohesive structure. The vacuum bag acts as a barrier, maintaining consistent pressure throughout the curing process, which is critical for achieving optimal laminate quality. Vacuum bagging offers several advantages over traditional hand layup methods. One of its key benefits is improved consolidation, which leads to reduced void content within the laminate. This results in a stronger and more durable composite structure. Additionally, vacuum bagging provides more consistent thickness across the laminate compared to hand layup techniques, ensuring uniformity in structural properties. The method also delivers higher strength-to-weight ratios and more consistent quality, making it particularly beneficial for medium-sized fuselage structures. However, there are some disadvantages associated with this process. Vacuum bagging requires additional equipment such as vacuum pumps and bagging film, which can increase costs slightly compared to hand layup methods. Furthermore, operator proficiency is essential to prevent leaks during the process, as the maximum pressure achievable is limited to atmospheric pressure (approximately 14.7 psi). Vacuum bagging is commonly employed for primary fuselage structures where moderate strength and weight efficiency are essential. Its ability to produce consistent and high-quality laminates makes it an ideal choice for applications requiring reliable performance in medium-sized composite components. While it may not be suitable for all manufacturing scenarios due to its equipment requirements and cost considerations, vacuum bagging remains a preferred method for achieving structural integrity in aerospace applications where strength-to-weight ratios are critical.

Additive Manufacturing (3d Printing):

Additive manufacturing, commonly referred to as 3d printing, is a process in which composite materials, such as carbon fiber-reinforced thermoplastics, are deposited layer by layer to construct parts. This technique eliminates the need for extensive tooling and allows for the precise fabrication of components directly from digital designs. By building parts incrementally, additive manufacturing offers a highly controlled and efficient method for producing composite structures while minimizing material waste. The advantages of additive manufacturing are significant, particularly in terms of design flexibility. This method enables the creation of intricate geometries and integrated features that would be challenging or impossible to achieve with traditional composite fabrication techniques. Additionally, additive manufacturing excels in rapid prototyping, allowing engineers to quickly test and iterate designs with minimal material waste. Despite these benefits, there are notable disadvantages. The mechanical properties of parts produced through additive manufacturing may be inferior to those achieved using conventional composite methods. Furthermore, this process is generally restricted to smaller scale parts and offers limited material options compared to traditional techniques. Additive manufacturing is particularly suited for prototyping fuselage components that require complex internal structures or lightweight core designs. Its ability to produce intricate geometries and lightweight parts makes it ideal for applications where design complexity and efficiency are prioritized. While it may not be suitable for large-scale production or high-performance structural components due to its limitations in mechanical properties and material selection, additive manufacturing remains a valuable tool for innovation in aerospace prototyping and lightweight design [9].

Resin Transfer Molding (RTM):

Resin Transfer Molding (RTM) is a composite manufacturing process that involves positioning dry fibers within a closed mold and injecting resin under pressure to impregnate the reinforcement thoroughly. The resin, often combined with catalysts, flows into the mold cavity to saturate the fiber preform, ensuring uniform distribution and complete impregnation. Once the resin cures, the mold is opened, and the finished component is removed. RTM enables precise control over fiber orientation and resin content, making it suitable for producing high-performance composite parts with excellent dimensional accuracy and surface finishes. This process is widely used in industries such as aerospace, where lightweight and durable components are essential. RTM offers several advantages that make it a preferred method for composite manufacturing. It produces high-quality parts with consistent dimensions and excellent surface finishes on both sides of the component. The process is particularly well-suited to complex geometries and integrated features, such as door cutouts, due to its ability to mold intricate shapes with tight tolerances. Additionally, RTM minimizes material waste by allowing near-net-shape production, reducing post-processing requirements. However, there are some disadvantages associated with RTM. The initial setup cost is high due to the need for specialized mold fabrication, which can be a barrier for small-scale production or prototyping. Moreover, achieving optimal results requires careful control of processing parameters and skilled operators. RTM is ideal for manufacturing high-performance fuselage sections that demand tight tolerances and reduced post-processing. Its ability to produce lightweight yet durable components make it particularly valuable in aerospace applications where structural integrity and weight optimization are critical. While its high initial costs may limit its use in certain scenarios, RTM remains indispensable for applications requiring precision-engineered composite parts with complex geometries and superior mechanical properties [5].

Filament Winding Filament winding is a composite manufacturing technique that involves winding continuous fibers, such as carbon, glass, or aramid, onto a rotating mandrel. The fibers are impregnated with resin either before or during the winding process to ensure proper bonding and structural integrity. The mandrel rotates while a carriage system moves horizontally, laying down the fibers in predetermined patterns to achieve the desired orientation and thickness. Once the winding is complete, the resin is cured using heat or other methods, and the mandrel is removed to leave behind a hollow composite structure. This process is particularly effective for creating cylindrical or spherical components with high mechanical strength and precision. Filament winding offers several advantages, making it an efficient and reliable method for composite manufacturing. It provides high hoop strength due to its ability to optimize fiber placement for cylindrical shapes, making it ideal for pressure vessels or structures subjected to hoop loading. The process efficiently utilizes continuous fibers, resulting in strong and lightweight components with minimal material waste. Additionally, filament winding is highly automated, ensuring repeatable quality and reducing labor costs. However, there are limitations to this method. It is primarily restricted to axisymmetric geometries and cannot accommodate complex shapes with openings, such as fuselage sections with integrated features. Furthermore, filament winding requires specialized equipment, which can be costly to acquire and operate. Filament winding is particularly suitable for manufacturing fuselage tubes or pressure vessels that demand significant hoop strength and relatively simple geometries. Its ability to produce lightweight yet durable components make it an excellent choice for applications where internal pressure resistance is critical. While its geometric constraints limit its use for more intricate designs, filament winding remains a preferred method for producing high-performance cylindrical structures in industries such as aerospace, automotive, and industrial manufacturing [5].

Method	Cost (4)	Manufacturing Time (4)	Quality (5)	Implementation (4)	Flexibility (4)	Compliance (5)	Total Weighted Score
Hand Layup	5	2	2	5	2	5	91
Vacuum Bagging	4	3	4	4	3	5	105
RTM	2	4	4	2	4	4	88
Automated Fiber Placement	1	5	5	1	5	4	93
Filament Winding	3	3	4	3	2	5	89
Additive Manufacturing	2	4	4	3	5	5	101

Table 4: Decision Matrix for various manufacturing types.

