THE INTEGRATION OF ACTIVE FLOW CONTROL DEVICES INTO COMPOSITE WING FLAPS

A Thesis
Presented to
The Academic Faculty

by

Abigail Kuchan

In Partial Fulfillment
of the requirements for the Degree
Master of Science in Mechanical Engineering

Georgia Institute of Technology
August, 2012

THE INTEGRATION OF ACTIVE FLOW CONTROL DEVICES INTO COMPOSITE WING FLAPS

Approved by:

Dr. Jonathan Colton, Advisor
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Steven Danyluk
School of Mechanical Engineering
Georgia Institute of Technology

Dr. Ari Glezer
School of Mechanical Engineering
Georgia Institute of Technology

ACKNOWLEDGMENTS

I would like to thank everyone at Georgia Tech who made this thesis possible. I would first like to thank Dr. Colton for giving me the opportunity to perform this research. Under his advisement, I have grown as a researcher, technical writer, and, most importantly, as an engineer. This research was funded by the Boeing-GT Strategic University Program in Manufacturing Technologies, with John Griffith (Boeing) and Steven Danyluk (Georgia Tech) as principal investigators. Thanks to Dr. Glezer for the opportunity to incorporate his active flow control device into a composite wing flap. Additionally, I would like to thank Dr. Glezer and Dr. Danyluk for their time and support as my thesis committee members. Special thanks are due to both Jordan Zeigenbein and Aaron Hoffman. Jordan who helped me at the start of my research, teaching me how to perform composites manufacturing and showing me the ropes of research at Georgia Tech. Aaron who helped me at the end of my research by assisting in the development of design concepts and hashing out ideas not only for the designs but also for my thesis. I would like to thank Dae-Han Sung and Jason Park who assisted me in my research over the summer semester. My classmates for their ideas and opinions on researching and writing a thesis. Lastly, I would like to thank my friends and family without whom this thesis might not have been completed. I am truly grateful for all of the input and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Delaying stall is always an attractive option in the aerospace industry. The major benefit of delaying stall is increased lift during takeoff and landings as well as during high angle of attack situations. Devices, such as fluidic oscillators, can be integrated into wing flaps to help delay the occurrence of stall by adding energized air to the airflow on the upper surface of the wing flap. The energized air from the oscillator allows the airflow to remain attached to the upper surface of the wing flap. The fluidic oscillator being integrated in this thesis is an active flow control device (AFC). One common method for integrating any device into a wing flap is to remove a section of the flap and mechanically secure the device. A current trend in the aerospace industry is the increased use of fiber-reinforced composites to replace traditional metal components on aircraft. The traditional methods of device integration cause additional complications when applied to composite components as compared to metal components. This thesis proposes an alternative method for integration of the AFC devices, which occurs before the fabrication of wing flaps is completed and they are attached to the aircraft wing.

Seven design concepts are created to reduce the complications from using current methods of integration on composite wing flaps. The concepts are based on four design requirements: aerodynamics, manufacturing, maintenance, and structure. Four of the design concepts created are external designs, which place the AFC on the exterior surface of the wing flap in two types of grooved channels. The other three designs place the AFC inside the wing flap skin and are categorized as internal designs. In order for the air exiting the AFC to reach the upper surface of the wing flap, slots are created in the wing flap skin for the internal designs.

Within each of the seven design concepts two design variants are created based on foam or ribbed core types.

Prototypes were created for all of the external design AFC devices and the side inserted AFC and retaining pieces. Wing flap prototypes were created for the rounded groove straight AFC design, the semi-circular groove with straight AFC, and the side inserted AFC designs. The wing flaps were created using the VARTM process with a vertical layup for the external designs. The rounded groove and semi-circular groove prototypes each went through three generations of prototypes until an acceptable wing flap was created. The side inserted design utilized the lessons learned through each generation of the external design prototypes eliminating the need for multiple generations. The lessons learned through the prototyping process helped refine the designs and determine the ease of manufacturing to be used in the design evaluation.

The evaluation of the designs is based on the four design requirements stated above. The assessment of the designs uses two levels of evaluation matrices to determine the most fitting design concept. As a result of the evaluation, all four of the external designs and one of the internal designs are eliminated. The two remaining internal designs' foam core and ribbed variants are compared to establish the final design selection. The vertically inserted AFC foam core design is the most fitting design concept for the integration of an AFC device into a composite wing flap.

Chapter 1:

INTRODUCTION

A flap is one type of trailing edge device that is commonly used to delay the occurrence of stall on aircraft wings. Figure 1.1 shows an example of stall which occurs when the attached airflow on the upper surface of the wing loses energy and separates (Lan & Roskam, 1981). This separation will occur when the energy within the attached airflow is depleted before the trailing edge of the wing is reached. Stalls can be caused by reducing the relative air speed around the wing or increasing the angle of attack past the critical value. As the air speed decreases, the energy in the airflow is lessened, thereby causing a premature separation from the wing. When a wing is at a high angle of attack, energy is expended faster because of a pressure increase due to the angle. One of the major benefits of delaying stall is increasing the maximum coefficient of lift of a wing, resulting in the wing generating more lift at lower air speeds and higher angles of attack when compared to the unaltered wing.

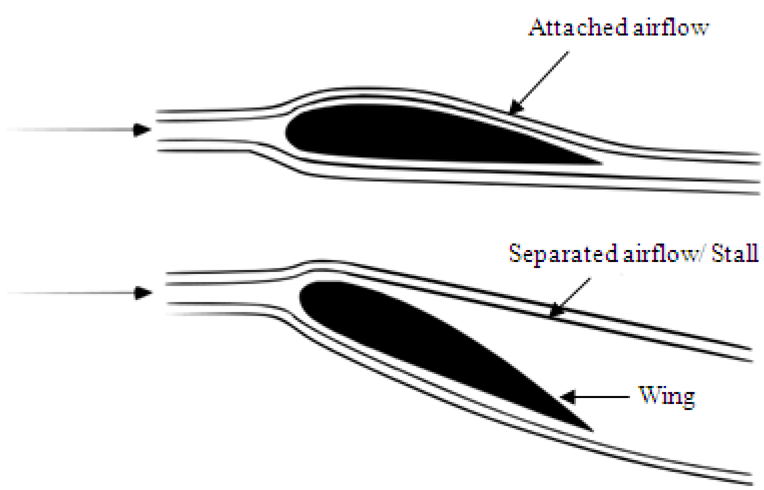


Figure 1.1: Wing stall (Interiot)

A fowler flap is a type of flap that can be added to an aircraft wing to change the wing camber and add energy to the attached airflow on the upper surface of the flap (Dole & Lewis, 2000). When engaged, the fowler flap extends backwards and then rotates as shown in Figure 1.2. When extended, the fowler flap can change the angle of the chord line, effectively altering the angle of the wing without tilting the wing (Lan & Roskam, 1981). The fowler flap is also considered an energy adder because air from the bottom surface of the wing flap will pass through the area between the original airfoil and the fowler flap, reenergizing the attached air flow over the flap.

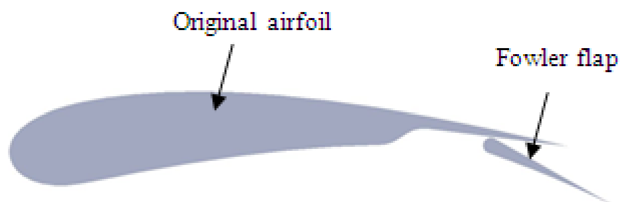


Figure 1.2: Fowler flap

Although the addition of flaps to aircraft wings delays stall, it is still present during high angle of attack and low air speed situations such as takeoffs and landings. The energy added to the upper surface of the flap by using a fowler flap can be enhanced with the addition of fluidic oscillators. A fluidic oscillator is a feedback-controlled sweeping jet which blows energized air back into the attached airflow on the upper surface of the wing. Fluidic oscillators were developed in the 1960's at the Harry Diamond Research Laboratory (Glenn, Hale, Lippincott, Longson, & Simmons, 1965). The energized air exiting the fluidic oscillator causes the air on the upper surface of the wing flap to remain attached, delaying stall. A fluidic oscillator is integrated into the fowler flap's upper surface near the leading edge. Figure 1.3 shows the location of a fluidic oscillator on the flap. The fluidic oscillator being integrated is an active flow control (AFC) device.

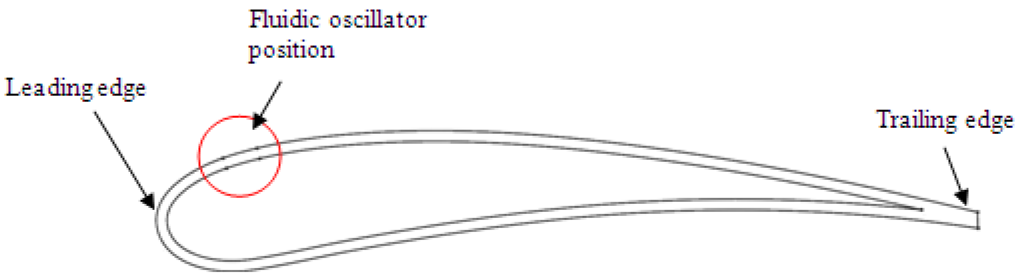


Figure 1.3: Wing flap with fluidic oscillator position

The energized air exits the fluidic oscillator as a sweeping jet. The sweeping jet occurs because the air flowing through the oscillator will randomly attach to one of the two walls present within the main airflow as chamber shown in Figure 1.4. When a pressure pulse is introduced perpendicular to the airflow, it will separate from its current location and attach to the opposite wall. The relocation of the airflow in the main airflow chamber causes the oscillating jet. The pressure pulses are normally generated by feedback tubes on either side of the main air corridor. A portion of the main airflow is diverted into one of the feedback tubes which allows for an oscillation free of external inputs (Gregory, Sakaue, & Sullivan, 2002).

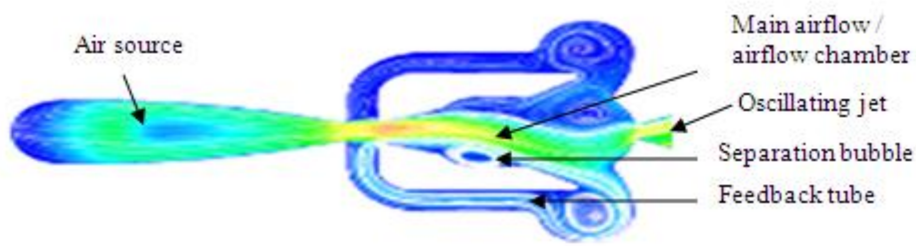


Figure 1.4: Basic fluidic oscillator (Oertel, 2010)

The fowler flaps, into which the fluidic oscillators will be integrated in this thesis, are composed of carbon-fiber epoxy composites. The frequent use of composites in aerospace applications comes from the composite's weight, strength, and fatigue advantages over standard metals (Strong, 1989). Since their introduction into the aerospace industry in the 1970's, carbon fibers have become the primary reinforcing material for wing, fuselage and empennage composite components on many aircraft (Mallick, 2008). The first all composite aircraft wing flaps came in 1982 on the AV-8B aircraft and were comprised of carbon fiber-epoxy composites (Mallick, 2008). The number of composite components on modern aircraft has continually increased culminating in the development of the Boeing 787. Figure 1.5 shows the Boeing 787 aircraft and its component materials.

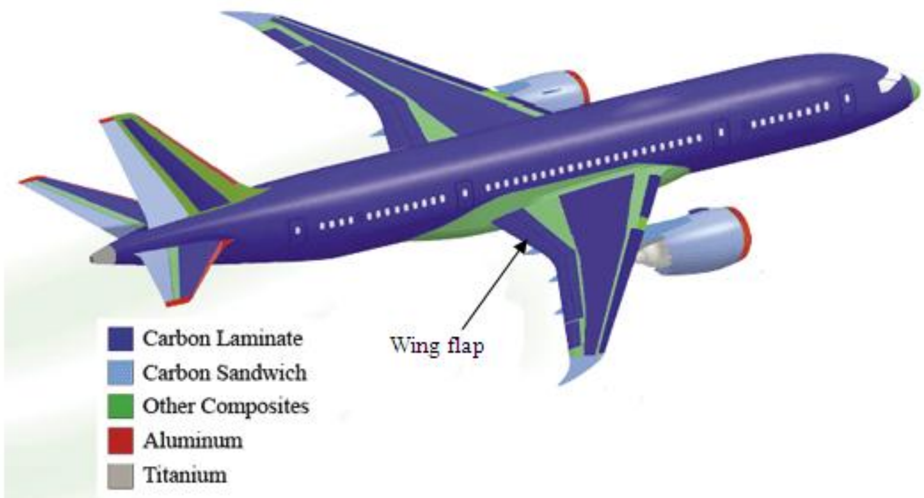


Figure 1.5: Boeing 787 component materials (Wright & Makowski, 2006)

The traditional methods of integrating a fluidic oscillator into composite wing flaps pose unique complications as compared to its metallic wing flap counterparts. A common method of device integration involves cutting holes into wing flaps and mechanically fastening the devices. Cutting holes into composite components causes the same structural issues as with metal components, but with composites adverse environmental effects and delamination between the layers of composite fibers must also be considered. This thesis poses an alternative method for device integration that incorporates the fluidic oscillators into the flap during the wing flap manufacturing and before the flap is placed on the aircraft wing. This method of integration will eliminate detrimental environmental effects because the carbon fibers will not become exposed when sections are removed from the components. Creating holes in the carbon-fiber layers prior to the infusion of the resin will allow each fiber to be properly encased instead of becoming exposed. The issue of delamination will also be resolved because there is no required machining once the wing flap is fabricated.

Composite wing flaps are commonly fabricated in sections which are assembled onto a frame. The composite sections are created using a precision composite tape layers that lay layers of prepreg composite material onto a flat mold. An autoclave is utilized to cure the components. This research employs the VARTM layup process without an autoclave because neither a composite tape layer nor an autoclave is available for use. Instead, a continuous-skin wing flap with sections removed for AFC integration is created with a hand layup process.

The alternate integration methods for the fluidic oscillators developed in this thesis were based upon four primary design specifications: aerodynamics, manufacturing, maintenance, and structure. The aerodynamic requirement is crucial to a successful design because the overall integrated system needs to fly. The manufacturing specification refers directly to how a prototype of the wing flap can be fabricated and assembled with the fluidic oscillator. The maintenance design consideration takes into account the functionality of the AFC over the life span of the wing flap. The final design specification is structure. The structural stability of any component on an aircraft is vital in maintaining flight readiness. These four design specifications are used to create seven unique designs which satisfy the original objective of integrating the fluidic oscillator into a composite wing flap. Of the seven designs, four are external designs which place the fluidic oscillator on the exterior profile of the wing flap and three of them are internal which place the oscillator within the wing flap skin. Each design concept has a foam core and ribbed variant within them.

Chapter 2 includes the theoretical background on airfoil aerodynamics, composites manufacturing, and stress concentrations. The airfoil aerodynamics overview discusses the occurrence of stall and two main techniques for delaying or eliminating it. The composite manufacturing discussion details the basics of prepreg layup techniques, resin transfer molding (RTM), and vacuum assisted resin transfer molding (VARTM). The stress concentrations overview provides guidelines for identifying and reducing areas of high stress concentrations within the composite wing flap. Chapter 3 details the seven design concepts created to satisfy the aerodynamics, manufacturing, maintenance, and structure design requirements. The designs are broken into two main categories, the external designs and the internal designs. Within each design, the option of a foam core or a ribbed design is discussed. Each design is discussed in detail, highlighting the governing design requirements. Chapter 4 discusses the prototypes created for the AFC devices and the wing flaps. The prototypes assist in the refinement of the designs as well as the ease of manufacturing utilized in the design evaluation. Chapter 5 analyzes the design concepts to determine the most fitting concept. The designs are first analyzed within the categories of foam core and ribbed designs. Two levels of evaluation matrices are utilized and discussed to determine the best design from each core option. The top two designs from each core option are compared head to head to determine the most fitting design concept. Chapter 5 discusses the conclusions drawn from the design evaluation. Further work is also suggested for the continuation of this research.

Chapter 2:

BACKGROUND

There are four main design requirements for the integration of active flow control (AFC) devices into composite wing flaps: aerodynamics, manufacturing, maintenance, and structure. Each of the requirements is essential to the functionality of both the wing flap and the active flow control device. The benefits of adding the device can be recognized once a general knowledge of airfoil aerodynamics, composite manufacturing and stress concentrations is attained. An examination of basic aerodynamics is conducted to gain an understanding of stall, when it occurs, and why delaying it is beneficial. To be able to integrate the active flow control device into a composite wing flap, some basics of composites manufacturing are examined. The wing flap can then be adapted to accommodate the device insertion without performing damaging modifications to the composites. The integration of the AFC devices requires that the original wing flap geometry be modified. An analysis of the modifications to the wing flap will determine any points of structural instability that may lead to premature failure of the wing flap. This chapter explains the background information for the design requirements and how it applies to the integration of active flow control devices into composite wing flaps.

2.1 Airfoil Aerodynamics

The aerodynamic flight characteristics of aircraft wings are set by the wing's primary airfoil and any additional devices attached (Cowley & Levy, 1920). When an airfoil is placed into an airflow, the airfoil's lift, drag, and stall characteristics can be examined. Understanding the stall characteristics determines the flight limitations of the airfoil because the stalling of a wing causes it to stop producing lift (Lan & Roskam, 1981). Stalling occurs when the attached airflow of boundary layer on the upper surface of the wing flap separates from the surface. If the airfoil stall limitations do not meet the specific needs of the aircraft, stall control devices can be added to modify the wing characteristics. The seamless combination of airfoils and stall control devices is important to the efficiency and functionality of the aircraft wing (Lan & Roskam, 1981). Two of the most common stall control device categories are high coefficient of lift devices and boundary layer control devices.