Conclusion

Based on the outcomes of the comprehensive decision matrix, vacuum bagging is identified as the most suitable manufacturing method for composite fuselage production. This technique offers an optimal balance of cost efficiency, manufacturing quality, and ease of implementation, aligning well with the rigorous performance requirements of the fuselage. Although additive manufacturing presents significant potential for producing complex geometry and innovative designs, its current limitations in scalability and mechanical performance render it less practical for mid-scale fuselage fabrication. The established reliability of vacuum bagging, along with its capacity to deliver consistent and high-quality results, reinforces its selection as the preferred method for manufacturing high-performance composite fuselages. Additionally, along with the decision matrix, the constraint of manufacturing needs to be considered as well, which allows two types of processes, i.e. resin infusion with dry fabric and vacuum bagging of the prepreg. The vacuum bagging with prepregs proves to provide better handling. It also avoids the chances of more accumulation of resin possible in the resin infusion case and works as a faster turnaround cycle for the wherein multiple curing is required since we need to use layers of prepregs and honeycomb structure as well which in the multiple curing cycle of prepreg vacuum bag process would be able to be bonded perfectly well. Additionally, vacuum bagging of prepregs would provide the extra pressure during the autoclave procedure required to make a sturdier material

2.1 Manufacturing Process Summary: Vacuum Bagging and Autoclave Curing of E-Glass Prepreg for Cylindrical Cross-section

For the fabrication of the fuselage structure, the team selected **vacuum bagging using E-glass prepreg followed by autoclave curing** as the manufacturing process. Between the two available processes in the Composites Manufacturing lab — **resin infusion using dry fabric** and **vacuum bagging using prepreg** — vacuum bagging with prepreg was chosen to ensure greater process control, part quality, and compliance with competition manufacturing standards.

Several critical factors influenced this decision:

- **Equipment Availability**:
  The laboratory provides access to a vacuum bagging setup and an operational autoclave, enabling high-pressure, high-temperature curing. This enables manufacturing of high-quality composite parts by combining vacuum compaction with high-pressure, controlled temperature autoclave curing, resulting in improved laminate consolidation, minimized void content, and increased fiber volume fraction.

- **Process Manageability and Quality Control**:
  Although the team has limited prior experience with both vacuum bagging and resin infusion, vacuum bagging of prepreg materials was deemed more manageable due to the inherent stability of prepregs.
  Prepreg materials offer highly controlled resin content and uniform fiber alignment, significantly reducing variability compared to resin infusion methods.
  This results in improved control over fiber alignment, reduced risk of dry spots or resin-rich zones, and ensures consistent laminate thickness. Which factors into improving the laminate quality compared to resin infusion processes.

- **Manufacturing Simplicity and Risk Reduction**:
  Vacuum bagging prepreg reduces the number of variables involved in the fabrication process (such as infusion pressures, flow media setup, resin pot life, and mold sealing quality), which in turn lowers the likelihood of manufacturing defects.
  It is especially advantageous when working with curved or cylindrical structures like the fuselage, where maintaining uniform resin flow in an infusion process could be challenging.

  Prepreg layup eliminates the risk of dry spots, uneven resin distribution, and complex infusion troubleshooting.

- **Surface Finish and Dimensional Accuracy**: The combination of vacuum bagging and autoclave curing allows for excellent surface finish quality and precise dimensional control, reducing the need for extensive post-processing and ensuring better geometric tolerance. Autoclave-cured prepreg parts achieve superior surface finishes and require minimal post-processing. This reduces sanding, filling, and cosmetic repair work after curing — important for maintaining structural integrity and saving manufacturing time.

- **Compatibility with Fuselage Design**:

  Vacuum bagging and autoclave curing are well-suited for cylindrical structures, where uniform pressure application is critical to avoid wrinkles, fiber distortion, and dimensional deviations. This method aligns with the manufacturing assumptions made during the fuselage design optimization process.

- **Material Availability and Sourcing Constraints**: While the initial plan considered using S-glass braided sleeves with vacuum-assisted resin transfer molding (VARTM), difficulties in sourcing appropriately sized braided sleeves (5.5-inch inner diameter) made this approach impractical.

  Transitioning to **woven E-glass prepreg** ensures material availability, while still meeting design stiffness and strength targets.

- **Alignment with Design Report Findings**: Vacuum bagging and autoclave curing were identified as the most viable manufacturing approach during the design phase, based on a thorough review of literature, industry best practices for fuselage manufacturing, and feasibility analysis of various composite manufacturing methods.

The intended fuselage design features a cylindrical cross-section, with the following dimensions optimized through engineering design calculations:

- Inner Diameter: 5.5 inches
- Outer Diameter: 6 inches
- Length: 24 inches

Material Selection:

- **Reinforcement**: Woven E-glass prepreg (14086)
- **Curing Method**: Vacuum bagging of prepreg followed by autoclave curing (pressure-assisted high-temperature cure).

This approach ensures the production of a structurally sound, competition-compliant fuselage structure with high mechanical performance, minimal void content, and superior surface quality.

2.2 Alternate Manufacturing Approach: Rolled Tube Method with Oven Curing

In case vacuum bagging and autoclave curing cannot be successfully completed, the team has identified an alternate manufacturing approach to ensure that fabrication of the fuselage structure can still proceed.

The alternate method would involve the **rolled tube technique**, followed by **oven curing**. In this approach, woven E-glass prepreg would be manually wrapped around a polished aluminum mandrel in sequential layers according to the designed fiber orientation schedule. After layup, the laminate would be consolidated using high-temperature shrink tape, which applies radial pressure during the oven curing process. Curing would be performed in a conventional oven following the specified prepreg cure cycle After curing and cooling, the part would be demolded and trimmed as needed.

While this method provides a practical backup plan, it is acknowledged that it is not ideal for fuselage manufacturing. However, the rolled tube method offers several advantages that make it a reasonable alternate approach:

- **Simplified Equipment Requirements**
- **Material Compatibility**: The woven E-glass prepreg material can be used.
- **Manufacturing Flexibility**: Manual wrapping around a mandrel is less sensitive to vacuum bag sealing and leak issues compared to vacuum bagging large, curved molds.

In summary, although the rolled tube method would not produce an ideal aerospace-grade fuselage structure, it remains a viable alternate manufacturing method to ensure project completion if autoclave-based vacuum bagging cannot be executed.

2.3 Prepreg Handling

A prepreg is a composite material which has already been pre-impregnated with a resin system. They are a complex system of composite materials which must be handled very carefully. The current project uses a 14086-d-group E-Glass prepreg for use as the principal composite layup, along with a NOMEX core. Following are a few salient points which should be followed while handling prepreg systems:

1. Storage: When handling prepreg, it is very crucial to store it in the freezer to prevent the resin from curing completely. The prepreg was stored in a cold storage freezer where the temperature was maintained low enough to ensure that the curing process of the resin was arrested.
2. Defrosting: Before using the prepreg for manufacturing it is let to recover to room temperature on its own, without any external influence. This is to let the resin revert to a workable temperature. Manually influencing the procedure could result in condensation forming on the prepreg, affecting results. It is recommended that the prepreg be left out at least 20 hours at room temperature.
3. It is also important to note that every prepreg has a specific shelf-life corresponding to the storage conditions. Keeping the prepreg outside for a longer time proportionally reduces its shelf-life.

2.4 Preparation of the Composite Assembly for Curing

There are several steps which must be executed before the composite can be sent for its first cure.

2.4.1 Cutting

1. The Prepreg was rolled out from its stack, measured, and then cut using a rolling cutter. The measurement of the prepreg was based on hand calculations which computed the total length of the composite required per ply to wrap the entire mandrel, without any overlap.
2. Correspondingly, the breather and release film and the vacuum bag were cut as well.

2.4.2 Preparation of the Mandrel

The Mandrel is perhaps the most important component of the assembly process, as the prepreg plies and the core will be laid up on it. Considering that the mandrel is going to be cured along with the composite, it must be able to withstand high temperatures, as well as not expand much due to the heat being supplied to it. Therefore, the team decided to go with Aluminum as the choice of material for the mandrel. It has a small two-step process for preparation, which is listed below:

1. The Mandrel is first held upright. To remove any contaminants which might be present on the surface of the mandrel, it is first cleaned with acetone. The acetone is first applied on an applicator which may be a cloth or a paper towel, and this is then rubbed on the surface of the mandrel thoroughly.
2. Care must be taken to ensure that the Acetone is sprayed onto the applicator only and is not spilled anywhere else.
3. Post the acetone swab, the mandrel is treated with a chemical release agent. The chemical release agent available at the Composites Laboratory has its own swab, thus not requiring additional supplies of applicator.
4. The chemical release agent should be applied uniformly on the surface of the mandrel, and while applying, special care must be taken to ensure that it is applied in a single direction.
5. Allow some time for the agent to dry. Post drying, it is possible that the color of the application may change, and this can be considered as completely normal.
6. Note that the personnel operating with the chemical release agent should not breathe too much of it as it may contain harmful and poisonous fumes.

2.4.3 Fixture and Setting of the Mandrel

1. Ideally, the Mandrel should be laid on a fixture for the entire curing process. An illustration of the ideal fixture is shown here.
2. The two stands on either side are the main components which are responsible for handling the entire weight of the Mandrel and the Composite Assembly.
3. The Top Clamps are responsible for restricting any movement in the vertical direction and completely close the mandrel from either end, thus allowing only rotation of the mandrel.
4. There are extrusions on one end of the clamps, which provides a holding area for the hand to aid easier removal of the clamp from the fixture.

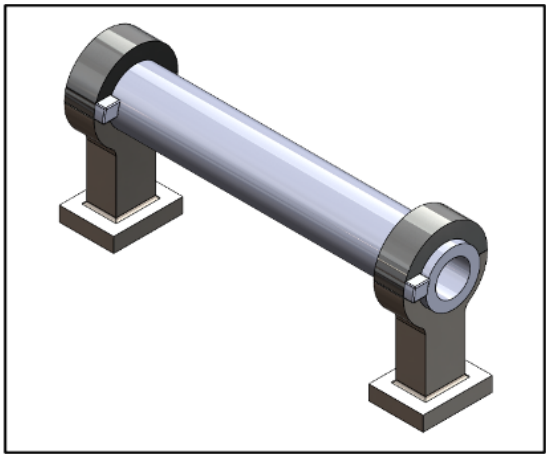

Figure 1: The Ideal Composite Fixture

5. While a fixture should be able to restrict movement in all orientations, allowing rotation provides a very convenient way to apply the prepreg onto the surface of the prepared mandrel.
6. The fixture is set up on the autoclave stand, with the stands being placed at a set distance from each other.
7. The Mandrel is placed on the stand, ensuring that neither part is damaged while doing so. The studs for the clamps are set on the fixture.
8. The clamps are placed, closing off the mandrel and completing the fixture assembly.

Reality Check: For manufacturing in the Composites Lab, we as students obviously do not have the capacity to manufacture or order a bespoke fixture for the sole purpose of a final project. Thus, the team plans to utilize clamps/vises and chocks to restrict movement of the mandrel. Additionally, to create some height which will allow easy application of the prepreg on the mandrel, the team envisions placing cinder blocks and bricks on top of the autoclave cart, thus mimicking the ideal fixture assembly proposed above.

2.4.4 Layup of the Prepreg

1. Before the prepreg is to be laid up on the mandrel, steps need to be taken to ensure that the alignment of the prepreg with the mandrel is accurate.
2. This is done in two ways. Post the cleanup with acetone, markings are made on the mandrel which help the personnel align the prepreg with the mandrel. Secondly, the separator paper can be used as a pressure and alignment measure relative to the mandrel as well.
3. For the first layer on the mandrel, the vacuum bag is placed. The Vacuum bag is wrapped around the entire mandrel ensuring that there is some excess length of bag lengthwise. This is to allow some space for the vacuum seal to be applied on the assembly.
4. Now, the initial layers of the prepreg are applied on the mandrel. Once the prepreg attaches to the mandrel, complete adherence is ensured by applying pressure on the separator paper layer using a tool.
5. Next, the separator paper is removed gently. The pressure applied on removing the separator paper is important because too much pressure can cause the fiber to separate, and too less pressure might maintain voids in the composite layup.
6. After every 4-6 plies, perform light vacuum debulking for 10-15 minutes. This is essential to remove voids (if any) from the composite.
7. The perforated release film and the breather cloth are applied on the assembly respectively. The breather cloth is essential to collecting the excess resin which may leak out of the prepregs during the curing process.
8. This entire setup is wrapped in a vacuum bag and then attached to a thru-bag vacuum connector and is sealed using the yellow sealant tapes.
9. A pipe is attached to the sealed assembly, and this pipe is then connected to a vacuum pump. The vacuum pump is turned on, and the assembly is finally vacuum sealed with the vacuum reaching close to 28 inHg.
10. A thorough leak check should be performed to check for any regions which may not be sealed perfectly.
11. This setup is then sent into the oven for curing.
12. Once cured and back to room temperature, the composite is removed from the mandrel slowly. This is where the chemical release agent proves its utility and allows convenient and easy removal. There is very little scope of removing the composite in one piece should it become stuck on the mandrel.
13. If possible, it is recommended that the mandrel be used again for the 2nd layup as well.
14. To adhere the core to the 1st composite layup, an epoxy adhesive is used. Alternatively, an easier method is to use an adhesive film.
15. Prior to applying the adhesive, the top surface of the cured composite is worn down with abrasive sandpaper. This is done to create microscopic grooves and increase the surface area for the adhesive to be applied over, increasing chances of clean adhesion.

16. The adhesive is mixed in a manufacturer recommended ratio of 1:1, and then uniformly applied on the surface of the composite.
17. Cure time is relatively long at 77F (6-7 hours) so personnel must take their time in ensuring that the NOMEX is adhered satisfactorily to the composite.
18. The NOMEX is placed on the composite in like how the prepreg layup was done. If required, the NOMEX core can be filled with resin as well. In the interest of weight savings, this is not done here.
19. After the NOMEX is applied, the final plies of the prepreg are applied on the assembly. The vacuum bagging process is repeated, and the entire assembly is cured in the autoclave for a second time.
20. The completed fuselage structure is now removed and prepared for finishing touches such as creating the door cutouts through a water jet facility, and then the final finishing and polishing to give the assembly a good surface finish.