2.1.1 Boundary Layers

A fluid flow around an immersed airfoil induces boundary layers on the surfaces of the wing, which determine the stalling characteristics and maximum lift of the wing (Dole & Lewis, 2000). A boundary layer occurs because the fluid close to the immersed surface moves slower than the surrounding airflow due to the effects of viscosity (Street, Watters, & Vennard, 1996). Figure 2.1 shows an example of a laminar boundary layer on a flat surface. The particles of air closest to the surface have approximately the same velocity as the surface (Dole & Lewis, 2000). As the distance from the surface is increased, the velocity of the particles increase until the free stream velocity is matched. The thickness of the boundary layer is determined by the distance from the surface where 99% of the free stream fluid flow velocity is reached (Street, Watters, & Vennard, 1996).

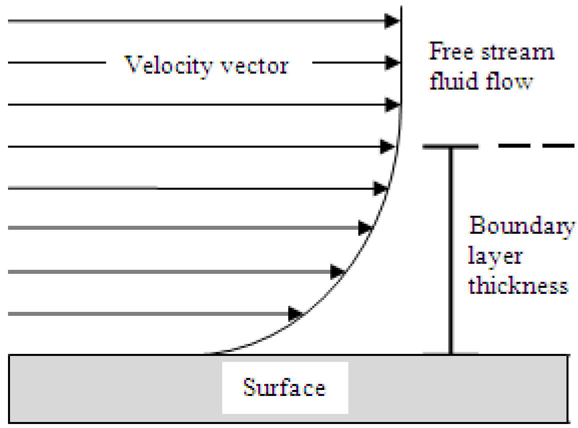


Figure 2.1: Laminar boundary layer

For an airfoil immersed in free flowing air, the upper surface boundary layer dictates the stall characteristics of the wing. Along the length of the airfoil, the boundary layer experiences pressure gradients which are not normally seen in flat surface boundary layers (Street, Watters, & Vennard, 1996). The two pressure gradients along the top surface of the wing are considered either favorable or adverse. As the air passes over the top surface of the wing, the flow accelerates due to Bernoulli's principle causing a favorable pressure gradient. Once the flow passes the point of minimum pressure, the adverse pressure gradient reduces the velocity of the flow and increases the static pressure (Dole & Lewis, 2000). The airflow must expel more energy to counteract the effects of the adverse pressure gradient to continue along the surface of the airfoil. If the energy within the airflow is depleted before the trailing edge is reached, the airflow will separate from the wing surface, causing the wing to stall and lose lift (Lan & Roskam, 1981). The stall can be as simple as a dip in the aircraft nose, a more serious spin, or an unrecoverable deep stall.

Stalls can be caused by reducing the relative air speed around the wing or increasing the angle of attack past the critical value. As the air speed decreases, the energy in the airflow is lessened causing a premature separation from the wing. The stall speed of an aircraft is critical during low speed flight such as takeoffs and landings because the stall may be unrecoverable due to altitude (Dole & Lewis, 2000).

2.1.2 Angle Of Attack

The angle of attack of an airfoil is defined as "the acute angle between the relative wind and the chord line of the airfoil (Dole & Lewis, 2000)." The chord line, shown in Figure 2.2, is a straight line that connects the leading and trailing edges of an airfoil. When the chord line is parallel to the ground, it is said to be at a 0° angle of attack. As the leading edge of the wing elevates, the angle of attack increases generating more lift. The angle that generates the maximum lift is referred to as the critical angle of attack. Any further increase in the angle of attack from this point will result in a decrease of lift due to stall (Dole & Lewis, 2000).

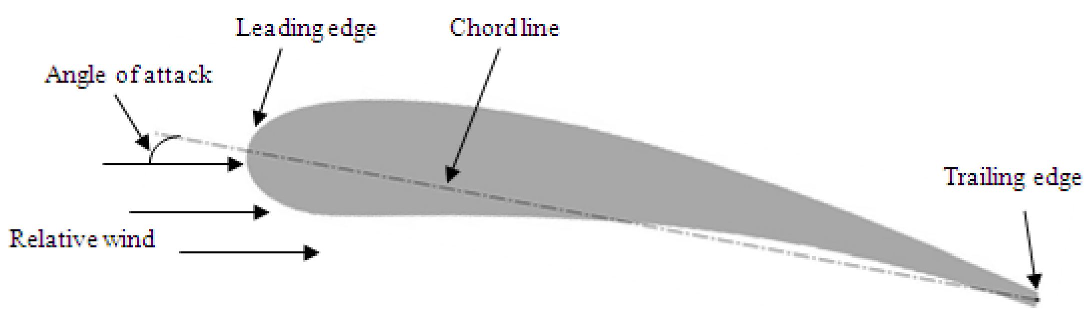


Figure 2.2: Angle of attack

As the angle of attack of an airfoil is altered, the point of minimum pressure will change locations along the upper surface of the airfoil. An increase in angle of attack will increase the negative pressure on the upper surface of the wing and increase the positive pressure on the bottom surface (Denker, 2008).The intensity of the negative pressure along the top surface will cause the boundary layer to begin separation at the trailing edge. As the separation at the trailing edge moves toward the leading edge, the lift generated by the wing will begin to reduce and eventually the wing will completely stall (Dole & Lewis, 2000). Figure 2.3 shows a separated airflow from a wing which causes stall.

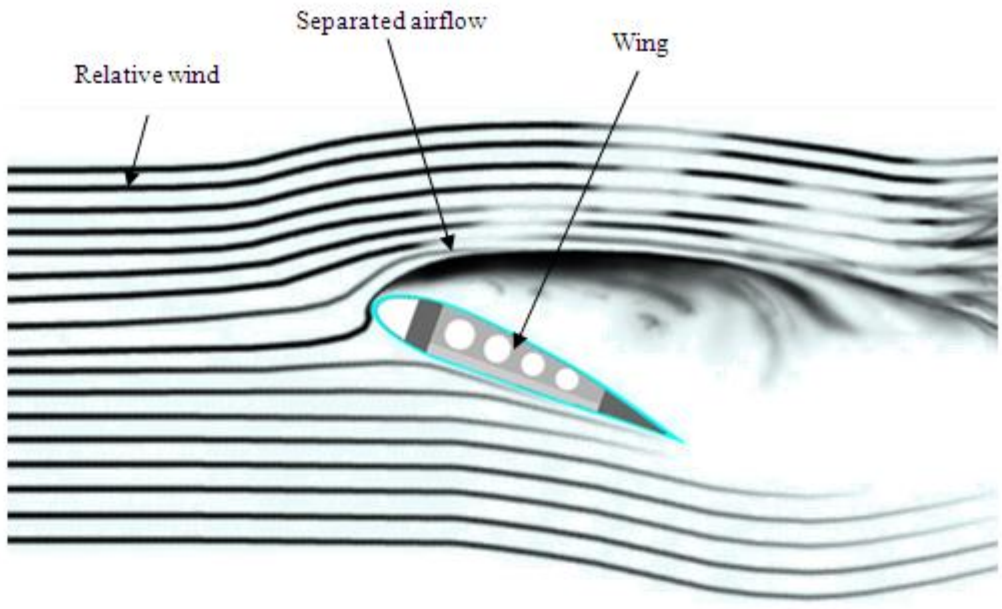


Figure 2.3: Airflow separation over a wing (Cislunar Aerospace, 1999)

2.1.3 Stall Control Devices

There are several different techniques used to delay the occurrences and severity of stall in wings such as the addition of stall control devices. Two of the most common stall control device categories are high coefficient of lift devices and boundary layer control devices. These devices can assist both in high angle of attack situations and lower air speed situations (Dole & Lewis, 2000). The main benefits of delaying stall on aircraft wings are the increased lift and continuous control during low air speed or high angle of attack situations.

High coefficient of lift devices are used to delay or alter the stall characteristics of an airfoil with the intention of generating more lift. There are two main types of high coefficient of lift devices, leading edge devices and trailing edge devices. Both types of devices enable an aircraft to take off and land at lower airspeeds because they generate greater lift than the original wing. The function of high coefficient of lift devices is to generate more lift by either changing the effective camber of the wing or adding energy to the upper surface boundary layer (Dole & Lewis, 2000).

The angle of attack of a wing is determined by the chord line which connects the leading and trailing edges of the wing. The addition of leading and trailing edge devices can change the angle of the chord line by relocating the leading or trailing edge, effectively altering the angle of attack without tilting the original airfoil (Lan & Roskam, 1981). By effectively changing the angle of attack of the wing, the main body of the wing can remain at an angle of attack of 0° but the angle of attack for the entire wing is no longer at 0°. Adding energy to the upper surface of the wing will reenergize the boundary layer allowing it to remain attached to the wing for a longer period of time, delaying stall. The leading and trailing edge devices can be designed to redirect the higher energy air from the lower surface of the wing to the lower energy upper surface boundary layer (Dole & Lewis, 2000).

Three common leading edge devices are slots, flaps, and slats. The slot, shown in Figure 2.4: (A), is created by separating the original airfoil into two pieces leaving a small gap between them. The purpose of the slot is to allow air from the bottom surface to pass through the wing and into the boundary layer of the upper surface (Lan & Roskam, 1981). The leading edge flap, shown in Figure 2.4: (B), is created by hinging the front section of the wing and allowing it to rotate. The rotation can either be fixed on a pivot point or the flap can extend forward then rotate. The leading edge flap changes the effective camber of the entire wing by relocating the leading edge (Lan & Roskam, 1981). The slat, shown in Figure 2.4: (C), is a secondary airfoil located at the leading edge that provides both a camber change and an addition of energy to the boundary layer. When extended, the slat reveals a small gap similar to the slot and it also relocates the leading edge like the flap (Lan & Roskam, 1981).

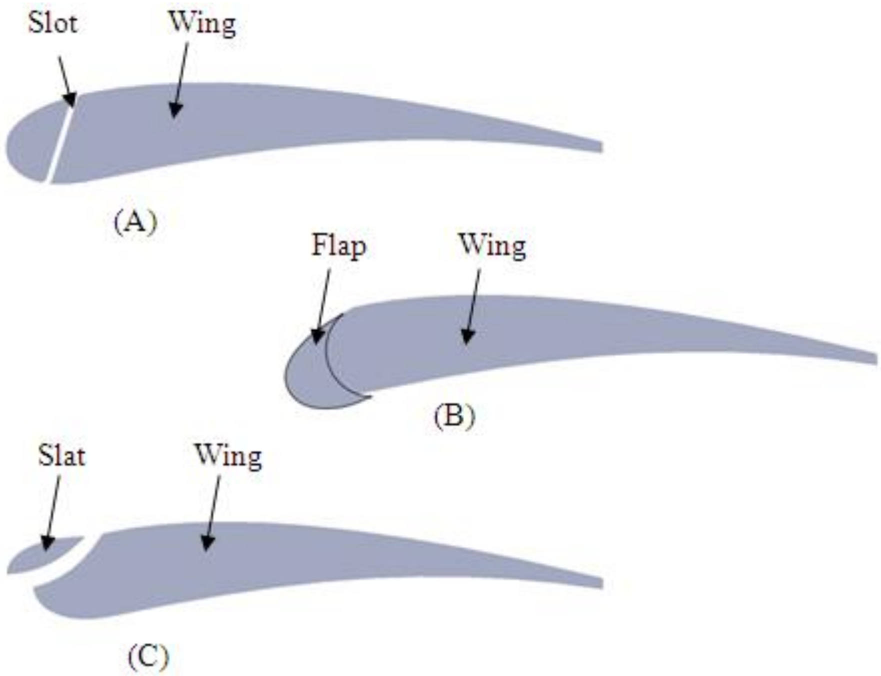


Figure 2.4: Common leading edge devices
(A) Slot
(B) Flap
(C) Slat

Trailing edge devices, also commonly known as flaps, are used to delay the occurrence of trailing edge stall. Three of the most common types of trailing edge devices include: plain flaps, fowler flaps, and slotted flaps. Plain flaps, shown in Figure 2.5: (A), are the most basic trailing edge device. The trailing edge of the airfoil is hinged about a contour cut in the airfoil. With the flap at its neutral point, the wing looks like the original airfoil. As the flap is rotated, the effective camber of the wing is altered because the chord line moves with the trailing edge of the flap (Lan & Roskam, 1981). The fowler flap, shown in Figure 2.5: (B), only employs the bottom section of the trailing edge of the wing as compared to the plain flap. When engaged, the fowler flap extends backwards and then rotates. This motion allows the fowler flap to be a camber changer, energy adder, and it also increases the effective area of the wing (Dole & Lewis, 2000).

The slotted flap, shown in Figure 2.5: (C), acts as both a camber changer and an energy adder. When the flap is rotated, a small gap opens allowing the air from the bottom surface to re-energize the upper surface boundary layer (Dole & Lewis, 2000).

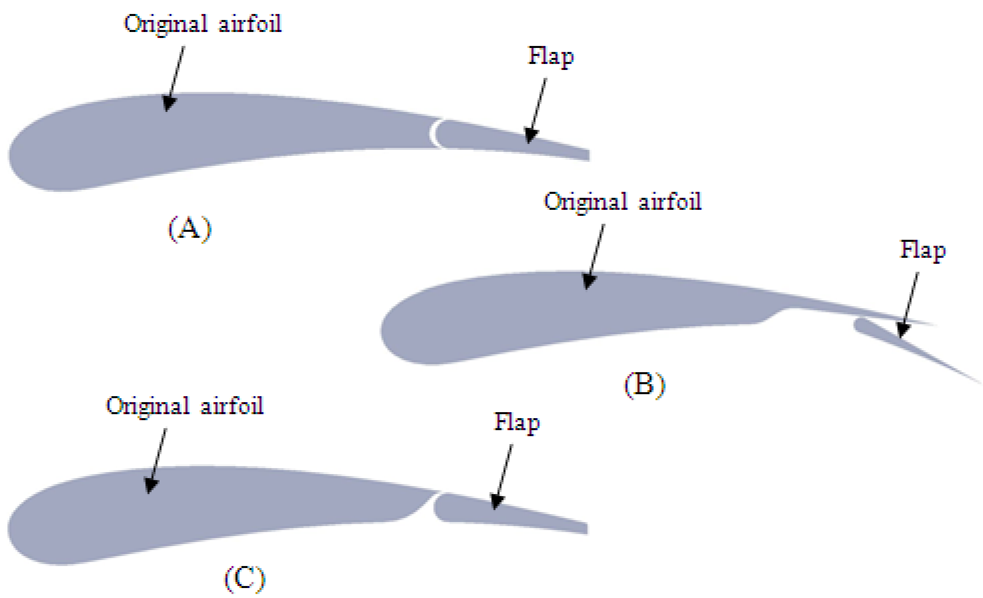


Figure 2.5: Common trailing edge devices
(A) Plain flap
(B) Fowler flap
(C) Slotted flap

Boundary layer control devices manipulate the energy within the boundary layer on the upper surface of the wing to modify the behavior of stall (Lan & Roskam, 1981). As stated previously, the separation of the airflow from the wing surface is due to a lack of energy in the upper surface boundary layer. Two distinctive approaches are used to modify the stall characteristics, the addition of suction devices and blowers. By manipulating the energy in the boundary layer with these two methods, the air will not separate at the same location and could delay or eliminate stall (Dole & Lewis, 2000). Boundary layer control devices can be used on any of the three main wing elements: leading edge devices, main wing bodies, and trailing edge flaps; although, they are most commonly used on trailing edge flaps.

Suction devices remove the low energy layer closest to the wing surface allowing the high energy areas of the boundary layer to flow past and remain connected to the surface of the wing (Lan & Roskam, 1981). A suction pump is utilized to extract the low energy layer through a porous wing skin. The faster moving air higher in the boundary layer will replace the air removed by the suction device (Dole & Lewis, 2000). The effects of the low energy layer removal are an increase in lift as well as a decrease in skin friction drag (Lan & Roskam, 1981).

Blowing is the addition of energized air to the boundary layer which allows the attached flow to remain affixed to the airfoil. The location of the blowing is most commonly at the leading edge of the flap (Dole & Lewis, 2000). Although this blowing can be natural such as with the slot and slat of the leading edge devices and the fowler flap and the slotted flap of the trailing edge devices, additional devices can be utilized to increase the effectiveness of flow re-energization. The lift generated by the wing can also be increased by the addition of blowing devices on flaps (Lan & Roskam, 1981).

This thesis focuses on the integration of active flow control devices which is a specific type of blower know as a fluidic oscillator. The fluidic oscillator is a feedback-controlled sweeping jet. The concept for modern fluidics was developed at Harry Diamond Research Laboratories in 1959 (Glenn, Hale, Lippincott, Longson, & Simmons, 1965). Fluidic components can be classified as sensors, amplifiers, and interface devices; each of these may be passive or active (Joyce, 1983). The fluidic oscillators used for this project have no moving parts, so the jet itself requires no additional power other than the pressurized air making it a passive system.