3. Curing Procedures (Three-Stage Curing Process)

The curing approach for this project uses a step curing method because we are using a two-part epoxy adhesive to bond the Nomex® honeycomb core to the first set of cured prepreg layers.

In many sandwich structures, the face sheets and core are cured together at once by using film adhesives or by co-curing methods. However, in this project, because only a liquid epoxy adhesive was available in the lab, the first set of prepreg plies must be cured first to create a solid surface for the honeycomb core to bond to.

Using a step cure makes sure the core is properly attached and avoids trapping too much resin or air between the layers. This method also prevents weak bonding and reduces the chances of defects inside the structure.

The selected ramp rates and dwell times follow normal industry standards for epoxy-based prepregs. A slow heating rate of 2–3°C per minute avoids overheating the laminate, prevents resin from leaking out, and ensures uniform heating through the laminate thickness.

The temperatures and times chosen were based on a careful understanding of the resin behavior. The first ramp goes to 220°F (105°C) and holds for 30–45 minutes. This temperature was selected because it is high enough for the resin to begin gelling (partially solidifying), giving the layup "green strength" without causing the resin to fully cure. This is important to make the structure stable before proceeding to final cure.

After the first hold, the temperature is ramped up again to 275°F (135°C) and held for 90 minutes. This final cure temperature and time are based on the manufacturer's datasheet for the 7781 prepreg system and standard aerospace curing practices. It allows full cross-linking of the epoxy resin, achieving the desired final mechanical properties like strength and stiffness.

Cooling is done slowly under pressure (around 2°C/min) to avoid introducing residual stresses or warping in the part.

The step curing process, the chosen temperatures, and the slow ramp rates together ensure high-quality bonding of the Nomex® core and produce a structure suitable according to the requirements.

3.1 Preparation for Autoclave Curing

- The vacuum bag is checked to ensure a stable vacuum of approximately 28 inHg. A leak check should be performed by ensuring the setup holds the pressure when left for about 15 minutes, i.e. the vacuum pump pressure does not drop over time.
- The vacuum port installed on the vacuum bag connected securely to the autoclave vacuum system, ensuring that vacuum would be maintained during the heating and curing processes.
- The vacuum bagged assembly was carefully placed onto a perforated steel or aluminum tray inside the autoclave. Care was taken to avoid puncturing the bag or disturbing the layup. High-temperature supports are intended to be used where necessary to prevent deformation during curing.
- Personal protective equipment (PPE), including heat-resistant gloves, are worn during the setup process.
- All vacuum lines, thermocouples, and connectors are inspected to confirm they are properly routed and secured to avoid damage during the cycle.
- After confirming that vacuum is maintained and autoclave parameters such as temperature ramps, pressure levels, and dwell times matched the defined cure cycle, the autoclave is set up.

Following completion of setup, the curing cycle is initiated using the established two-stage ramp and hold profile.

a. Initial Skin Curing

- Autoclave external pressure (~60-85 psi) is applied before heating.
- Two- step ramp cycle is applied according to the technical data sheet of E-glass prepreg that is used.
- The first cycle is determined by the glass transition temperature of the resin.
- Dwell or hold times are provided, so that the deviation for actual and intended temperatures effects can be controlled.
- The second cure cycle is determined by the cure temperature of the resin.
- The following table provides the detailed curing cycle of the prepreg.

b. Autoclave Cure Schedule:

Step	Action	Parameters
1	Apply vacuum and pressure	28 in Hg vacuum, 60-85 psi pressure
2	Ramp 1	2-3°C/min to 220°F (105°C)
3	Hold 1	Hold at 220°F for 30-45 minutes (gelation stage)
4	Ramp 2	2-3°C/min to 275°F (135°C)
5	Hold 2	Hold at 275°F for 90 minutes (full cure)
6	Cool Down	2°C/min to room temperature under pressure

3.2 Finishing Techniques

After the final autoclave cure and full cooling, the part undergoes several finishing steps to achieve the required surface quality and dimensions:

1. **Demolding**:
    - Carefully remove all vacuum bagging materials.
    - Gently demold the fuselage using plastic or Teflon wedges to avoid surface damage.
2. **Flash and Resin Trim**:
    - Excess resin bleed-outs and flashing along the edges are removed using a diamond-coated bandsaw or abrasive cutoff wheels.
3. **Surface Sanding**:
    - Light sanding is carried out using 320 to 600 grit sandpaper.
    - Initial sanding is performed dry to remove surface imperfections.
    - Wet sanding may be used afterward to achieve a smoother finish and to minimize dust.
4. **Surface Cleaning**:
    - After sanding, the surface is cleaned using compressed air and lint-free wipes with isopropyl alcohol to remove sanding debris.
5. **Dimensional Inspection**:
    - Critical dimensions such as outer diameter, inner diameter, and wall thickness are measured to confirm conformity to design specifications.
6. **Cutout Creation**:
    - According to the design report, specific cutouts and access features must be introduced into the structure.
    - To achieve precise, clean cuts without damaging the composite layers, **water jet cutting** is selected as the preferred method.
    - The cured fuselage tube is positioned securely on the water jet table.
    - Cutouts are programmed into the CNC water jet system following the CAD drawings.
    - A fine abrasive stream is used to make clean and accurate openings without delaminating the composite laminate.
7. **Final Surface Preparation**:
    - If needed, additional minor sanding and polishing are performed around the cutout edges to remove burrs.
    - A final wipe-down with alcohol ensures the part is ready for structural testing or assembly.

These finishing techniques ensure that the manufactured fuselage not only meets the mechanical performance requirements but also presents a high-quality surface and dimensional accuracy, as expected in aerospace-grade components.

3.3 Testing Plan

Mechanical Testing:

- **Flexural Testing**:
  - ASTM D790 — Standard Test Methods for Flexural Properties of Plastics.
  - Conduct 3-point bend tests to determine flexural modulus and strength.

3.4 Void Content Analysis

- **Void Measurement**:
  - ASTM D2734 — Standard Test Methods for Void Content of Reinforced Plastics.
  - Resin burn-off or optical microscopy cross-sectional analysis.

3.5 Post Failure Analysis

- Post-failure microscopy (optical or SEM) to identify failure modes

4. Risk and Mitigation Strategies for Vacuum Bagging

4.1 Introduction to Risk Management in Vacuum Bagging

The vacuum bagging process is a cornerstone in the manufacturing of advanced composite structures for aerospace applications, valued for its ability to produce high-quality laminates with improved fiber volume fraction, reduced void content, and consistent mechanical properties.[6] However despite its advantages over traditional methods like hand layup, vacuum bagging comes with unique risks that can compromise structural integrity and reliability if not properly mitigated. These risks are particularly significant in the context of aerospace fuselage manufacturing, where even minor defects can lead to catastrophic failure.[7]

Research has shown that the quality and performance of vacuum-bagged composite parts are highly sensitive to process parameters such as vacuum pressure, temperature, and resin flow. For instance, Haschenburger (2023) [8] demonstrated that vacuum bag leaks, uneven pressure, and environmental fluctuations are leading contributors to porosity, resin-rich or resin-starved areas, and delamination. Similarly, Mujahid et.al (2020) [9] found that variations in vacuum pressure and bag integrity during consolidation directly affect fiber alignment and void content, resulting in significant reductions in interlaminar shear strength and fatigue life.

Given these challenges, the aerospace industry emphasizes a systematic approach to risk management, involving the identification of key process risks, quantitative assessment of their likelihood and impact, and the implementation of evidence-based mitigation strategies.

In this section, we systematically identify the most critical risks associated with vacuum bagging for composite fuselage manufacturing, assess their probability and potential consequences using a 5x5 risk matrix, and propose mitigation strategies grounded in empirical research and industry standards. This analysis is essential for ensuring not only the structural performance of the manufactured fuselage but also compliance with the aerospace standards.

4.2 Identification of Key Risks:

4.2.1 Vacuum bag leaks or seal Failures:

Vacuum bag leaks or seal failures arise when the vacuum bag's integrity is compromised, permitting air to enter the bagged assembly during resin infusion or curing. This intrusion disrupts the critical pressure differential required for laminate compaction, causing inadequate air removal, diminished consolidation, and elevated void content in the resulting composite component. Even small leaks can substantially impact the internal pressure distribution, weakening the effectiveness of the vacuum process [8].

Research by Haschenburger (2023) [8] indicates that vacuum bag leaks, particularly those creating a direct connection between the laminate and external environment, represent some of the most significant contributors to porosity and quality degradation in aerospace composite manufacturing. The study emphasizes that the manual procedures involved in vacuum bag preparation and leak testing cause this stage to be highly dependent on operator proficiency. Consequently, numerous quality issues and process uncertainties originate here. Industrial experience also verifies that vacuum bag leaks are a primary reason for scrapped parts and rework, prompting the growing implementation of advanced leak detection methods, such as ultrasonic techniques, for quality assurance.

Immediate Consequences: Components affected by vacuum leaks frequently show elevated void content and inadequate fiber wet-out, resulting in non-compliance with mechanical property specifications. This issue typically leads to scrapping or extensive rework of parts.

Downstream Consequences: Elevated void content decreases interlaminar shear strength and fatigue life, potentially causing premature structural failure during service or failure to satisfy aerospace certification standards.

4.2.2 Uneven Pressure Distribution:

Uneven pressure distribution occurs due to incorrect placement of breather materials, wrinkles in the vacuum bag, or geometric complexity of the mold. These issues can lead to localized differences in compaction pressure, causing resin-rich or resin-starved areas, fiber misalignment, and variations in laminate thickness [10].

Studies by Ma et al. (2020) [10] indicate that complex geometries and sharp corners are particularly vulnerable to uneven pressure distribution during vacuum bag-only prepreg processing. This can result in microstructural defects, including corner thinning, warpage, and dimensional inconsistencies. The research underscores that these pressure irregularities are significant contributors to defects in contoured aerospace laminates, recommending debulking procedures and mold design modifications to address these challenges.

Immediate Consequences: Localized flaws such as resin pooling, dry areas, and thickness variations often require rework or lead to scrapped parts [10].

Downstream Consequences: The resulting stress concentrations and fiber misalignment reduce load-bearing capacity, heighten the risk of delamination, and undermine the fuselage's long-term durability [10].

4.2.3 Resin Pooling and Dry Spots:

Resin pooling denotes localized accumulations of excess resin, whereas dry spots are regions where the fibers are insufficiently wetted. Both defects generally arise from suboptimal resin-flow paths, improper port placement, or inadequate working time during infusion—conditions that become more pronounced in large or complex layups.

According to the CKN Knowledge in Practice Centre, all liquid composite molding (LCM) processes—including vacuum bagging—are vulnerable to flow-induced dry spots and pooling. These flaws are commonly traced to poor flow strategies, race tracking (where resin bypasses fiber regions), or premature resin gelation, and are well documented in industrial practice as principal sources of variability in composite part quality.

Immediate Consequences: Regions with dry spots or resin pooling frequently fail initial quality inspections, necessitating localized repairs or leading to part rejection.

Downstream Consequences: Insufficient fiber wet-out or excessive resin content lowers interlaminar strength and stiffness, heightening the likelihood of delamination and structural failure under service loads.

4.2.4 Voids and Porosity:

Voids are air pockets or trapped gas regions within the laminate that originate from entrained air during layup, dissolved moisture in the resin, or insufficient evacuation during vacuum application. Porosity exceeding 1–2 % markedly degrades the mechanical properties of composite laminates [11].

Recent studies demonstrate that both interlaminar and intralaminar void content rises sharply when porosity surpasses 1.5–2.0 %, typically due to inadequate vacuum pressure or moisture absorption during processing. These voids serve as crack-initiation sites and weaken the fiber–matrix interface, as verified by ultrasonic C-scan and metallographic analyses of aerospace-grade carbon/epoxy laminates [11].

Immediate Consequences: Elevated void content reduces short-beam shear strength and flexural modulus, frequently causing parts to fail mechanical property tests [11].
Downstream Consequences: Voids accelerate crack growth and moisture ingress, thereby shortening fatigue life and diminishing the long-term durability of fuselage structures [11].

4.2.5 Environmental Factors (Temperature and Humidity Variations)

Fluctuations in ambient temperature and humidity during layup and curing can modify resin viscosity, alter cure kinetics, and change the final cross-link density. Elevated humidity also promotes moisture uptake by the resin, increasing void formation and lowering the glass-transition temperature.

Aerospace polymers experience wide swings in temperature and humidity both during manufacture and in service. Studies show that uncontrolled environmental conditions can induce microcracking, elevate moisture absorption, and diminish stiffness and strength in composite structures—effects that are especially pronounced in large, non-autoclave-cured laminates.

Immediate Consequences: Variable cure, warpage, or incomplete polymerization often necessitate rework or result in part rejection.
Downstream Consequences: Increased moisture uptake and microcracking reduce long-term structural stability and mechanical performance, potentially complicating certification of the fuselage.

4.2.6 Staggering-Induced Stress Concentrations

Staggering refers to the deliberate offsetting of ply terminations in composite laminates to prevent continuous seams, which could otherwise serve as planes of weakness. However, improper staggering—characterized by insufficient gap widths, irregular stagger patterns, or abrupt ply drops—introduces localized geometric discontinuities. These discontinuities disrupt stress flow and lead to elevated strain concentrations (ε_{max}) and stress concentration factors (K_t) like those found around holes or notches [16].
Gaps between staggered ply ends create resin-rich zones with reduced fiber reinforcement. Under tensile or bending loads, these zones exhibit higher strains due to the stiffness mismatch between resin and fibers. For instance, Cairns et al. (1999) showed that gaps as small as 0.06 in. (1.5 mm) in a [0°] laminate increase strain concentrations by 12–18 % compared to a nominal, ungapped laminate.

Immediate Consequences: Premature matrix cracking during proof loading, leading to rework or part rejection. Failure to comply with ASTM D7137 (Compressive After Impact) standards due to localized weaknesses.