A fluidic oscillator functions due to the principle of wall attachment also known as the Coanda effect. When a fluid flows close to a wall or surface, the pressure differential will pull the flow towards the surface until it attaches (Meridian International Research, 2005). In the case of the fluidic oscillator, shown in Figure 2.6, the fluid flow will randomly attach to one of the two walls present. If a pressure pulse is introduced perpendicular to the attached airflow, a separation bubble will form. When the pressure within the bubble exceeds the pressure attaching the flow to the wall, the flow will detach and reattach to the opposite wall (Glenn, Hale, Lippincott, Longson, & Simmons, 1965). For fluidic oscillators, the pressure pulses are normally generated by feedback tubes on either side of the main chamber. A portion of the main fluid flow is diverted into one of the feedback tubes which allows for a self sustained oscillation (Gregory, Sakaue, & Sullivan, 2002).

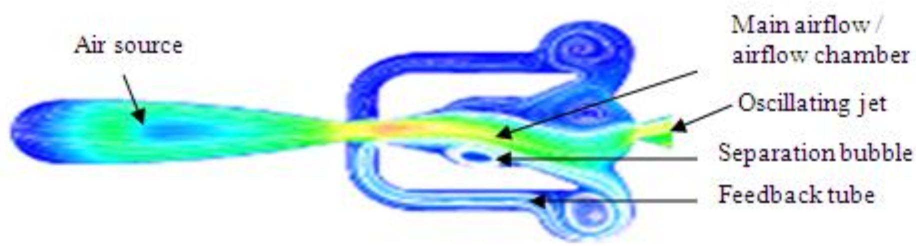


Figure 2.6: Basic fluidic oscillator (Oertel, 2010)

This section discussed airfoil aerodynamics. Understanding stall formation and characteristics is important when trying to delay it. Lift on a wing is generated because air flowing over the upper surface forms a boundary layer. When that boundary layer begins to separate, the wing begins to experience stall. The wing will continue to generate lift until the critical angle of attack is reached or the airflow around the wing is substantially decreased. High coefficient of lift devices and boundary layer control devices are two techniques utilized to delay the occurrence of stall in wings. High coefficient of lift devices add components to the leading and trailing edges to alter the angle of attack or add energy to the upper surface boundary layer. Boundary layer control devices either subtract low energy sections of the boundary layer or add high energy air to it. The device used for this thesis is a type of fluidic oscillator that adds energized air to the boundary layer, delaying the formation of stall.

2.2 Composite Manufacturing

Fiber-reinforced composites consist of high strength and high stiffness fibers surrounded by and bonded to a matrix. These types of composites are used extensively in the aerospace industry on both military aircraft and commercial aircraft. The use of composites in aerospace applications comes from the composite's weight, strength, and fatigue advantages over standard metals (Strong, 1989). Since their introduction into the aerospace industry in the 1970's, carbon fibers have become the primary reinforcing material for wing, fuselage and empennage composite components of many aircraft (Mallick, 2008).

Some of the more important advantages of carbon fibers are their tensile strength to weight ratio, high fatigue strength, and very low coefficient of linear thermal expansion (Mallick, 2008). Carbon fibers are elastic at normal temperature which makes them highly resistant to creep and fatigue. The fibers are also chemically inert except when in the presence of a strongly oxidizing substance (Strong, 1989). One disadvantage of carbon fibers as a reinforcing material is its cost. Due to its high cost, carbon fibers are not used in many commercial industries, but in the aerospace industry, the cost is less important than the weight savings (Mallick, 2008). Other disadvantages for carbon fibers are their brittleness and low impact resistance (Strong, 1989).

The purpose of the matrix material in a composite component is to protect and transfer stresses between the fibers (Strong, 1989). The matrix materials most commonly used in aerospace applications are thermoset and thermoplastic polymers. The mechanical properties of the matrix are one of the major considerations when choosing a matrix material. The ideal matrix material has high tensile modulus, high tensile strength, and high fracture toughness (Mallick, 2008). Along with the mechanical properties, the operational temperature of the composite must be examined when deciding between matrix materials. In a thermoset matrix, the polymer has chemically joined molecules that cross-link to generate a rigid network structure (Strong, 1989). The addition of heat to a thermoset matrix will not cause the bonds to break, but softening may occur at elevated temperatures. The molecules in a thermoplastic polymer are held in place by weaker secondary bonds such as van der Waals or hydrogen bonds which can be broken by the addition of heat. When heated, the molecules in a thermoplastic will break their bonds and reconfigure until solidification occurs during cooling (Mallick, 2008).

The combination of fibers and matrix into a defect-free part requires resin flow and compaction of the fibers, both of which require an application of pressure normal to the part (Mallick, 2008). The majority fiber-reinforced composites are fabricated using a thermoset matrix although other matrix materials can be used (Strong, 1989). Two common fiber-reinforced composite manufacturing techniques used in the aerospace industry are prepreg layups and resin transfer molding. The biggest difference between the two techniques is that the fiber and matrix are previously combined in a prepreg layup while the resin is infused into a dry fiber preform in resin transfer molding (Mallick, 2008). It is common for both of these techniques to be performed with the use of an autoclave, but its use is not always necessary for the resin transfer molding.

2.2.1 Prepreg Layups

The prepreg, or pre-impregnated fiber, process begins by wetting out dry fibers with a resin solution. The most common matrix for prepreg composites is epoxy resin although other thermoset and thermoplastic materials can be used. The sheets of fiber, which are most commonly unidirectional or in a multidirectional weave, are pulled through a resin, and solvent bath to wet all of the fibers. The fiber then travels through a heating chamber that begins the curing process in a controlled manner allowing the prepreg to be rolled and stored in a partially cured state, the B-state. The average shelf life of prepreg is approximately one week at 73º F. This shelf life can be significantly extended if the prepreg is stored as temperatures as low as 0º F. The average prepreg machine can produce sheets with widths between 1 in and 18 in. The thickness of a prepreg sheet ranges from 0.005 in -0.01 in with a resin content between 30% and 45% by weight (Mallick, 2008).

The predominant prepreg molding process in the aerospace industry is bag-molding (Mallick, 2008). Although the production rate is low, the quality of the final part is more important than the manufacturing time. The most important aspect of the bag-molding process is the evacuation of the excess resin from the fibers. Prepregs typically contains 42% resin by weight before the bagging process. If cured without resin loss, the final part would contain 50% fiber by volume, with the industry standard requiring 60% (Mallick, 2008).

The prepreg layers are laid up in the chosen angle orientation and stacking sequence either by hand for complex mold shapes or by a laminate tape layer. Additional layers are then added around the prepreg before the curing process can begin shown in Figure 2.7. The nonporous Teflon layers shown above the aluminum tool plate, above the second layer of bleeder, and above the aluminum caul plate are used to protect the molds from exposure to resin. The porous Teflon layers, shown above and below the laminate, allow the excess resin to flow from the laminate to the bleeder layers where it is absorbed.

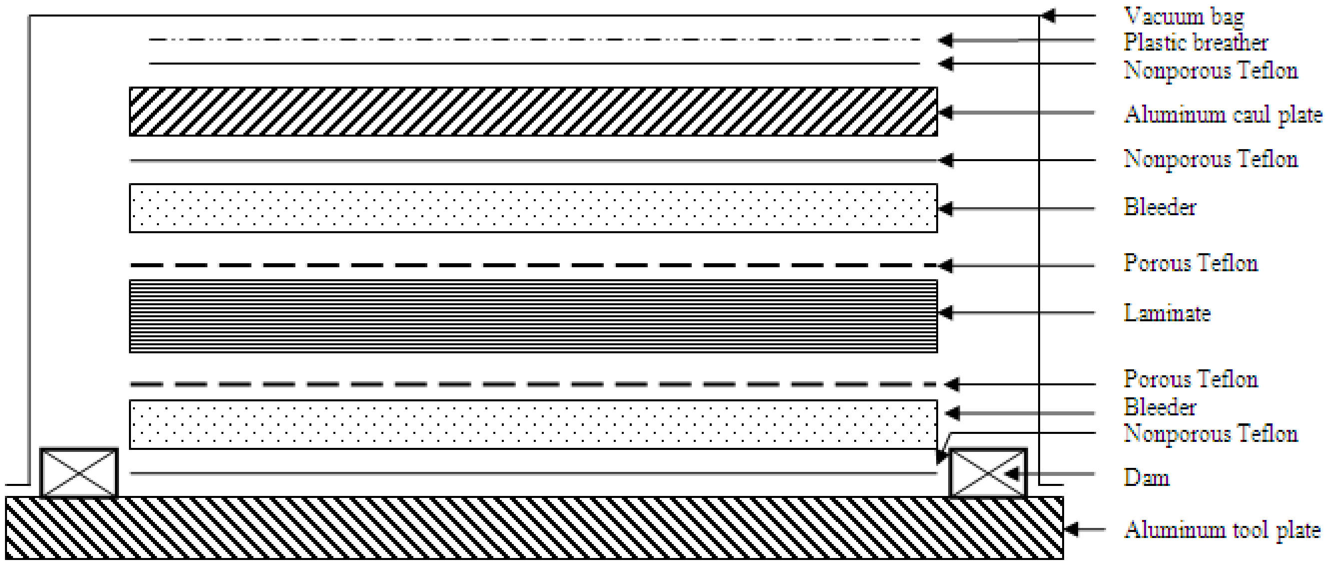


Figure 2.7: Bag-molding schematic (Mallick, 2008)

Once the stacking sequence is complete the entire system is covered with a heat resistant vacuum bag and placed in an autoclave. The evacuation of the excess resin begins when the curing process resumes (Mallick, 2008). As the resin is heated, it leaves its B-state, becoming a liquid which is capable of flowing. The combination of the curing and the compression of the fibers, caused by the external pressure of the autoclave, allow the resin to flow through the porous Teflon and into the bleeder cloth. The flow of the resin improves the volume fraction of the fibers, and removes the entrapped air and residual solvents, thereby reducing the occurrences of voids (Mallick, 2008).

Some of the major advantages to prepreg layup methods are the accurately controlled resin ratios, the uniform resin distribution, and an automated process to increase production time. Disadvantages to prepregs are difficult bagging operations due to complex shapes, the necessity of an autoclave, and the limited life span of the material (Strong, 1989).

2.2.2 Resin Transfer Molding

Resin transfer molding (RTM) is a dry fiber layup process where thermoset resins are introduced to the fibers in liquid form. In RTM, dry layers of fiber are placed in a two-sided, rigid mold that produces the desired part shape or preform. Once the mold is sealed, the resin is injected into the mold via intake ports between 10-100 psi. As the resin enters the mold, it forces out the air that occupied the space between the layers of preform encasing the fiber strands (Mallick, 2008). The mold can also be put under a vacuum to increases the speed of the RTM process and assists in the evacuation of the entrapped air (Strong, 1989).

Vacuum assisted resin transfer molding, or VARTM, is a variation of the standard RTM technique. VARTM is characterized by the use of a vacuum line, and commonly the use of a vacuum bag instead of a second mold half. The vacuum line, which is located on the opposite side of the component as the resin inlet line, serves two main purposes. The first purpose is to evacuate the air from the surrounding mold, between the fiber layers, and between the individual fibers of the preform material (Mallick, 2008). The vacuum causes the dry fibers to take the shape of the mold, while supplying a compaction force without the use of an autoclave. The second purpose of the vacuum line is to promote the flow of the resin material throughout the entire part.

VARTM is the manufacturing process selected to produce the prototypes for this research. The VARTM process can be utilized to create the wing flap as a single piece without the use of an autoclave or laminate tape layer. Although not commonly used, this VARTM process may prove to be an efficient out of autoclave manufacturing process for the creation of continuous skin wing flaps.

The VARTM layup process begins by arranging the dry fiber layers in the proper angle orientations. A layer of peel ply material is applied over the dry fibers so that the flow media is removable. The flow media is placed under the inlet and vacuum tubes, as well as over the part to assist in the resin flow through the fibers. The final layer of the setup is the vacuum bag which seals the whole system. After the apparatus is set up as shown in Figure 2.8, the air is evacuated from the system via the vacuum pump. The resin flows through the inlet tube into the dry preform material due to the pressure differential established by the vacuum. The consolidation pressure for the part is atmospheric pressure due to the near zero pressure inside the vacuum bag (Mallick, 2008).

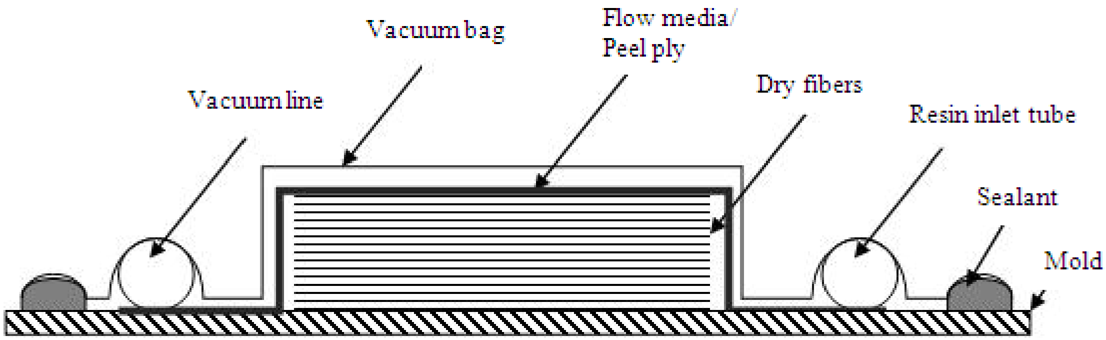


Figure 2.8: VARTM schematic

The quality of parts manufactured with VARTM depends almost entirely on the efficiency of the resin flow. Common defects in VARTM parts are dry pockets, void formations, and incomplete wetting of the fibers. Most of these defects are caused by pockets of trapped air that are not eradicated by the vacuum or the uniform flow of the resin. If the resin viscosity rises too quickly due to curing, the flow may be hindered causing defects. Another cause of defects is motion of the preform during the resin flow (Mallick, 2008). VARTM is most commonly used when making thermoset parts of differing size because the size of the part is only limited by the size of the mold being used.

Some advantages of VARTM over traditional RTM are higher part quality, shorter mold fill times, and use of a wider variety of polymer resins (Hall, 1998). The higher part quality comes from the consolidation pressure applied when the vacuum is initiated. The shorter mold filling times and the use of a wider variety of polymer resins come from the improved resin flow due to the vacuum line. A higher viscosity polymer is more likely to leave voids in an RTM part versus a VARTM part because the resin will not flow properly and wet out all of the fibers without vacuum assistance (Hall, 1998). The VARTM process forces the higher viscosity polymer to continue flowing through the part reducing the occurrence of defects.

This section discusses the basics of prepreg layup as well as VARTM as a variation of RTM without the use of an autoclave. Prepregs are most commonly used with simple geometry components because the process can be automated. An autoclave is required to bring the prepreg out of its B-state and begin the curing process. RTM uses dry fibers and molds to create more complex components. Resin is infused through the mold and the dry fibers to create the composite. With VARTM, a vacuum line is utilized to increase the compaction force on parts as well as increase the resin flow through the dry fibers.

2.3 Stress Concentrations

The structure of a wing flap is mainly composed of a wing skin and an internal support structure. The two main support structures inside of a wing flap are foam cores and ribs. Both internal support types transfer stresses from the wing flap skin to the spars. The spars attach the wing flap to the body of the main wing. Independent of the internal support selection, the wing flap skin needs to be able to handle the aerodynamic stresses and strains applied to it during normal flight. By applying a pressure of 0.75 psi to the lower surface of the original wing flap, a maximum stress of 4351.13 psi was seen for normal flight. The 0.75 psi value was the pressure difference between the top and bottom wing surfaces based on the wing area and the maximum takeoff weight of the Boeing 787. The properties of the carbon fiber-epoxy material being used show that the stress of 4351.13 psi exerted on the wing flap is well within the 210,000 psi limit of the material. When integrating the AFC devices, modifications to the wing flap geometry will be required. These modifications must be examined to determine if extra support is required to ensure that the wing skin will still be capable of carrying the stresses and strains without failure.

A wing flap without an active flow control device integrated into it is considered to have a uniform stress distribution. The thickness of the skin is continuous around the entire flap and there are no changes in geometry through the wing span. When integrating the active flow control devices, the external geometry of the wing flap will change. These changes can disrupt the original stress pattern causing stress concentrations (Gere & Timoshenko, Mechanics of Materials, 1997). The concentrations can cause high stresses in small areas of the wing flap which might exceed the limits of the wing skin material. Some examples of stress concentrators are holes, notches, and other sharp geometry changes (Gere & Timoshenko, Mechanics of Materials, 1997). Figure 2.9 shows a bar with a circular hole as a sharp geometry change and the increase of stress directly around that hole. The stresses around a small hole can be up to three times the normal stresses seen by the bar. Identifying the areas of stress concentration is important because of the repetitive loading and unloading of the wing flap. The cyclic loading of a wing flap can amplify the effects of a stress concentration causing cracks and other fatigue failure types during the wing flap's life span.

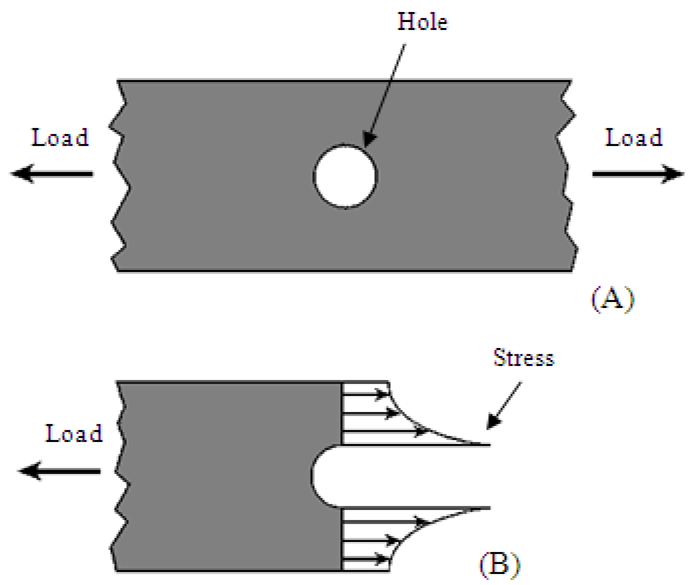


Figure 2.9: Example of a hole causing a stress concentration (Gere & Timoshenko, Mechanics of Materials, 1997)
(A) Bar with a circular hole
(B) Stress concentrations around the circular hole

Areas of stress concentrations can be reduced by smoothing sharp geometry changes or by adding reinforcement around the area. By smoothing the geometry, the stresses are able to more smoothly flow around the geometry change reducing the stress concentration intensity. The aerospace industry is proficient at reducing stress concentrations within composite components on aircraft. Stress concentrations will not be analyzed in this thesis because the industry is adept at handling them but the possibility of stress concentrations within the design concepts must be acknowledged. Reinforcement around the stress concentration area can assist in reducing failures because the increased material may raise the strength of the material beyond the stress encountered, thereby reducing the possibility of failure. The additional material may also help reduce the formation of cracks in the high stress area (Gere & Timoshenko, Mechanics of Materials, 1997). By recognizing the problem areas in the design stage, stress concentration failures can be reduced or eliminated once production has begun. This section discusses the identification and basic steps for reducing stress concentrations.

2.4 Chapter summary

This chapter discussed the basics of airfoil aerodynamics, composite manufacturing, and stress concentrations. An airfoil has a distinct set of stall characteristics which include critical angle of attack and stall speed. The stalling of an airfoil occurs when the upper surface boundary layer separates from the airfoil. This separation occurs because the energy required to keep the boundary layer connected to the wing is exhausted before the air reaches the trailing edge. The wing stall characteristics can be modified with the addition of leading edge devices, trailing edge devices, and boundary layer control devices. The leading and trailing edge devices affect the stall characteristics by either changing the effective camber of the wing by moving the leading or trailing edges or re-energizing the upper boundary layer with the addition of slots. Boundary layer control devices are utilized to change the stall characteristics by modifying the energy in the boundary layer. The evacuation of low energy layer of airflow from the boundary layer or the addition of energized air, both allow the air stream to remain attached to the wing, delaying stall. The device utilized in this thesis is a fluidic oscillator which adds energized air to the boundary layer using a self sustained oscillation.

Two major composite manufacturing techniques used in the aerospace industry are prepregs and resin transfer molding. Prepreg layup utilizes partially cured wet fibers laid into a bag-molding process which evacuates the excess resin. The production rate of the prepreg process is low but the quality of the final part high. The resin transfer molding process begins with dry fibers laid in either a two sided rigid mold or into a vacuum bag-molding process and resin is infused to encase the fibers. The VARTM process is a variation of resin transfer molding that uses a vacuum tube to assist in the resin flow. The VARTM process uses the vacuum bag process almost exclusively as opposed to two molds with RTM. Both the prepreg process and the

VARTM process are commonly completed with the use of an autoclave. The quality of a composite component in both processes is directly related to resin flow and compaction of the fibers.

Any modifications to the wing flap to integrate the AFC must be examined to determine if extra reinforcement is required to ensure that the wing skin will still be capable of carrying the stresses and strains within it without failure. One of the more important structural considerations is stress concentrations which are located at sharp geometry changes. Areas of stress concentrations can be reduced by smoothing geometry changes or adding reinforcement. The designs created to integrate the active flow control devices into composite wing flaps will address each of the aerodynamics, manufacturing, maintenance, and structural design requirements in Chapter 3. Each design concept will optimize one or more of the design requirements while attempting to satisfy the others.

Chapter 3:

DESIGNS

The integration of an active flow control device (AFC) into a composite wing flap is based upon four primary design specifications: aerodynamics, manufacturing, maintenance, and structure. The goal of this thesis is to determine a design concept which successfully incorporates the AFC device into a composite wing flap while attempting to optimize the design specifications. The aerodynamic requirement is crucial to a successful design because the overall integrated system needs to fly. If the aerodynamics of the wing flap is significantly compromised by the integration of the AFC, the benefits of adding AFC may be lessened or nonexistent. The manufacturing qualification refers directly to how the wing flap prototype is fabricated and assembled. The ideal level of difficulty for the manufacturing process would be the same as that of the wing flap without the AFC integrated. The basic method for manufacturing the wing flap prototype is the same for all of the designs because all the wing flaps are made of carbon fiber plain-weave fabric sheets. The differences between the manufacturing processes of the designs are due to the difficulty of the layup, the post processing required, and the assembly of the wing flap. The maintenance design consideration takes into account the functionality of the AFC over the life span of the wing flap. In order to repair a damaged AFC component, the AFC needs to be accessible as well as easily removed if it needs to be replaced. This removal ability comes directly from the manufacturing process where instead of fabricating the wing flap with the AFC already imbedded; the AFC is attached later, thereby creating an assembly. The final design specification is structure. The structural stability of any component on an aircraft is vital to maintain flight readiness. The wing flap with the integrated AFC needs to be comparable in strength to the wing flap without the AFC. The strength of the wing flap may be partially compromised by adding the AFC. Some methods for counteracting these effects are adding reinforcement or de-rating the wing flap. Each of the designs is geared toward distinct design specifications while seeking to accommodate the remaining requirements.

3.1 Design Overview

Figure 3.1 shows the AFC integration design tree that includes all of the major design branches within the Design chapter. The external and internal designs are the two main design categories to be examined. The external designs are broken into two sections based on the groove type which will seat the AFC. Within the rounded groove and semi-circular groove designs, an option for a straight AFC or a tilted AFC is examined. The internal designs category is broken into three sub sections: side inserted, vertically inserted, and attached. All of the design options highlighted symbolize the primary designs which are optimized based on either a foam or rib core type.

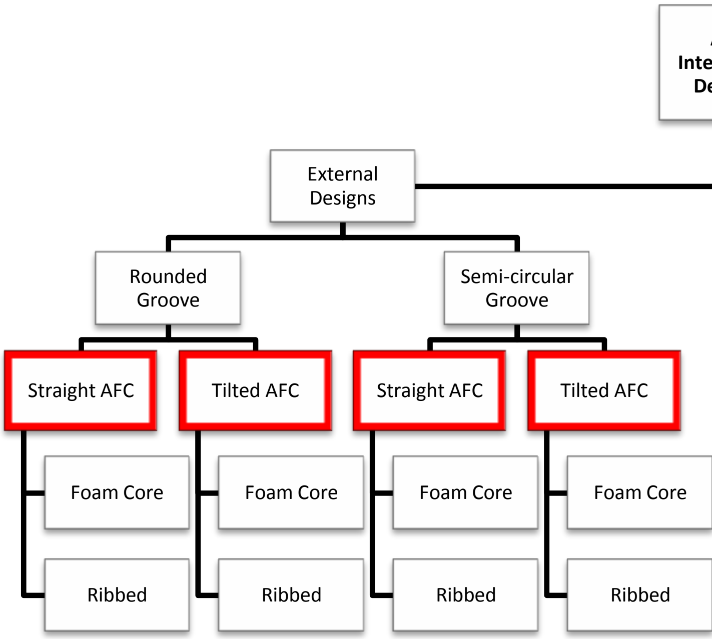


Figure 3.1: AFC integration design tree

Examples of the two main design categories can be seen below. The external AFC designs, shown in Figure 3.2: (A), place the AFC on the exterior of the wing flap in a grooved channel. The internal AFC designs, shown in Figure 3.2: (B), place the AFC inside the wing skin. It can be seen that the AFC for the external design is open to the free stream environment while the AFC for the internal design is encapsulated within the wing flap.

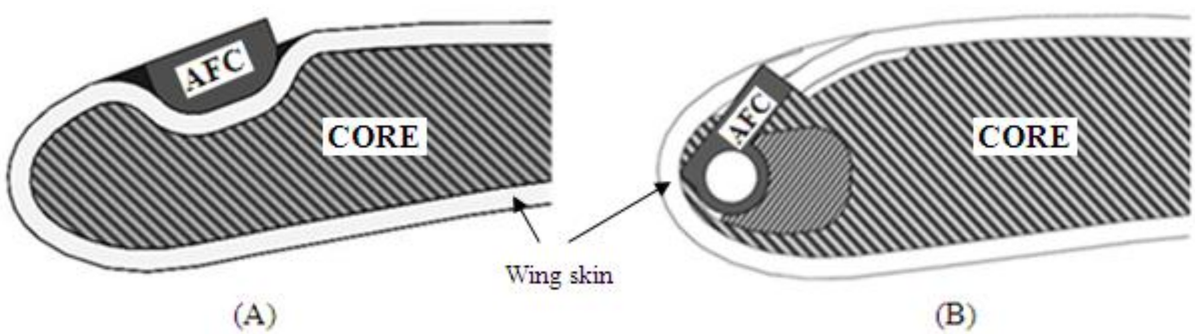


Figure 3.2: External and internal AFC design examples
(A) Example of an external design
(B) Example of an internal design

3.1.1 Core Selection

As shown in the design tree, all of the primary designs have two main variants within them, a ribbed core and a foam core. A rib serves as the primary chord-wise structural member in the wing flap. Ribs are a skeleton for the skin giving it shape and rigidity while also transmitting stresses from the skin to the spars. For all of the ribbed designs, the ribs are carbon fiber plates cut in the shape of the airfoil with other cut-outs pertaining to the fitment of the AFC. The major benefits of ribs are weight savings and component space considerations. Because the space between the ribs is open, monitoring sensors for the AFC and tubing can be easily inserted into the wing flap. Figure 3.3: (A) shows a wing flap supported by ribs shown while Figure 3.3: (B) shows the foam core. The foam core of a wing distributes the stresses of the skin within itself and then to the spars. The foam core also gives the wing flap shape and rigidity but its structure is throughout the entirety of the flap as opposed to being spaced out like the ribs. The major benefits of the foam core are the ease of manufacturing of the wing flap, impact resistance, and a more uniform distribution of aerodynamic loading from the skin to the structure. The aerodynamics for the wing flap will not be altered due to the core selection because the cores will not interface with the external airflow around the wing flap. No additional analysis on the weight, cost, or structural benefits of the core type will be performed in this thesis. The scope of this thesis is to develop design concepts to integrate the AFC devices into the composite wing flaps. The creation of the ribbed and foam core design variants allow for two distinct design options and assists in the development of the manufacturing processes.

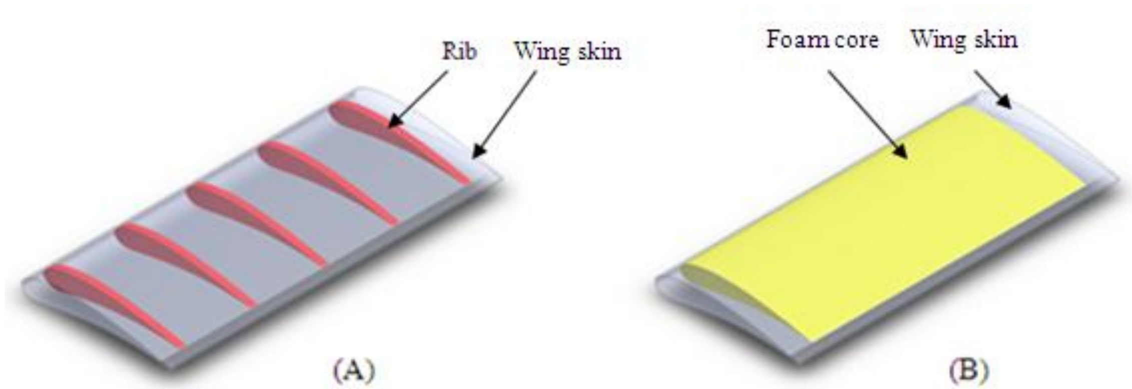


Figure 3.3: Wing flap core options
(A) Wing Skin with Ribs
(B) Wing Skin with Foam Core

3.1.2 Active flow control Devices and Aerodynamics

The AFC device being integrated into the composite wing flap is a fluidic oscillator which converts compressed air into oscillating jets, reducing airflow separation over the wing flap. The compressed air enters the AFC via an inlet tube; the jets exit the AFC on the active side through the exit ports shown in Figure 3.4. The inlet tube also functions both as a reservoir for the main air chamber and as the connection method between the AFC devices. There is an additional reservoir chamber located behind the main chamber and above the inlet tube. For all of the subsequent designs except the vertically inserted AFC design, the AFC devices will be chained together so that their combined length is equal to the span of the wing flap. The chained AFC devices will act as a single unit with a single inlet once integrated into the composite wing flap. The air exiting the AFC must be tangential to the wing flap skin to properly interact with the attached boundary layer.

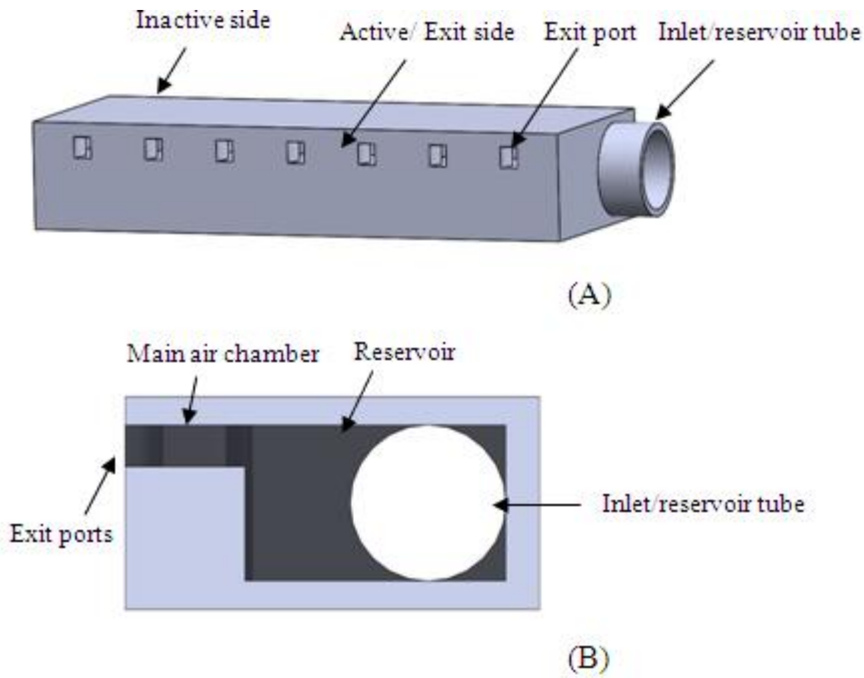


Figure 3.4: Fluidic oscillator (AFC)
(A) Isometric view of AFC
(B) Side view of AFC

The AFC is to be located on the top surface of the wing flap as shown in

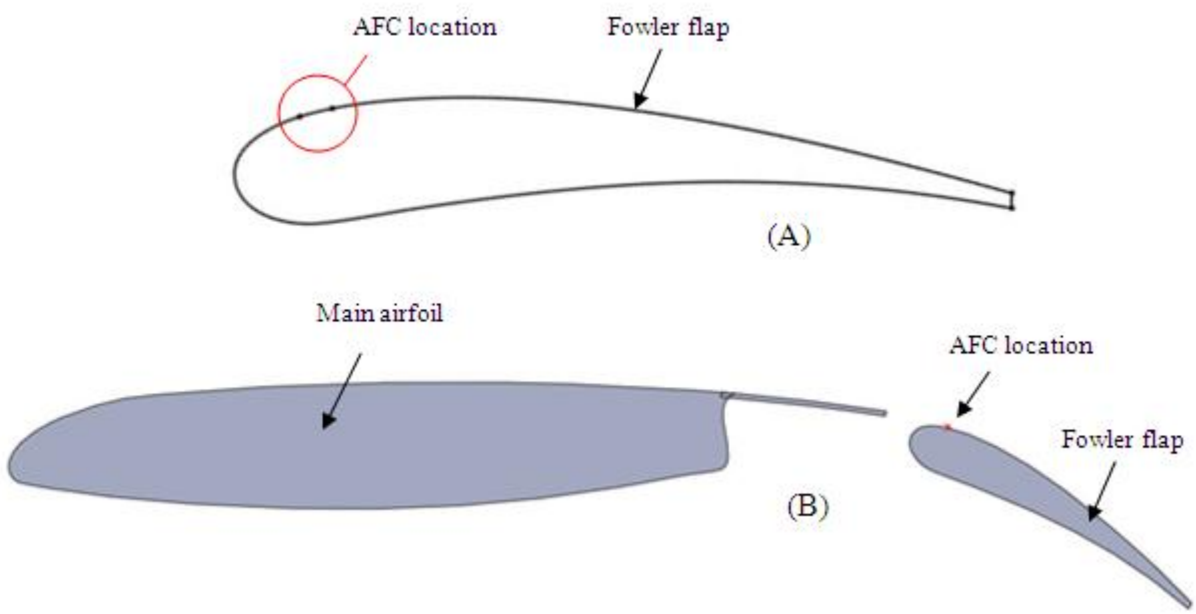


Figure 3.5: (A). The position is determined by the most effective aerodynamic location for the AFC device. The airfoil used for this thesis is part of a high lift wing acting as the fowler flap as

described in the Background chapter. Figure 3.5: (B) shows the main airfoil and the location of the AFC device on the deployed fowler flap.