Downstream Consequences: Reduced fatigue life, with up to a 50 % decrease under cyclic loading caused by crack propagation at gap sites. Certification delays resulting from non-destructive evaluation (NDE) findings, such as ultrasonic detection of delamination.

4.3 Risk Assessment Methodology

A systematic, quantitative risk-assessment methodology is essential for ensuring the reliability and safety of composite-fuselage manufacturing, particularly when vacuum bagging is employed. Accordingly, this work adopts the 5 × 5 risk matrix, a structured and widely recognized framework for evaluating and prioritizing process risks by likelihood and impact.

4.3.1 5×5 Risk Matrix Framework

The 5×5 risk matrix is both a visual and analytical tool that allows teams to assess, compare, and prioritize risks by assigning each one a score across two axes: Likelihood (Probability) and Impact (Severity/Consequence). This degree of granularity enables a more detailed understanding of risk than simpler 3×3 or 4×4 matrices, which is particularly valuable in high-stakes aerospace manufacturing settings.

Likelihood (Probability) Scale

Score	Descriptor	Definition
1	Rare	Unlikely to occur; may happen only under exceptional circumstances.
2	Unlikely	Possible but not anticipated; has occurred in other contexts but not in this process.
3	Moderate	Could occur occasionally; has been observed at times in similar processes.
4	Likely	Expected under most conditions; has occurred repeatedly.
5	Most Likely	Anticipated in most cases, occurs frequently or continuously.

Impact (Severity/Consequence) Scale

Score	Descriptor	Definition
1	Insignificant	No measurable impact on part quality or safety; negligible effect on cost or schedule.
2	Minor	Requires minor rework; does not significantly affect performance or regulatory compliance.
3	Moderate	Noticeable degradation in part quality may necessitate substantial rework or result in limited failure.
4	Major	Significant functional loss or non-compliance; part may be scrapped or require major rework.
5	Severe	Catastrophic failure resulting in loss of structural integrity or safety poses a risk to program success or certification.

Risk Rating Calculation

Each identified risk is assigned to a Likelihood and Impact score based on process knowledge, literature, and historical data. The Risk Rating is then calculated as:

$$\text{Risk Rating} = \text{Likelihood X Impact}$$

- 1–4: Acceptable (Low Risk)
- 5–9: Adequate (Monitor)
- 10–16: Tolerable (Mitigation Required)
- 17–25: Unacceptable (Immediate Action Required)

Color coding is used in the matrix to visually distinguish risk levels: green (low), yellow (moderate), orange (significant), and red (critical)

4.3.2 Risk Assessment Table

The table below provides a structured assessment of the key risks associated with vacuum bagging in composite fuselage manufacturing. Each risk is evaluated using the 5×5 risk matrix framework, which assigns numerical values to both likelihood (probability of occurrence) and impact (severity of consequences) on a scale from 1 (lowest) to 5 (highest). The overall risk score is determined by multiplying likelihood and impact, supporting the prioritization of mitigation strategies.

Risk	Likelihood	Impact	Risk Score	Justification
Vacuum Bag leaks	4	5	20	Manual setup and leak testing are operator-dependent; leaks can cause scrapped parts or certification failure.
Uneven Pressure Distribution	4	4	16	Complex fuselage sections are vulnerable; leads to stress concentrations and rework
Resin Pooling/Dry spots	3	3	9	Operator experience and process design are key; can cause part rejection or localized repair
Voids and Porosity	3	4	12	Voids >2% can reduce shear strength by 10% per percent void; frequent in vacuum bag-only processes
Environmental Factors	3	2	6	Workshop conditions and lack of environmental control can lead to process variability and part inconsistency
Staggering/Ply Drops	3	4	12	NASA and recent studies show ply drops are critical sites for delamination and strength loss

Risk Matrix Visualization:

Impact → Likelihood ↓	Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)
Almost Certain (5)				Leaking of Vacuum bag/Imperfect Seal	
Likely (4)				Uneven Pressure	
Probable (3)		Environmental factors	Resin Pooling	Voids and Porosity Staggering	
Unlikely (2)					
Very Unlikely (1)					

Interpretation:

Vacuum bag leaks represent the most critical risk (score: 20) and require immediate and robust mitigation measures.

Uneven pressure distribution, Staggering and voids/porosity are classified as significant risks (scores: 12), necessitating focused process control strategies.

Resin pooling/dry spots and environmental factors are identified as moderate risks (scores: 9), highlighting the need for ongoing monitoring and procedural refinement.

This structured risk assessment facilitates the targeted allocation of resources and implementation of process controls, directly supporting the quality, safety, and certification requirements of composite fuselage manufacturing.

5. Integration of FMEA Methodology for Enhanced Risk Management

Failure Mode and Effects Analysis (FMEA) is a structured, quantitative method used to prioritize risks in composite fuselage manufacturing by assessing three key dimensions: Severity (S), Occurrence (O), and Detection (D). This approach is consistent with aerospace regulatory standards (FAA, EASA) and offers a systematic framework for identifying failure modes, evaluating their effects, and implementing targeted mitigation strategies. The following section presents the integration of FMEA into the vacuum bagging risk assessment, drawing on academic research and established industry practices.

5.1 FMEA Framework for Composite Fuselage Manufacturing

FMEA Scales:

Severity	**Score**	**Occurrence**	**Score**	**Detection**	**Score**
Insignificant (No impact)	1	Rare (<1% probability)	1	Almost Certain Detection	1
Minor (Aesthetic defect)	2	Unlikely (1–10%)	2	High Likelihood of Detection	2
Moderate (Rework needed)	3	Possible (10–30%)	3	Moderate Detection	3
Major (Structural defect)	4	Likely (30–60%)	4	Low Likelihood of Detection	4
Catastrophic (Part scrap)	5	Almost Certain (>60%)	5	Very Unlikely Detection	5

Risk Priority Number (RPN):

$$RPN = S \times O \times D \text{ (Range: 1–125)}$$

FMEA Table for Vacuum Bagging Risks

Risk	Failure Mode	S	O	D	RPN	Mitigation strategies
Vacuum bag leaks	Air ingress → voids (Vf >2%)	5	4	3	60	- Automated leak detection (ultrasonic/pressure decay sensors)
	→ Reduced interlaminar shear strength					Redundant sealing (double tape + silicone at joints)
Uneven Pressure	Localized resin pooling/dry spots	4	3	3	36	- Pressure mapping sensors + flow simulation (ANSYS/PAM-RTM
	→ Delamination under bending loads					- Standardized breather layout SOPs
Resin Pooling/Dry Spots	Incomplete fiber wet-out	3	3	2	18	- Resin flow simulation + metered dispensing systems
	→ 15–20% strength reduction					- In-process visual inspection (transparent bagging films)
Environmental Factors	Cure kinetics variability	3	3	4	36	- Climate-controlled workspace (20–25°C, <60% RH)
	→ Residual stresses/warpage					- Resin selection with extended pot life (Hexcel RTM6)
Staggering/Ply Drops	Improper ply staggering or abrupt ply drops	3	3	3	27	Optimized stagger patterns (Fibonacci sequence)

						- Laser-guided ply placement
	Local stress concentrations (σmax≥1.5nom max≥1.5σnom), delamination, reduced CAI strength					

5.2 Key Findings from FMEA

Critical Risks (RPN ≥ 40):
Vacuum bag leaks (RPN = 60) demand immediate mitigation due to their high severity (S = 5) and likelihood (O = 4). Implementation of automated leak detection systems significantly improves detectability (D = 3 → 1), thereby reducing the RPN to 20. Haschenburger (2023) demonstrated that automated leak detection reduces void content by 15–20 % in aerospace-grade laminates.