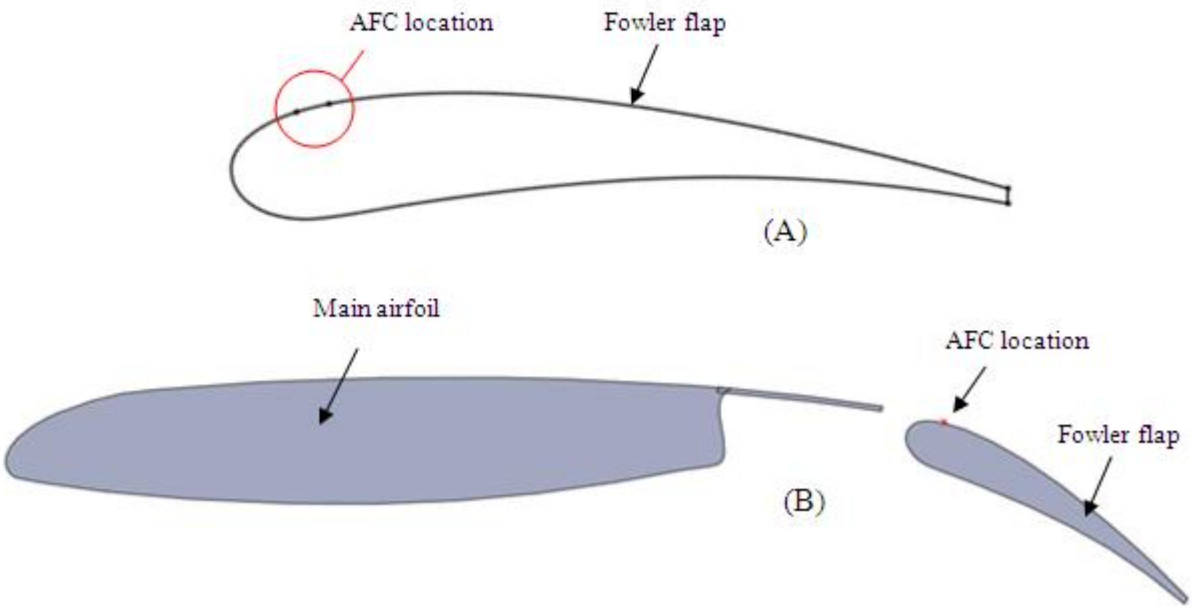


Figure 3.5: Fowler flap depicting AFC location
(A) Location of AFC on wing flap
(B) Deployed fowler flap with AFC location

3.1.3 Manufacturing

The manufacturing process used to determine the fabrication steps for each design prototype comes from the VARTM layup process. This process is defined by the use of dry carbon fiber layers that are infused with liquid resin in a vacuum bag system. The manufacturing steps for the design prototypes are shown in Figure 3.6. The eight steps shown cover all of the steps required for both the ribbed layup as well as the foam core layup.

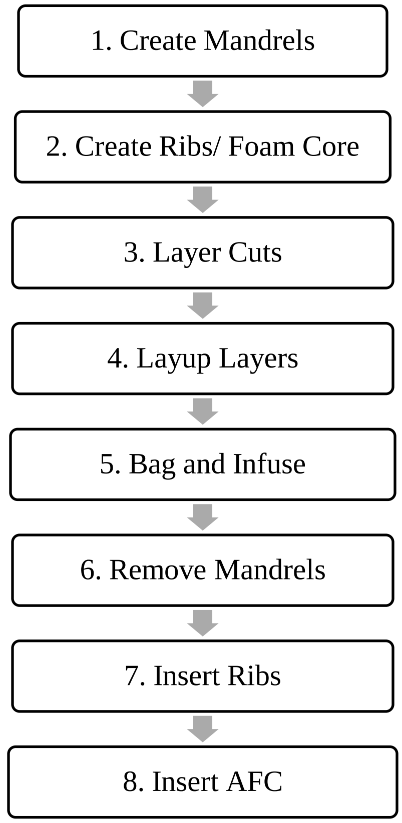


Figure 3.6: Manufacturing steps

The first step of the manufacturing process is the creation of the mandrels. All of the ribbed designs and some of the foam core designs will require removable mandrels to act as a mold for the carbon fiber layers. The mandrels can be fabricated using either a traditional machining process such as milling or CNC machining, or with a non-traditional process such as wire EDM cutting. The mandrels are made of aluminum and are coated in release agent so that neither the carbon fibers nor the epoxy matrix will remain attached once the curing process is complete. The specific geometry of the mandrels for each design will be discussed within the design section. The second step of the manufacturing process is to create the ribs or foam core. As stated previously, the ribs are cut from a carbon fiber plate, while the foam cores are created using a hot wire foam cutting machine or a CNC mill. The shape of the core corresponds to the geometry of the internal wing flap skin. Some of the designs require that sections of the core be removed for fitment of the AFC devices. These sections are removed at the time of core fabrication. The third step of the manufacturing process is layer cuts. To form each layer of the wing skin, a sheet of carbon fiber that is the width of the airfoil and the length of the outer contour of the wing flap must be cut. Some designs require additional cuts to form features and will be described in those design sections. Once the carbon fiber layers are prepared, they can be laid onto the mandrels, for the ribbed designs, or the foam cores to be infused with resin. The fifth step of the manufacturing process performs the vacuum bagging setup seen in Chapter 2 and infuses the resin. The wing flap is then cured until it is hard. The sixth step is to remove the mandrels. If the wing flap being manufactured is a foam core variant, the base foam core remains inside the wing skin because it has been cured at the same time as the carbon fiber skin, also known as being co-cured. For the ribbed designs, the entire inside of the wing flap is removed to prepare for the insertion of the ribs. The seventh step inserts, positions, and secures the ribs into their final locations. This step also includes any sub-assemblies that may be required before the final step of the manufacturing which is the insertion of the AFC. This final step includes all processes required to insert and secure the AFC, as well as to prepare the assembly for flight. The manufacturing of the wing flaps is unique for the ribbed and foam cores for all of the designs and therefore may require some or all of the manufacturing steps shown. The steps required for each design will be discussed in that design section.

3.1.4 Maintenance

To remain a viable design option, the AFC device must be removable from the wing flap and it must be modular so only the damaged section of the AFC device is replaced. The method used for fastening the AFC device to the wing flap is crucial when ensuring that it is removable. There are many methods of mechanical fastening but two alternatives to co-curing, which forms permanent bonds that cannot be removed without damaging components, are pin connections and stud connections.

Pins are a simple mechanical fastener. Pin connections insert a piece of material, or pin, through an opening in the component being secured and an opening in the base component to create a mechanical locking system (Society of Manufacturing Engineers, 2002). Figure 3.7 shows “Component A” inserted and connected to “Component B” with a pin. The pins can be any shape as long as the corresponding cut-outs are made to match. Pins can be inserted and removed as many times as necessary throughout the life spans of the components without any concern for the connection method weakening over time. This connection method can be removed by hand without the use of any kind of machining operation.

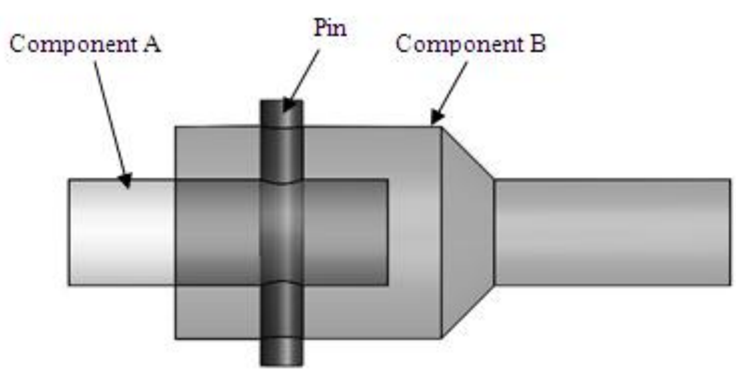


Figure 3.7: Pin connection method

The stud connection method is similar to the method used to connect LEGO® blocks together. For this connection method to work, one of the components being connected possesses studs while the other piece possesses corresponding sockets which will interlock. Figure 3.8 shows “Component B” with studs and “Component A” with the corresponding sockets. The studs fit within the sockets creating a bond that is strong enough to remain intact until deliberately removed. As with the pin connection method, the stud connection method will not have any weakening throughout the life spans of the two components due to connection and disconnection. The strength of the connection can be tailored to the application by resizing either the stud or socket. The separation of the connected pieces can be either done by hand or with the use of a basic lever depending on the strength of the bond.

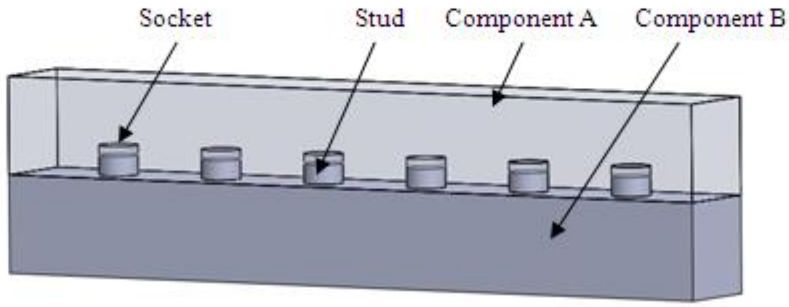


Figure 3.8: Stud connection method

Once integrated, the AFC can span the entire length of the wing flap making the modularity of the AFC important to the maintenance of the devices. The ability to replace only the damaged section of the AFC makes the maintenance more cost effective than replacing the entire wing flap length. The AFC devices are chained together using a modified stud connection method. Separating them does not require machining or any other damaging process. The ability of the AFC devices to chain together also allows for a single inlet source at one end of the chained assembly. The single inlet eliminates the necessity to feed each AFC individually which simplifies the designs and reduces the amount of tubing required to supply the devices with compressed air.

The maintenance procedures do not deviate between the ribbed and foam cores for the external designs because the AFC has no interaction with the cores. The maintenance for the internal designs will have distinct advantages and disadvantages based on the core selection because of the AFC's integration into the core of the wing flap. These advantages and disadvantages are related directly to the location and orientation of the AFC and will be discussed in the internal design sections.

3.2 External AFC Integration

All of the designs in this section place the AFC on the exterior surface of the wing flap in a grooved channel. The external designs are simple in concept and manufacturing. All of the external designs integrate the AFC on the exterior surface of the wing flap by co-curing the AFC and wing flap. The bond is permanent and should hold the AFC in place during flight but is very difficult to remove for repair. The simplicity in manufacturing comes from the continuity of the wing skin around the AFC. The wing skin is able to be laid up as a single piece that both begins and ends at the trailing edge of the flap. The external designs also require no additional layer cuts for the design. The core selection has no impact on any of the design specifications other than manufacturing for the external designs. For that reason, all of the external designs will be depicted with a foam core. The mandrels and rib designs will be described within each design concept section but no additional analysis will be performed at this time on the cores.

3.2.1 AFC Modifications

The AFC devices for the grooved designs are modified into two categories: the straight AFC and the tilted AFC. The straight AFC is left unmodified as seen in Figure 3.4. Its label "straight" refers to the top surface of the AFC which is a straight, horizontal surface. In order to integrate the straight AFC into the top surface of the wing without any vertically protruding features, the skin is raised to the level of the top surface of the AFC shown in Figure 3.9.

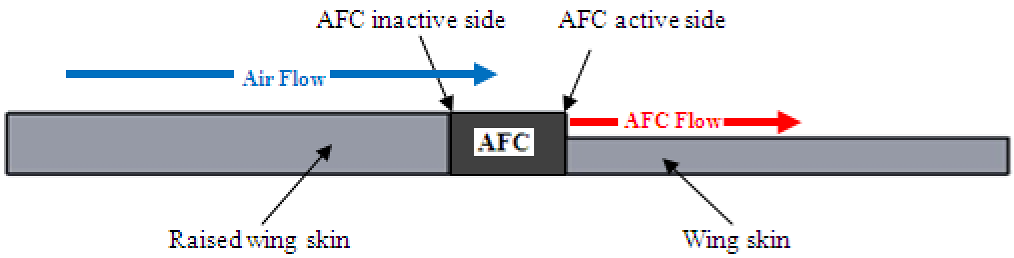


Figure 3.9: Straight AFC with raised wing skin

The second AFC design category is the tilted AFC shown in Figure 3.10. Unlike the horizontal top surface of the straight AFC, the tilted AFC has a slanted top surface which begins at the same elevation on the active side of the straight AFC and decreases until it reaches the height of the exit port bottom surface on the inactive side of the AFC. It can be seen in Figure 3.10: (B) that the main air chamber has been tilted at the same angle as the top surface of the AFC. The main air chamber changes from being parallel to the top surface to being horizontal so that it exits the AFC perpendicular to the active side.

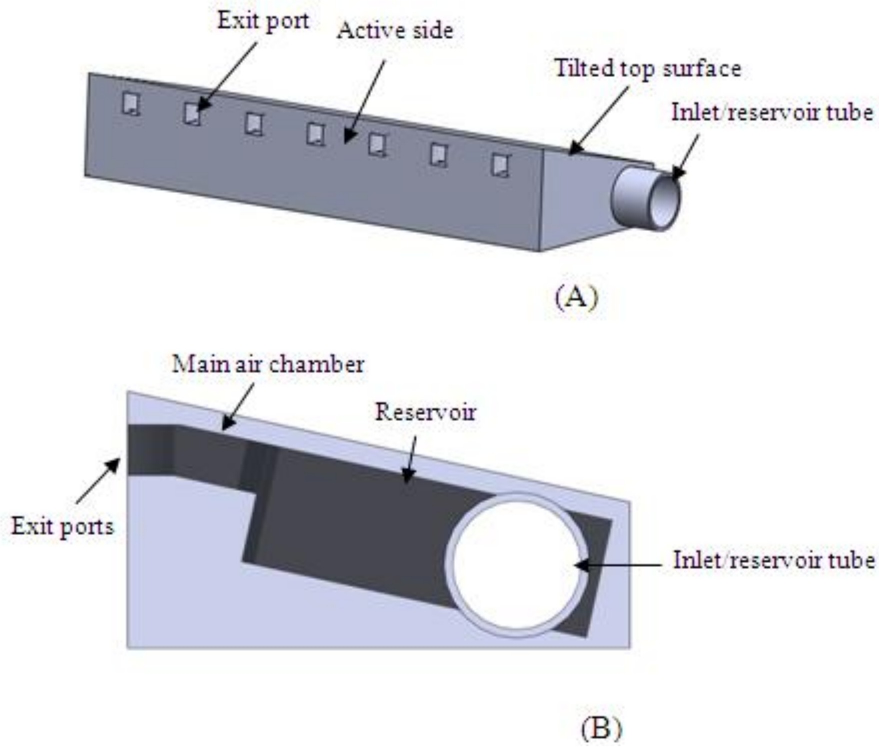


Figure 3.10: Tilted AFC
(A) Isometric view of tilted AFC
(B) Side view of tilted AFC

The tilted AFC is designed primarily to eliminate the raised wing flap skin by making the top surface of the tilted AFC the same height as the original wing skin. The surface is tilted to enable the free stream air to flow over the AFC without being impeded by a perpendicular surface. Figure 3.11 shows the tilted AFC integrated into a flat wing skin. Even though the tilted surface of the AFC allows airflow to continue over it, having anything protrude into the air stream is not ideal. The functionality of the AFC will assist in the reattachment of the air as it flows over the AFC back to the wing flap. This process should help eliminate the aerodynamic effects of having a protruding AFC.

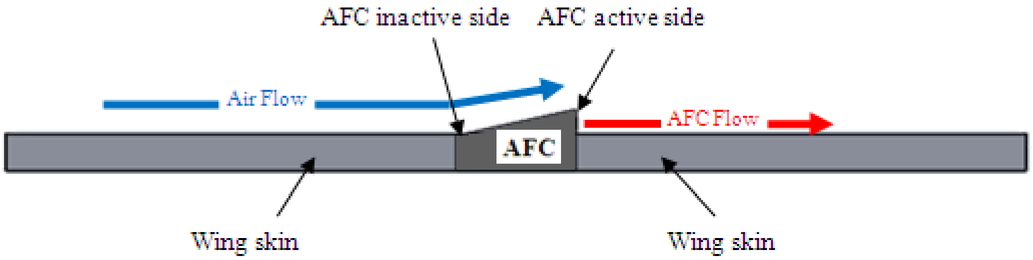


Figure 3.11: Tilted AFC with flat wing skin

3.2.2 Rounded Groove with Straight AFC

The simplest way to integrate the AFC into the wing flap is a groove on the outer surface of the wing flap. The original shape of the AFC devices has 90° corners on the bottom and top surfaces. When working with composite structures, it is important to note the influence of stress concentrations. To reduce the stress concentrations that the wing flap will encounter due to a square bottomed AFC, the edges of the AFC that come in contact with the composite wing flap were rounded. By rounding both the active and inactive bottom edges, the AFC seats easily into the composite skin positioning the exit ports correctly. Figure 3.12 shows the straight AFC with rounded bottom edges seated in the composite skin groove.