Moderate Risks (RPN 20–39):
Uneven pressure distribution (RPN = 36) can be effectively mitigated through the use of pressure sensors and simulation-based optimization of breather placement, in accordance with findings by Ma et al. (2020) [10].

Low Risks (RPN ≤ 19):
Resin pooling (RPN = 18) is addressed through flow simulation and comprehensive operator training, as recommended by the CKN Knowledge in Practice Centre (2021).

5.3 Continuous Improvement via FMEA

Integrating Failure Mode and Effects Analysis (FMEA) into composite fuselage manufacturing provides a structured methodology for risk management and process optimization [12]. The following expanded framework outlines a pathway for continuous improvement, supported by academic literature and industrial case studies.[13]

5.3.1 Data-Driven FMEA Updates

A data-driven FMEA approach ensures that risk assessments remain dynamic, adapting to real-world manufacturing outcomes. Through systematic collection and analysis of process and quality data, organizations can deepen their understanding of failure modes and adjust risk priorities accordingly.

Implementation:

a. Root Cause Analysis (RCA):

Post-process inspection data, such as ultrasonic C-scan maps identifying voids and porosity, are correlated with FMEA entries. Haschenburger (2021) demonstrated that linking vacuum pressure logs to defect locations enabled targeted enhancements in leak detection, resulting in a 15–20 % reduction in porosity in aerospace laminates [12].

b. Dynamic RPN Adjustment:

Severity, Occurrence, and Detection scores within the FMEA are updated routinely (e.g., quarterly) based on defect trends and process monitoring data. This dynamic approach aligns with advanced manufacturing risk prioritization frameworks. Hickmott et al. (2020) showed that refining process windows using porosity modeling and experimental results led to measurable improvements in composite part quality [13].

c. Workflow:

Defect data from NDE reports are mapped to FMEA failure modes through Pareto analysis, ensuring that high-priority risks are addressed with targeted mitigation measures [13].

By maintaining a data-driven FMEA, manufacturers ensure that risk management strategies are continuously refined, directly supporting reductions in defect rates and improvements in composite part quality [12]

5.3.2 Closed-Loop Feedback Systems

Closed-loop feedback mechanisms ensure that insights gained from automated process monitoring and operator experience are systematically integrated into the FMEA and corresponding risk mitigation strategies.

Implementation:

a. Operator-Driven Improvements:

Shop-floor feedback is regularly incorporated into FMEA updates. Ma et al. (2014) demonstrated that addressing operator-reported issues related to breather cloth alignment improved pressure uniformity, thereby reducing resin-rich zones and surface porosity [14].

b. Cross-Functional Reviews:

Routine FMEA review meetings—held monthly and involving design, manufacturing, and quality assurance teams—facilitate the discussion of defect trends and process improvements. This practice is widely recommended in advanced manufacturing literature [13].

c. Automated Data Integration:

IoT-enabled sensors monitoring parameters such as vacuum, temperature, and resin flow continuously feed real-time process data into FMEA systems. Haschenburger (2021) showed that integrating volumetric flow rate and infrared thermography data enhanced leak localization and reduced corrective action response times.

Closed-loop feedback ensures that both process data and human expertise are utilized to drive continuous risk reduction, promoting a culture of shared responsibility and sustained process improvement.

5.3.3 Integration with Lean and Digital Methodologies

Integrating FMEA with Lean, Six Sigma, and digital manufacturing methodologies enhances its effectiveness by embedding risk management within broader initiatives focused on quality and operational efficiency.

Implementation:

a. Six Sigma DMAIC:

FMEA supports the identification of critical-to-quality (CTQ) parameters and prioritization of process improvements, as demonstrated in aerospace applications by Ma et al. (2014) [14].

b. Statistical Process Control (SPC):

Detection controls defined in the FMEA are linked to SPC chart limits, enabling early identification of process drift and facilitating prompt corrective actions.

c. Digital Twin Integration:

Digital twins of the composite cure process can be integrated with FMEA to enable real-time risk assessment and virtual testing of mitigation strategies. Hickmott et al. (2020) demonstrated that digital modeling of porosity evolution informs FMEA updates and guides process window refinement [13].

Integrating FMEA with Lean and digital methodologies ensures that risk management remains proactive, data-driven, and aligned with best practices in advanced aerospace manufacturing.

d. Certification-Driven Improvement Cycles

Aligning FMEA updates with certification milestones ensures that risk management practices remain compliant with evolving regulatory requirements and industry standards.

Implementation:

a. Pre-Certification:

FMEA gap analyses are performed in accordance with FAA and EASA requirements, and detection controls are established for critical failure modes.

b. Post-Certification Monitoring:

In-service failures and audit findings inform updates to FMEA severity scores, with revised documentation submitted as part of annual review processes [13].

Certification-driven FMEA cycles ensure that risk management remains both proactive and adaptive, reinforcing ongoing compliance and enabling continuous process improvement across the entire product lifecycle.

Continuous improvement through FMEA is achieved by integrating process data, operator input, Lean and digital methodologies, and certification requirements into a dynamic risk management framework. This approach reduces defect rates, enhances product quality, and ensures both regulatory compliance and operational excellence in composite fuselage manufacturing.

6. Mitigation Strategies for Key Risks in Vacuum Bagging

The following section outlines evidence-based mitigation strategies for the principal risks identified in the vacuum bagging process used in composite fuselage manufacturing. Each strategy is derived from current research literature and established industry best practices, aiming to reduce both the likelihood and impact of process-related failures.

6.1 Vacuum Bag Leaks or Failures

Automated Leak Detection:
Implement automated leak detection systems, such as ultrasonic sensors or real-time pressure decay monitoring, to identify and localize leaks prior to resin infusion. Haschenburger (2023) emphasizes that advanced leakage detection methods, including those incorporating machine learning significantly enhance the reliability of vacuum bagging and reduce porosity, particularly in aerospace applications [8].

Redundant Sealing and Pre-Engineered Kits:
Utilize double-seal tape systems and apply silicone sealant at critical joints and corners. Both Haschenburger (2023) and operational practices at Airbus Operations GmbH underscore that redundant sealing and the use of pre-cut bagging kits effectively minimize operator error and lower the likelihood of vacuum leaks [8].