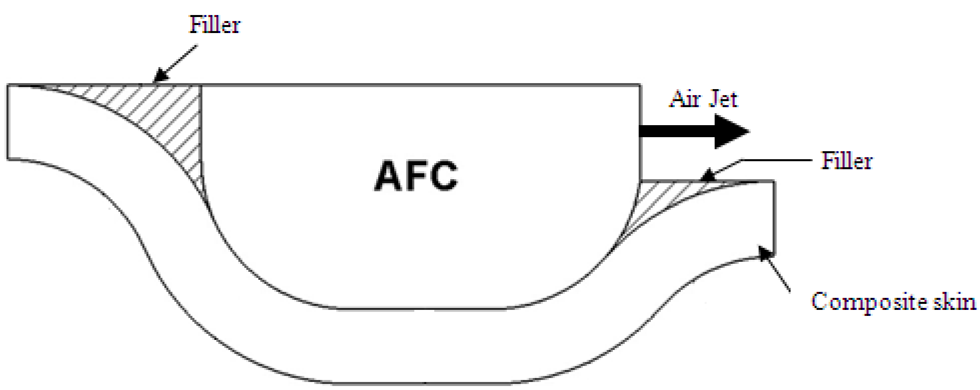


Figure 3.12: Rounded groove with straight AFC

The radius of the rounded edge is the same for both the active and inactive sides of the AFC. The rounding begins on the active side of the AFC just below the outlet ports ensuring that their geometry is not altered. The rounding on the inactive side extends slightly farther up the

AFC as compared to the active side rounding. The groove in the wing flap has been rounded to match the AFC bottom edges as well as the top edges where the groove rejoins the original flap profile. The upper edge rounding of the wing flap skin leaves areas that need to be filled in order to maintain a smooth wing flap surface.

The manufacturing process for the rounded groove with straight AFC foam core wing removes three steps from the original manufacturing process. The first step removed is the creation of mandrels. The foam core variant for the rounded groove with straight AFC design does not require any additional mandrels to lay up the carbon fiber layers. The foam core for the rounded groove with straight AFC design is shown in Figure 3.13. It can be seen that the foam core possesses the groove for the integration of the AFC device. Because no mandrels are required, steps six and seven can be ignored. Without mandrel pieces, there is nothing to remove after curing and the foam core is permanent so the insertion of ribs is also unnecessary.

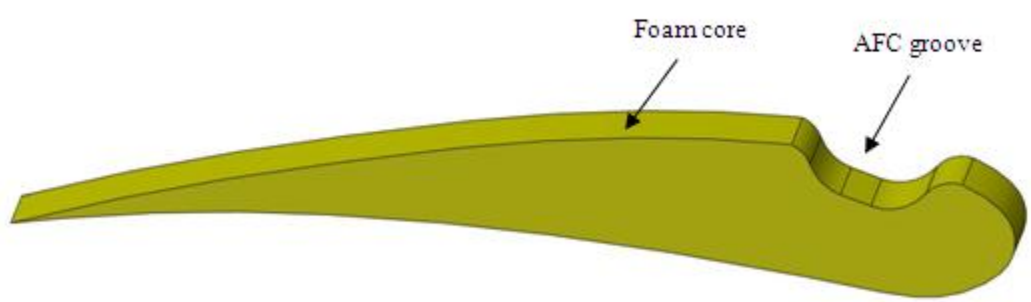


Figure 3.13: Foam core for rounded groove with straight AFC design

The rounded groove with straight AFC ribbed design's manufacturing process requires all eight steps of the original manufacturing process. A single mandrel is required in order to lay up the carbon fiber layers. The mandrel incorporates the groove for the AFC as with the foam core. Figure 3.14 shows the mandrel required to fabricate the wing flap. Once the mandrel is created, the ribs must be fabricated. The rib for the rounded groove with straight AFC is shown in Figure 3.15. It can be seen that the exterior profile of both the mandrel and the rib are identical. Once the wing flap has been cured, the mandrel is removed and the ribs are inserted. The final assembly is complete once the AFC device has been integrated.

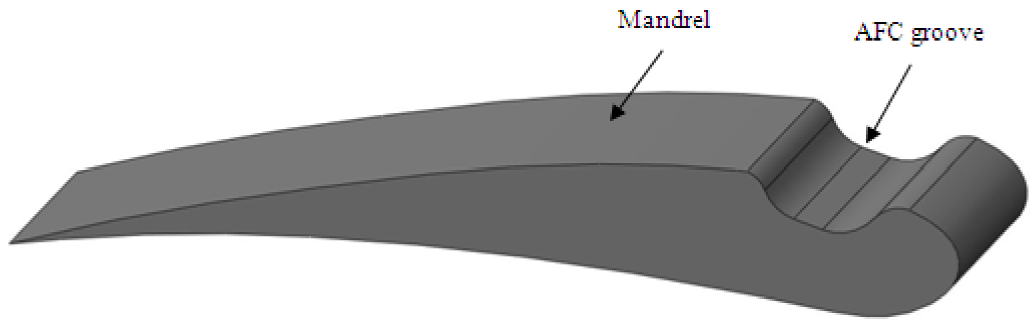


Figure 3.14: Mandrel for rounded groove with straight AFC ribbed design

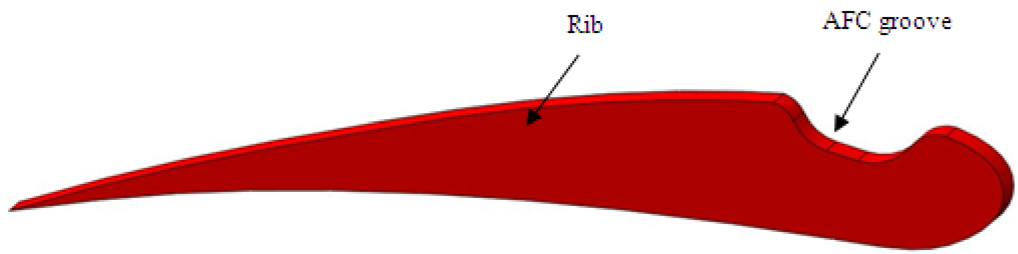


Figure 3.15: Rib for rounded groove with straight AFC ribbed design

The assembly of the rounded groove with straight AFC is simple for both design variants. Figure 3.16: (A) shows the insertion of the ribs into the wing flap skin. The storyboard depicts the ribbed design because it is the most complex between the two variants. Once the ribs are inserted, the AFC device is placed within the groove, shown in Figure 3.16: (B)-(C). The filler is then added to the assembly to smooth the wing flap, Figure 3.16: (D).

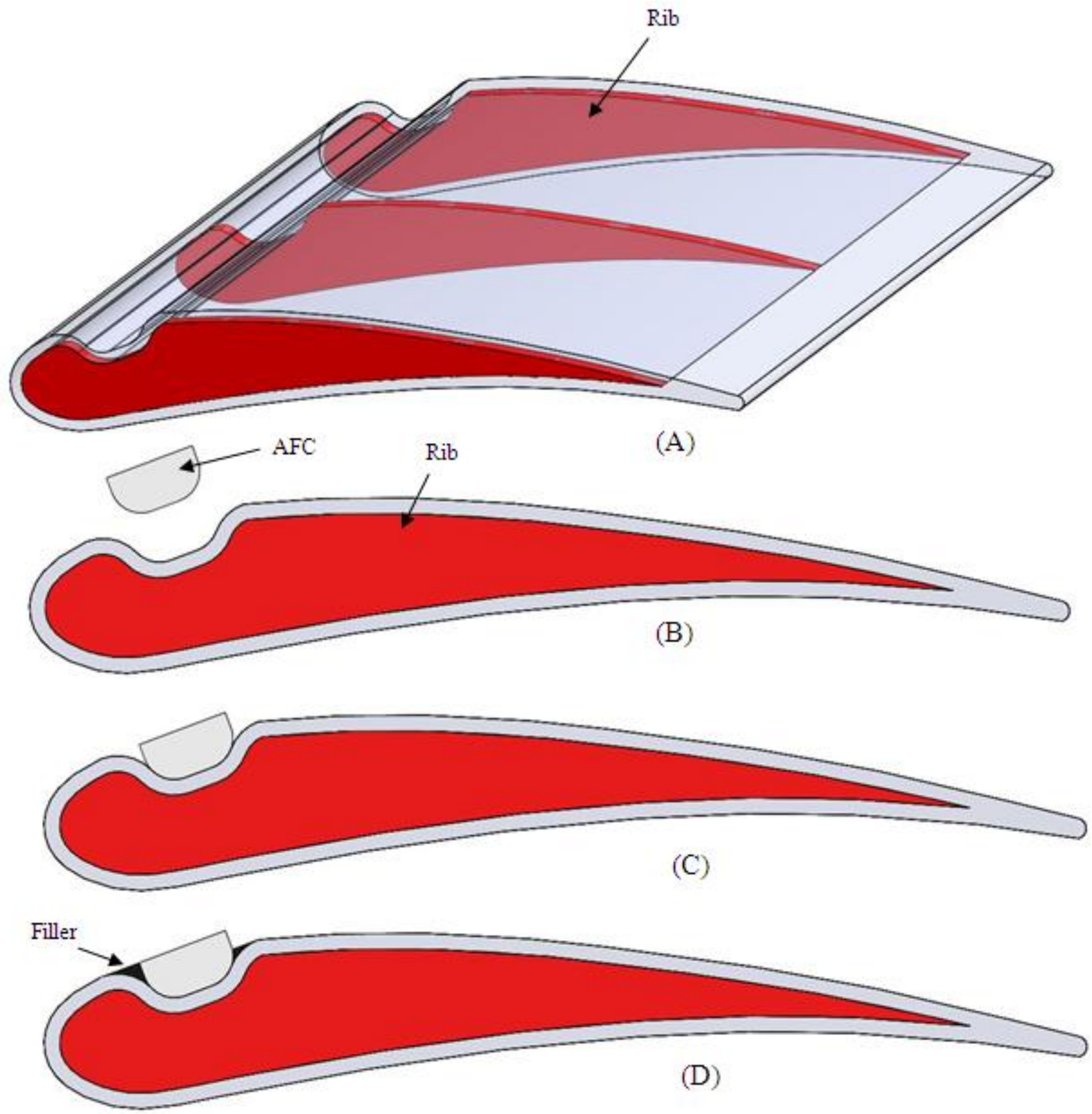


Figure 3.16: Rounded groove with straight AFC insertion storyboard

Figure 3.17 shows the assembled wing flap with integrated AFC. The isometric view of the wing flap assembly shows the location of the active side of the straight AFC while the side view shows the profile of the assembly. When integrating the groove into the wing flap profile, it is tilted slightly to compensate for the wing flap skin elevation change. If this is not done, the skin on the upper surface toward the trailing edge will have to be lowered, altering the entire wing flap profile. By tilting the rounded groove, a portion of the AFC device protrudes above the wing flap.

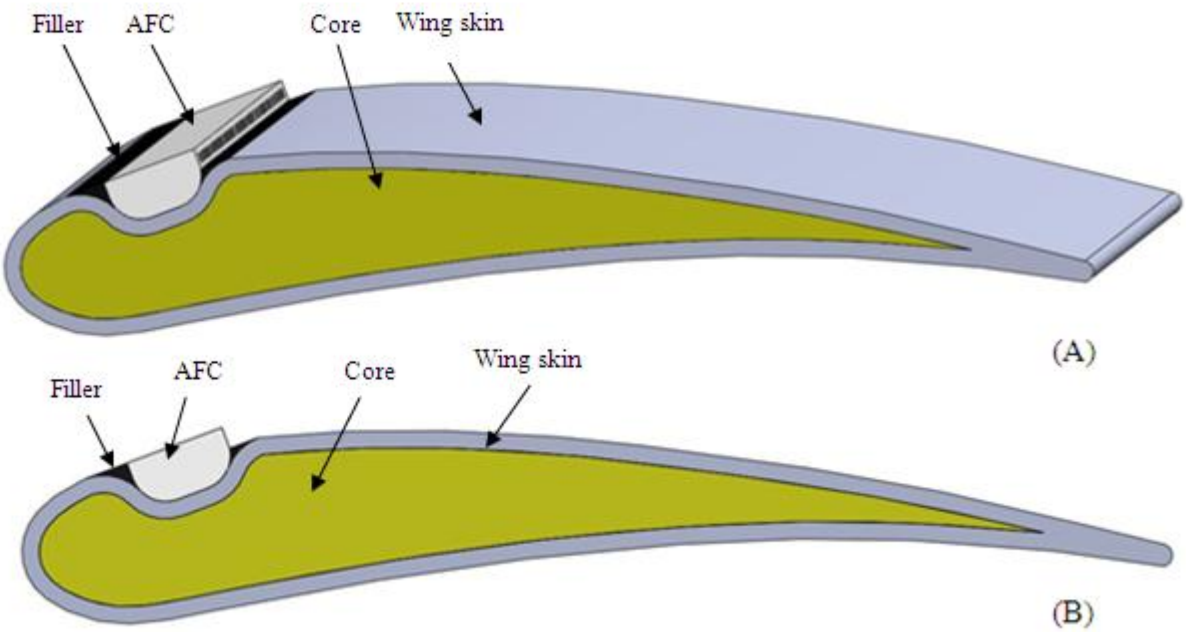


Figure 3.17: Rounded groove with straight AFC design
(A) Isometric view
(B) Side view

3.2.3 Rounded Groove with Tilted AFC

The design for the rounded groove with a tilted AFC is similar to the rounded groove with the straight AFC. The biggest difference for the tilted AFC design is that both the active and inactive sides of the groove within the composite skin have the same height, shown in Figure 3.18. The rounded active edge of the tilted AFC is exactly the same as the rounded active edge of the straight AFC. The inactive rounded edge of the tilted AFC does not extend to the same height as the straight AFC but rather stops at the same height as the active side rounded edge.

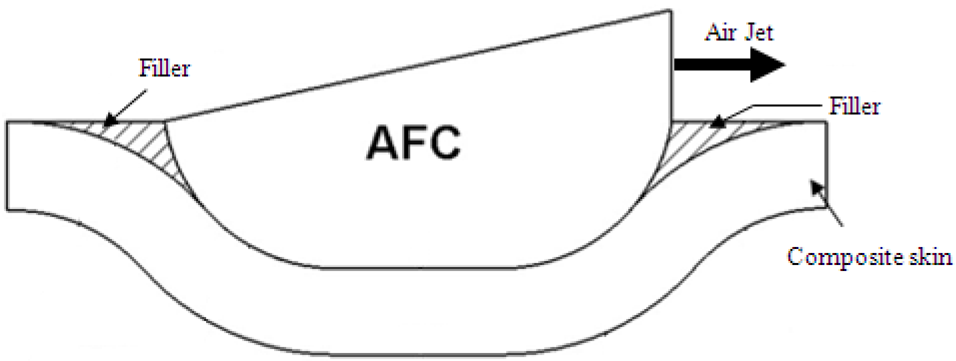


Figure 3.18: Rounded groove with tilted AFC

The manufacturing process for the rounded groove with tilted AFC foam core wing is identical to the rounded groove with straight AFC foam core design. The manufacturing process removes the same three steps from the original manufacturing process. The first step removed is the creation of mandrels. The foam core variant does not require any additional mandrels to lay up the carbon fiber layers. The foam core for the rounded groove with tilted AFC design is shown in Figure 3.19. It can be seen that the foam core possesses the groove for the integration of the AFC device. Because no mandrels are required, steps six and seven can be ignored. Without mandrel pieces, there is nothing to remove after curing and the foam core is permanent so the addition of ribs is unnecessary.

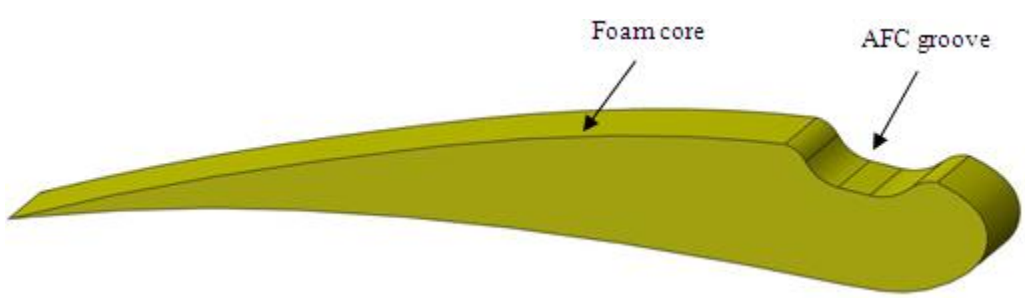


Figure 3.19: Foam core for rounded groove with tilted AFC design

The ribbed manufacturing process again requires all eight steps of the original manufacturing process. A single mandrel is created to lay up the carbon fiber layers. The mandrel incorporates the groove for the AFC as with the foam core. Figure 3.20 shows the mandrel required to fabricate the wing flap. Once the mandrel is created, the ribs must be fabricated. The rib for the rounded groove with tilted AFC is shown in Figure 3.21. It can be seen that the exterior profile of both the mandrel and the rib are identical. Once the wing flap has been cured, the mandrel is removed and the ribs are inserted. The final assembly is complete once the AFC device has been integrated.

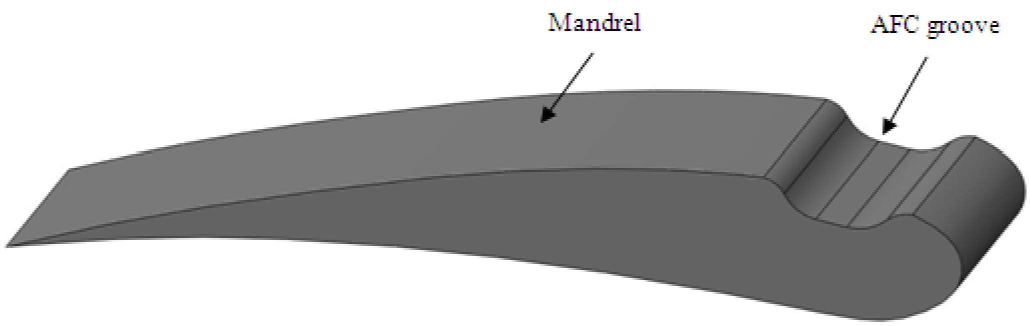


Figure 3.20: Mandrel for rounded groove with tilted AFC ribbed design

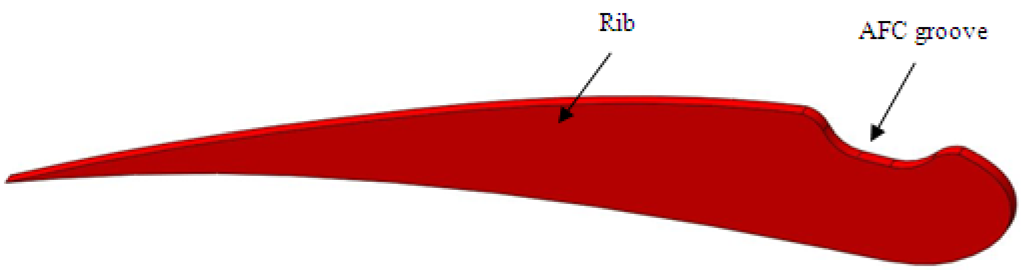


Figure 3.21: Rib for rounded groove with tilted AFC ribbed design

As with the straight AFC design, the rounded groove with tilted AFC design is a simple assembly for both design variants. Figure 3.22: (A) shows the insertion of the ribs into the wing flap skin. The storyboard again depicts the ribbed design because it is the most complex between the foam core and ribbed variants. Once the ribs are inserted, the AFC device is placed within the groove, shown in Figure 3.22: (B)-(C). The filler is then added to the assembly to smooth the wing flap, Figure 3.22: (D).

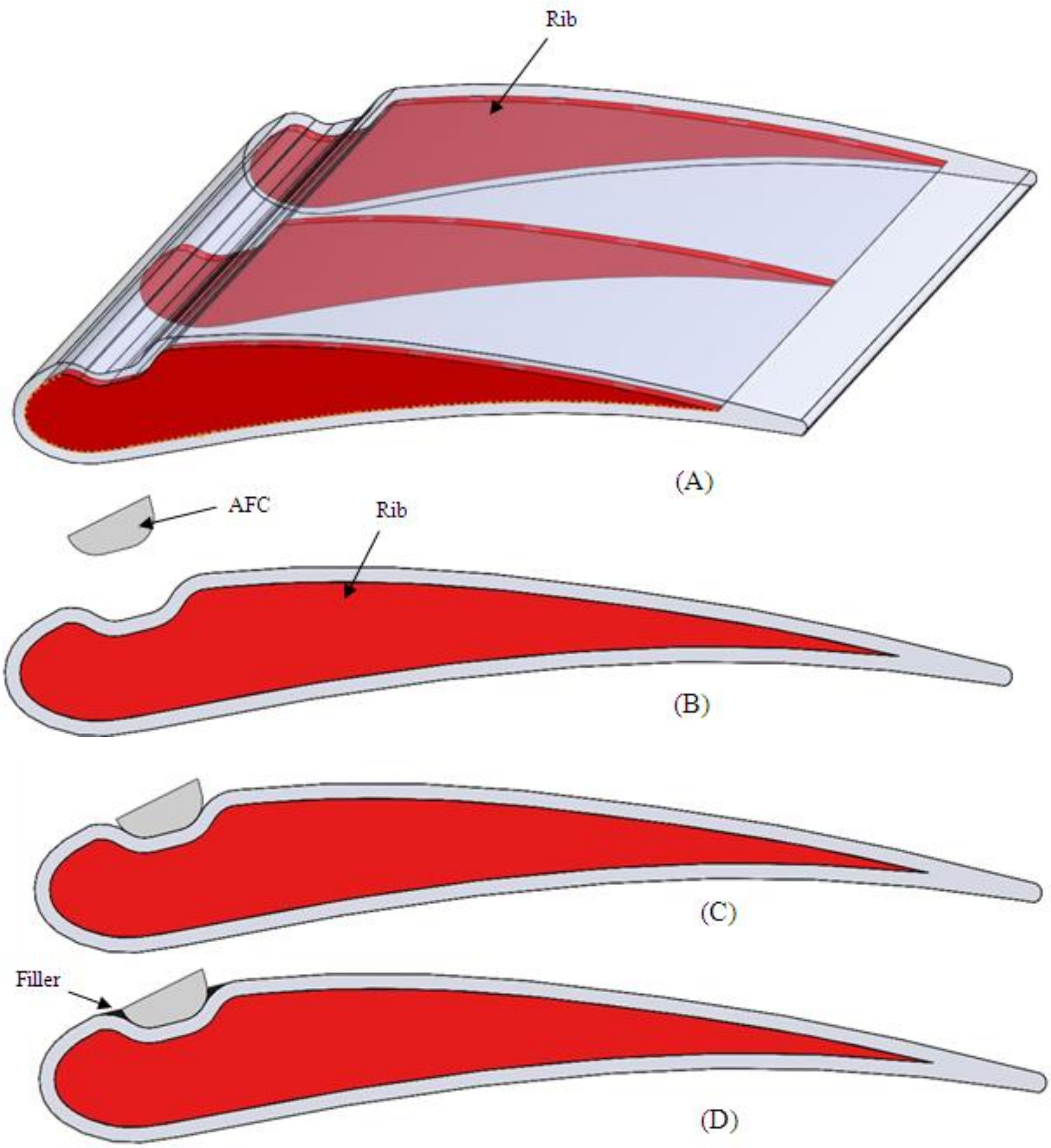


Figure 3.22: Rounded groove with tilted AFC insertion storyboard

Figure 3.23 shows the tilted AFC integrated into the full wing flap. The isometric view shows the exit ports for the AFC while the side view shows the external airfoil contour with the AFC inserted. The spaces created by the rounding of the wing skin are filled to create a smooth airfoil surface. The integration of this groove into the wing flap does not require any compensation, as did the rounded groove straight AFC design, because there is no skin elevation change around the AFC. Although the groove does not need to be tilted, the AFC still protrudes above the wing flap surface.

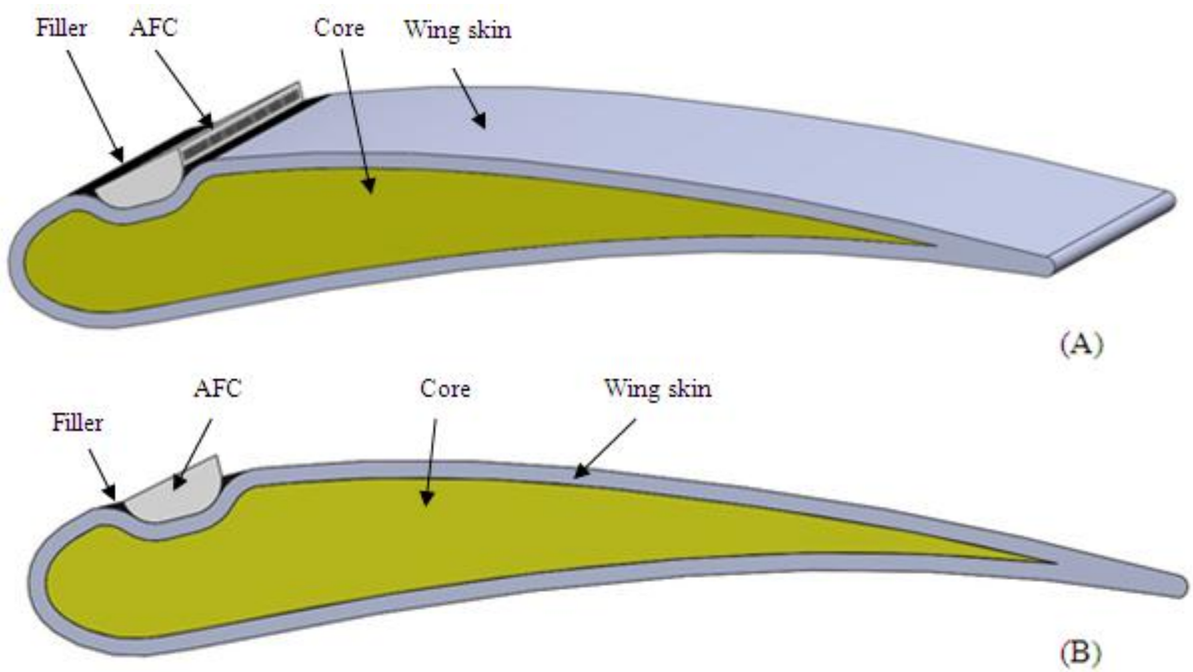


Figure 3.23: Rounded groove with tilted AFC design
(A) Isometric view
(B) Side view

The rounded groove designs modify the AFC devices as little as possible. The modifications that have to be made are done so because the sharp corners on the bottom of the AFC would cause stress concentrations in the wing skin. The corners are rounded so that the stresses can flow more easily around the AFC while a portion of the bottom of the AFC is left flat for ease of positioning. The design that incorporates the straight AFC has a slightly tilted groove so that the wing surface on the inactive side of the AFC is at the same height as the top surface of the AFC without changing the entire wing profile. The design that utilizes the tilted AFC does not need to tilt the groove because instead of the wing skin meeting the upper surface of the AFC, the AFC is modified to meet the surface of the wing skin. Regardless of the orientation of the groove, the AFC device protrudes above the upper surface of the wing flap. Both designs can employ either the foam core or the ribbed core without redesign.

3.2.4 Semi-Circular Groove with Straight AFC

The semi-circular groove with a straight AFC is a design that tries to reduce any stress concentration geometry much more than the rounded groove designs. Instead of rounding the active and inactive bottom edges and leaving a flat area in between, the semi-circular groove rounds the entire bottom surface of the AFC. The rounded surface of the straight AFC begins below the exit ports on the active side and ends at the same height on the inactive side. Figure 3.24 shows the semi-circular straight AFC inserted into the grooved composite wing skin.

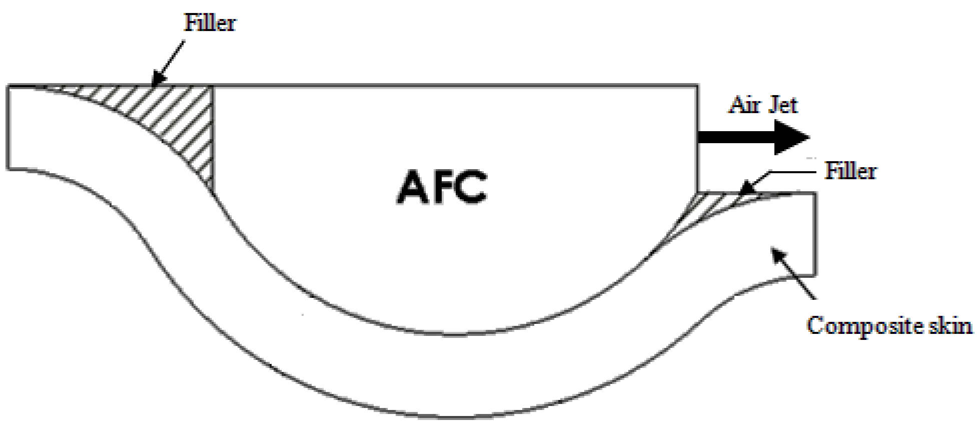


Figure 3.24: Semi-circular groove with straight AFC

The manufacturing process for the semi-circular groove with straight AFC foam core wing is the same as the rounded groove AFC foam core designs. The manufacturing process removes the same three steps from the original manufacturing process. The first step removed is the creation of mandrels. The foam core variant does not require any additional mandrels to lay up the carbon fiber layers. The foam core for the rounded groove with straight AFC design is shown in Figure 3.25. It can be seen that the foam core possesses the groove for the integration of the AFC device. Because no mandrels are required, steps six and seven can also be ignored.

With no mandrel pieces, there is nothing to remove after curing and the foam core is permanent so the insertion of ribs is unnecessary. The manufacturing process is completed by the insertion of the AFC device.

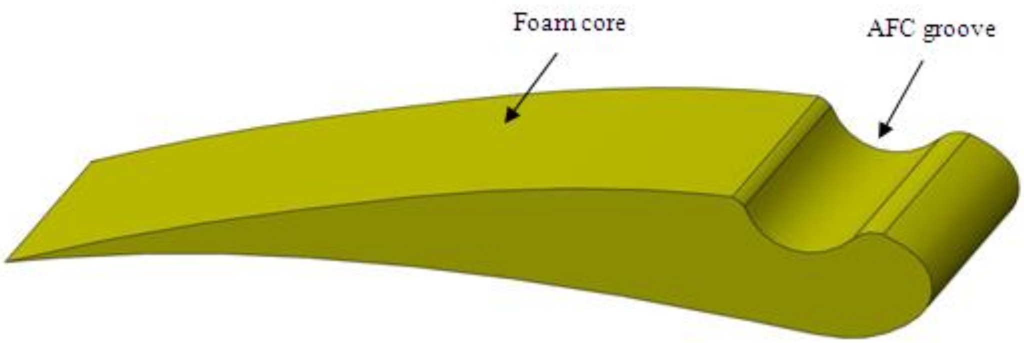


Figure 3.25: Foam core for semi-circular straight AFC design

The ribbed manufacturing process again requires all eight steps of the original manufacturing process. A single mandrel is created to lay up the carbon fiber layers. The mandrel incorporates the groove for the AFC as with the foam core. Figure 3.26 shows the mandrel required to fabricate the wing flap. Once the mandrel is created, the ribs must be fabricated. The rib for the rounded groove with straight AFC is shown in Figure 3.27. It can be seen that the exterior profile of both the mandrel and the rib are identical. Once the wing flap has been cured, the mandrel is removed and the ribs are inserted. The final assembly is complete once the AFC device has been integrated.

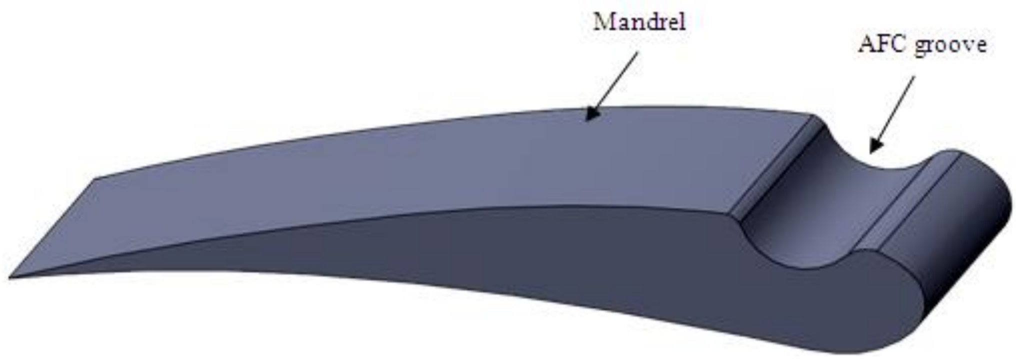


Figure 3.26: Mandrel for semi-circular straight AFC design

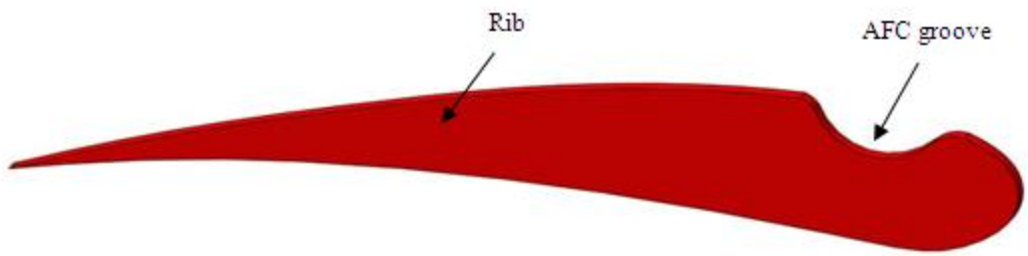


Figure 3.27: Rib for semi-circular straight AFC design

The assembly of the semi-circular groove with straight AFC is more difficult than the rounded groove designs for both design variants. Figure 3.28: (A) shows the insertion of the ribs into the wing flap skin. The storyboard depicts the ribbed design because it is the most complex assembly process between the two semi-circular groove straight AFC design variants. Once the ribs are inserted, the AFC device is placed within the groove, shown in Figure 3.28: (B)-(C). Since there is no flat portion on the bottom of the AFC, the device must be physically held in place until the filler can be added otherwise the AFC may rotate. Figure 3.28: (D) depicts the addition of filler to the assembly.