Operator Training and Standardization:
Establish standardized vacuum bagging procedures and deliver comprehensive operator training. Haschenburger (2023) notes that manual execution and leak detection are highly dependent on operator skill, with many quality issues originating at this stage. Therefore, structured training and procedural standardization are essential [8].

6.2 Uneven Pressure Distribution

Optimized Breather and Bagging Schedule:
Utilize computer-aided flow simulation to design optimal breather and flow media layouts that promote uniform pressure distribution, particularly in geometrically complex parts. Ma et al. (2020) show that strategic breather placement and a well-planned bagging schedule significantly reduce pressure gradients and related defects in contoured aerospace laminates [10].

Real-Time Pressure Monitoring:
Incorporate distributed pressure sensors within the vacuum bag to monitor compaction pressure throughout the cure cycle. Ma et al. (2020) advocate for real-time pressure monitoring as a critical quality assurance measure, particularly for identifying and correcting inconsistencies in complex components [10].

Standard Operating Procedures (SOPs):
Establish and enforce SOPs for breather placement and vacuum bagging to reduce operator-dependent variability and ensure process consistency. This approach is supported by findings from both Ma et al. (2020) [10] and Haschenburger (2023) [8]

6.3 Resin Pooling/Dry Spots

Resin Flow Simulation and Port Optimization:
Perform resin flow simulations to optimize the placement of inlet and outlet ports, minimizing the likelihood of race tracking or incomplete wet-out. Both Ma et al. (2020) and CompositesWorld (2025) emphasize that simulation-driven design effectively prevents dry spots and resin pooling [10].

Controlled Resin Application:
Utilize metered resin mixing and dispensing systems to maintain consistent resin viscosity and flow rates during infusion, thereby reducing the risk of localized resin excess or deficiency. This practice is standard in advanced composites manufacturing.

In-Process Visual Inspection:
Apply transparent bagging films and conduct in-process visual inspections to track resin front progression and detect potential dry spots during infusion. This approach aligns with the best practices outlined in CompositesWorld (2025)

6.4 Voids and Porosity

Pre-Layup Drying and Vacuum Hold:
Dry fibers and core materials in a controlled environment prior to layup and apply a vacuum hold or soak period before resin infusion to remove trapped air and dissolved gases. Ghiorse (1993) and Abraham et al. (2018) report that each 1 % increase in void content can reduce interlaminar shear strength by 7–10 %, underscoring the importance of void minimization [15].

Post-Cure Non-Destructive Evaluation (NDE):
Employ ultrasonic C-scan or X-ray CT after curing detecting and quantify voids, enabling targeted rework or rejection of nonconforming parts. This method is a standard quality assurance and control practice in aerospace composites manufacturing [15].

6.5 Environmental Factors

Climate-Controlled Workspace:
Maintain a controlled manufacturing environment with active temperature and humidity regulation to ensure consistent resin cure kinetics and reduce environmental variability. Both Haschenburger (2023) [8] and Ma et al. (2020) [10] highlight the critical role of environmental control in maintaining process consistency and part quality.

Resin Selection and Pot Life:
Choose resin systems with suitable pot life and cure characteristics for the prevailing environmental conditions to mitigate the risk of incomplete curing or premature gelation. This practice is widely recommended in composites processing literature.

Process Documentation:
Log environmental conditions during each manufacturing cycle to support traceability and facilitate root cause analysis in the event of defects. This approach is endorsed in both academic research and industry standards.

Staggering-Induced Stress Concentrations

Optimized Stagger Design:

Maintain minimum gap widths of 10× the ply thickness (e.g., 2 mm for 0.2 mm plies) to promote even stress distribution. Apply nonlinear stagger patterns (e.g., Fibonacci sequence) to prevent resonant stress accumulation.

Process Controls:

Utilize laser projection systems to achieve precise ply alignment within a ±0.5 mm tolerance. Perform in-process shearography to detect resin-rich zones prior to curing.

Material Adjustments:

Employ toughened epoxy resins (e.g., Hexcel® M21) with 50 % higher fracture toughness to mitigate matrix cracking. Introduce thin adhesive interlayers at stagger transitions to reduce interlaminar shear stresses.

6.6 Summary

This manufacturing report presents a comprehensive, research-based risk management strategy for the vacuum bagging process in composite fuselage fabrication. By systematically identifying, evaluating, and mitigating key process risks—such as vacuum bag leaks, uneven pressure distribution, resin pooling, void formation, and environmental variability, the report illustrates how evidence-based methodologies can be effectively integrated into advanced aerospace manufacturing.

The application of the 5×5 risk matrix and FMEA methodology enabled prioritization of risks based on their likelihood and impact, ensuring that the most critical threats to structural integrity and certification compliance were addressed first. Mitigation strategies were informed by current research and industry best practices, including automated leak detection systems [Haschenburger, 2023], simulation-optimized breather and resin flow layouts [Ma et al., 2020], real-time process monitoring, and climate-controlled environments. Continuous improvement was embedded through data-driven FMEA updates, closed-loop feedback, and integration with Lean and digital manufacturing methodologies, consistent with both academic and industrial frameworks [Hickmott et al., 2020; Ma et al., 2014].

Monitoring and review protocols such as in-process sensor arrays, non-destructive evaluation (NDE), and detailed data logging ensure that risk mitigation remains effective and adaptive throughout the production cycle. This integrated approach not only reduces defects and material waste but also reinforces regulatory compliance and operational excellence in composite fuselage manufacturing.

7. Bill of Materials

Part Number	Main Assembly	Component Name	QTY.	Remarks
1	Fuselage Components	E-Glass Prepreg	10 Yards	Substituted for S-Glass Prepreg due to Cost and Availability
2		NOMEX Core	1 Yard	
F1	Fixture Components	Mandrel	1	Is an Aluminum Tube of OD 5.5”
F2		Fixture Stands	2	Support the Weight of the Tube
F3		Closure Clamps	2	Help in Restricting Movement
C1	Curing Equipment	Oven	1	Will be placed in an Autoclave
C2		Autoclave Stand	1	Stand on which the Composite assembly will be placed
C3		Chemical Release Agent	1	Applied on the Mandrel for convenient release of composite post-cure
C4		Sealing Tape	1	Used to completely seal the package to induce vacuum
C5		2-Part Adhesive Epoxy Resin	1	Utilized to adhere the core to the composite

C6		Vacuum Bag	4	Each cure requires 2 layers of bags.
C7		Breather Cloth	2	
C8		Bleeder Cloth	2	
C9		Vacuum Bagging Kit	1	Includes a Thru-Bag Connector, The vacuum pump, tubes, sealant tapes, and pressure valves among other relevant parts.
M1	Miscellaneous Equipment	Gloves	12	Extra Capacity is necessary to comply with safety requirements
M2		Safety Glasses	4	
M3		Aprons/Lab Coats	4	
M4		Precision Cutter	4	Multiple Cutters can expedite the Manual Cutting process depending on manpower
M5		Water Jet Machine	1	For generating the Door Cutouts
M6		Acetone Solution	1	For Cleaning
M7		Swabs/Applicator Cloth	5	

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