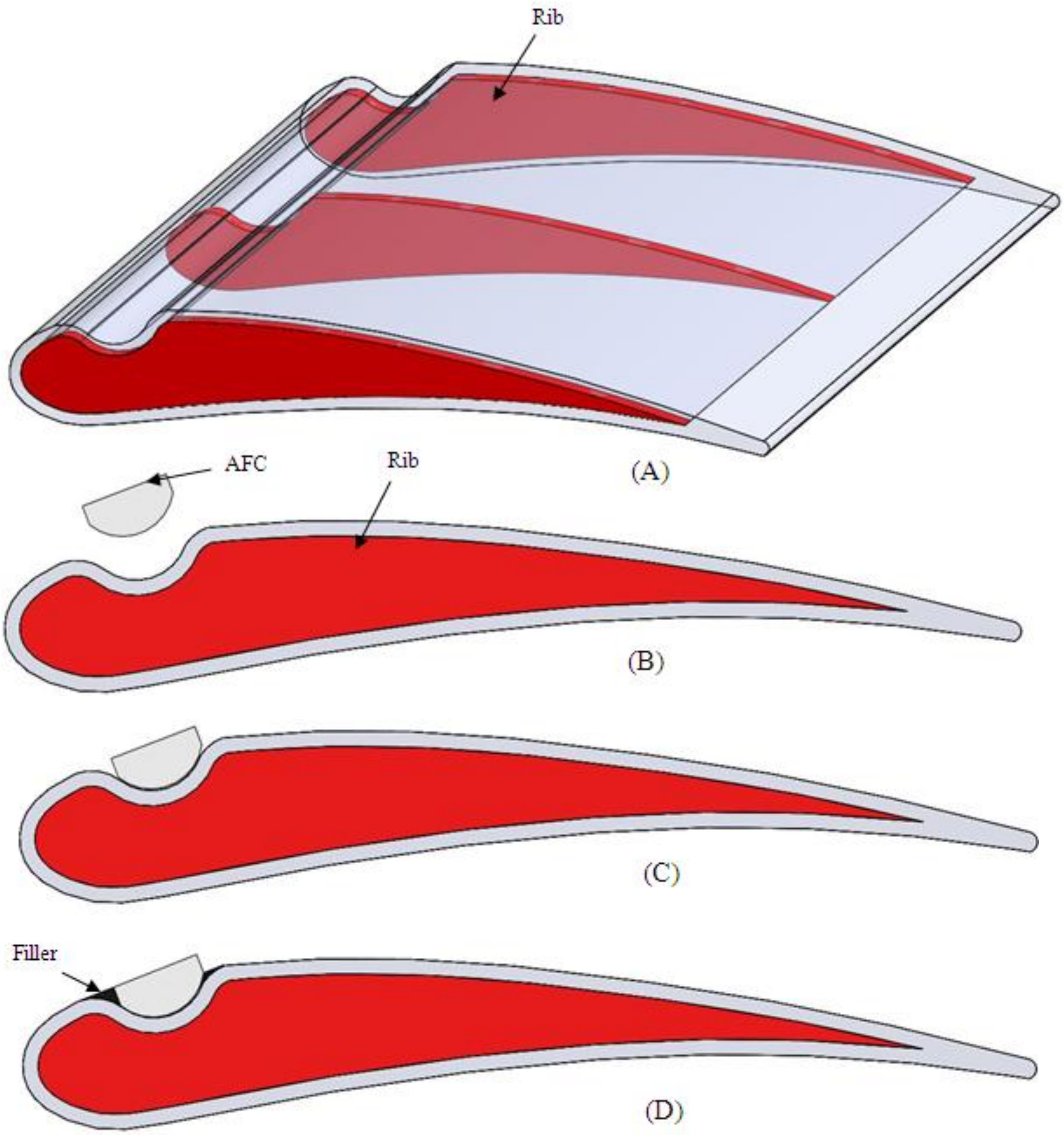


Figure 3.28: Rounded groove with tilted AFC integration storyboard

As with the rounded groove straight AFC, the wing skin on the inactive side of the AFC is higher so that it meets the top of the AFC. The integrated groove is tilted so that the exterior profile of the wing is not altered. Because there is no flat piece on the bottom of the AFC, it has more of an opportunity to rotate within the groove until it has been sealed into place. Special attention must be paid to ensure that the AFC device is not incorrectly located. Filler material is added to smooth the wing flap surface once the AFC has been inserted. Figure 3.29 shows the assembled wing flap with the straight AFC integrated into the semi-circular groove. The isometric view shows the location of the exit ports of the AFC while the side view shows the profile of the assembly. As with the rounded groove with straight AFC design, the AFC protrudes from the upper surface of the wing flap.

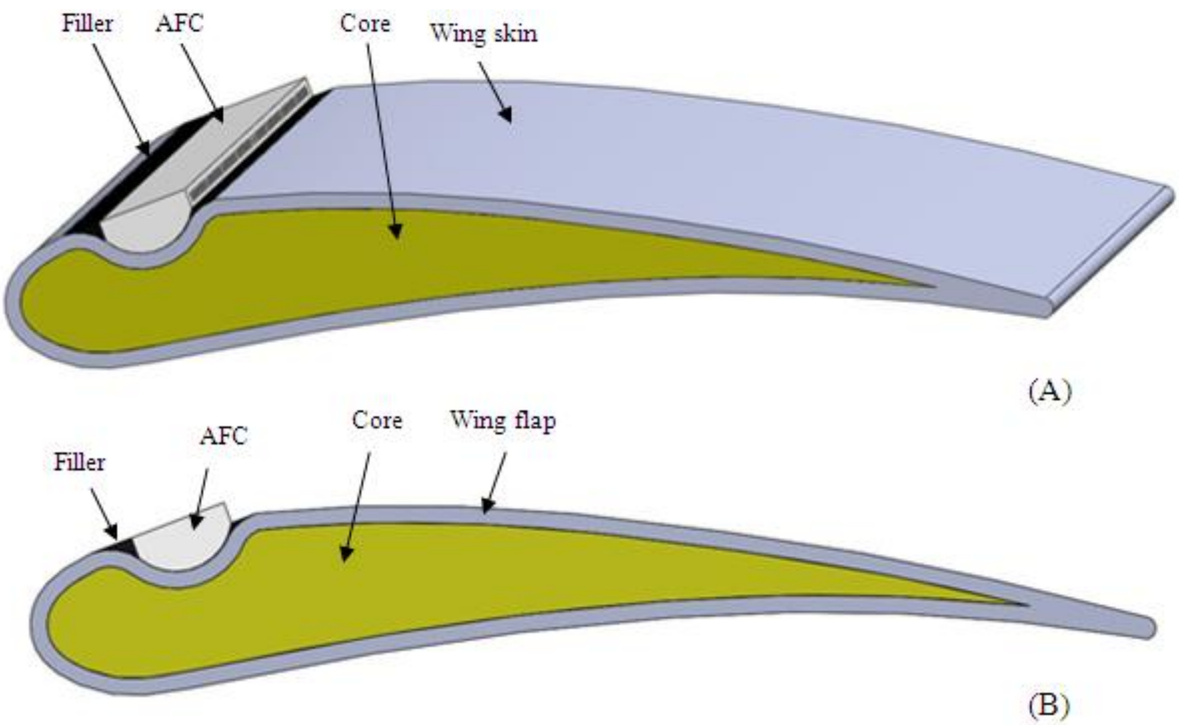


Figure 3.29: Semi-circular groove straight AFC design
(A) Isometric view of
(B) Side view

3.2.5 Semi-Circular Groove with Tilted AFC

The semi-circular groove with tilted AFC has the same style of rounding to the bottom surface of the AFC as the semi-circular groove with straight AFC. The rounding starts below the outlet ports on the active side of the AFC and ends at the same height on the inactive side. Figure 3.30 shows the tilted AFC with the semi-circular bottom and the groove into which it fits. It can be seen that the composite skin on either side of the AFC is at the same height while the top surface of the AFC protrudes above it.

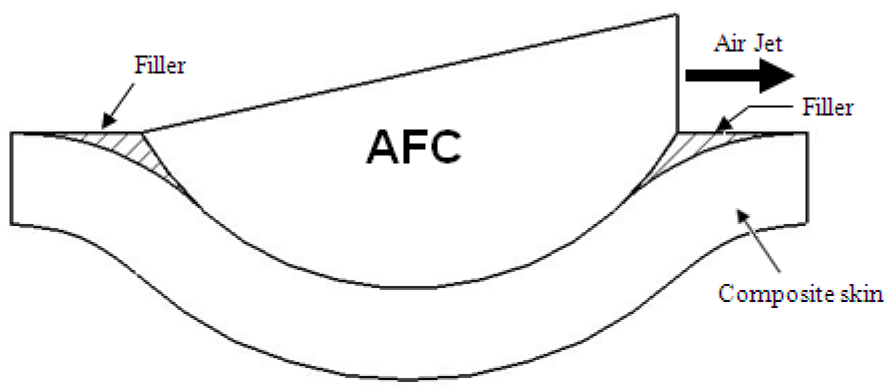


Figure 3.30: Semi-circular groove with tilted AFC

The manufacturing process for the semi-circular groove with tilted AFC foam core wing is identical to the semi-circular groove with straight AFC foam core design. The manufacturing process removes three steps from the original manufacturing process. The first step removed is the creation of mandrels. This foam core variant does not require any additional mandrels to lay up the carbon fiber layers. The foam core for the semi-circular groove with tilted AFC design is shown in Figure 3.31. It can be seen that the foam core possesses the groove for the integration of the AFC device. Because no mandrels are required, steps six and seven can be ignored. Without mandrel pieces, there is nothing to remove after curing and the foam core is permanent so the addition of ribs is unnecessary.

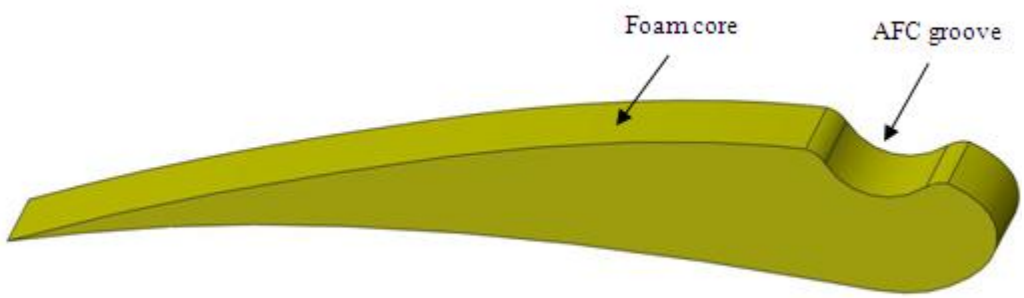


Figure 3.31: Foam core for semi-circular tilted AFC design

The ribbed manufacturing process requires all eight steps of the original manufacturing process. A single mandrel is created to lay up the carbon fiber layers. The mandrel incorporates the groove for the AFC. Figure 3.32 shows the mandrel required to fabricate the wing flap. Once the mandrel is created, the ribs must be fabricated. The rib for the rounded groove with straight AFC is shown in Figure 3.33. It can be seen that the exterior profile of both the mandrel and the rib are identical. Once the wing flap has been cured, the mandrel is removed and the ribs are inserted. The final assembly is complete once the AFC device has been integrated.

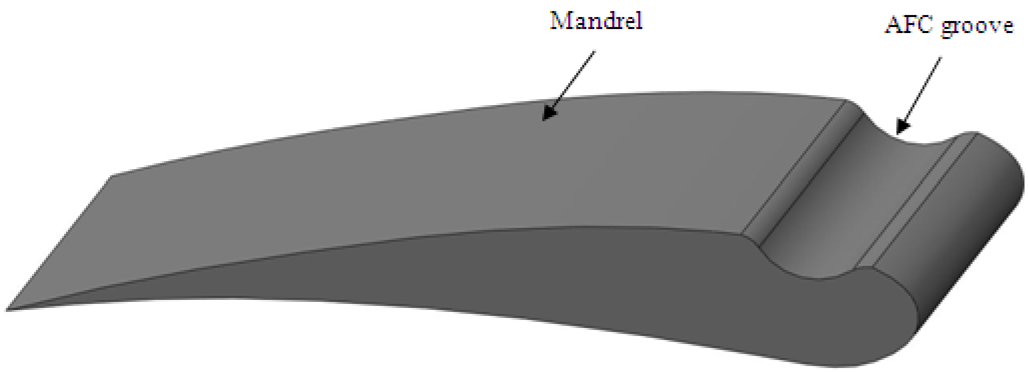


Figure 3.32: Mandrel for semi-circular tilted AFC design

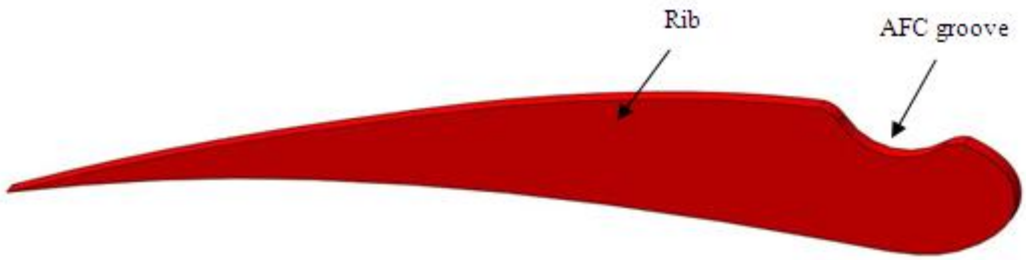


Figure 3.33: Rib for semi-circular tilted AFC design

The assembly of the semi-circular groove with tilted AFC is identical to the semi-circular groove with straight AFC design. Figure 3.34: (A) shows the insertion of the ribs into the wing flap skin. The storyboard depicts the ribbed design because it is the most complex assembly process between the two semi-circular tilted design variants. Once the ribs are inserted, the AFC device is placed within the groove, shown in Figure 3.34: (B)-(C). Since there is no flat portion on the bottom of the AFC, the device must again be held in place until the filler can be added. Figure 3.34: (D) shows the final step as the addition of filler to the assembly.

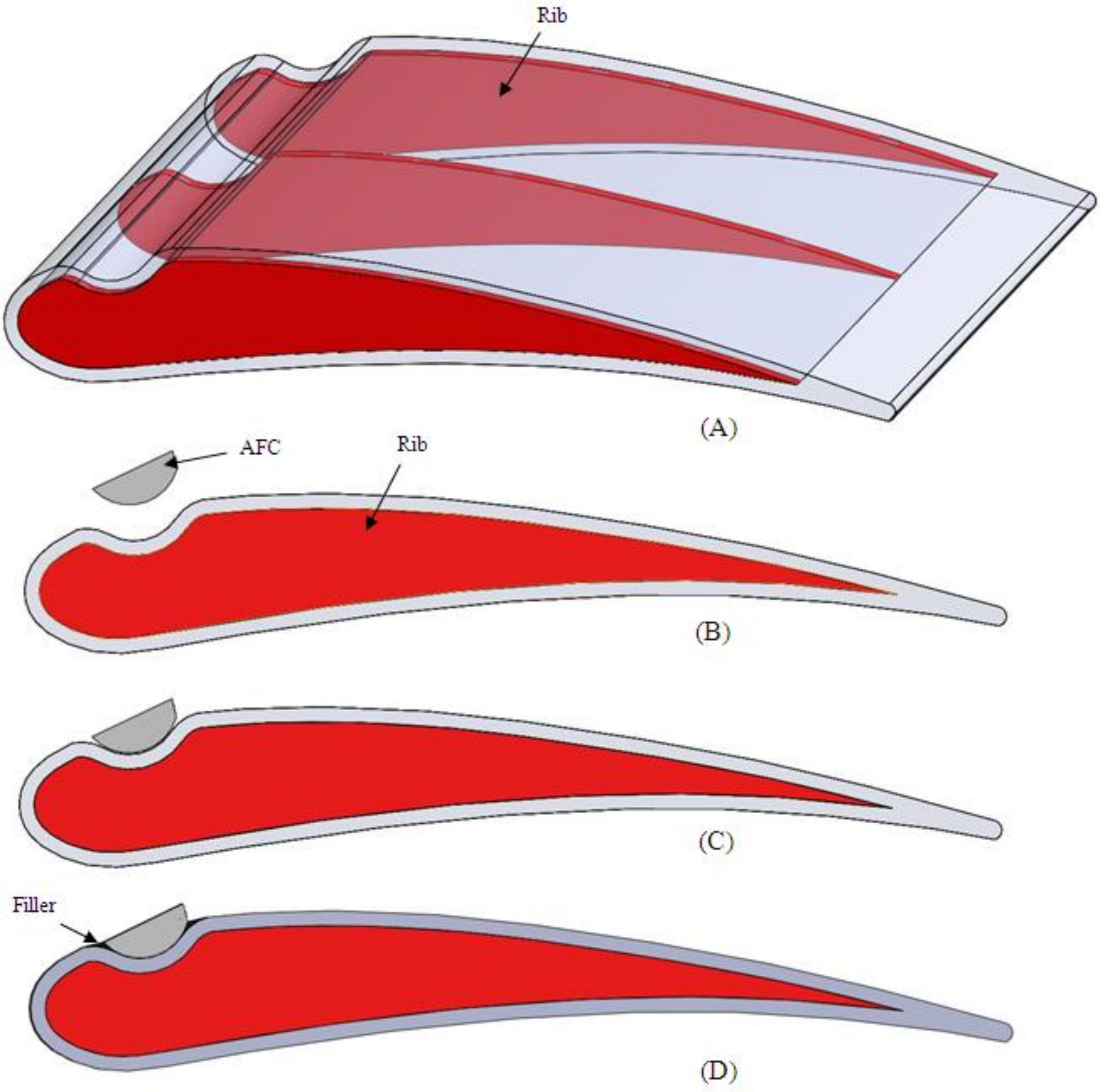


Figure 3.34: Rounded groove with tilted AFC insertion storyboard

The same special attention must be given to the final step of the manufacturing process as with the foam core design. Figure 3.35 shows the entire semi-circular tilted AFC design integrated into the composite wing flap. The isometric view shows the exit ports of the AFC while the side view shows the profile of the assembly. The gaps between the AFC and the wing skin are filled for a smooth transition between the skin and AFC. The AFC surface protrudes from the wing flap allowing the air to exit tangentially to the surface of the wing flap.

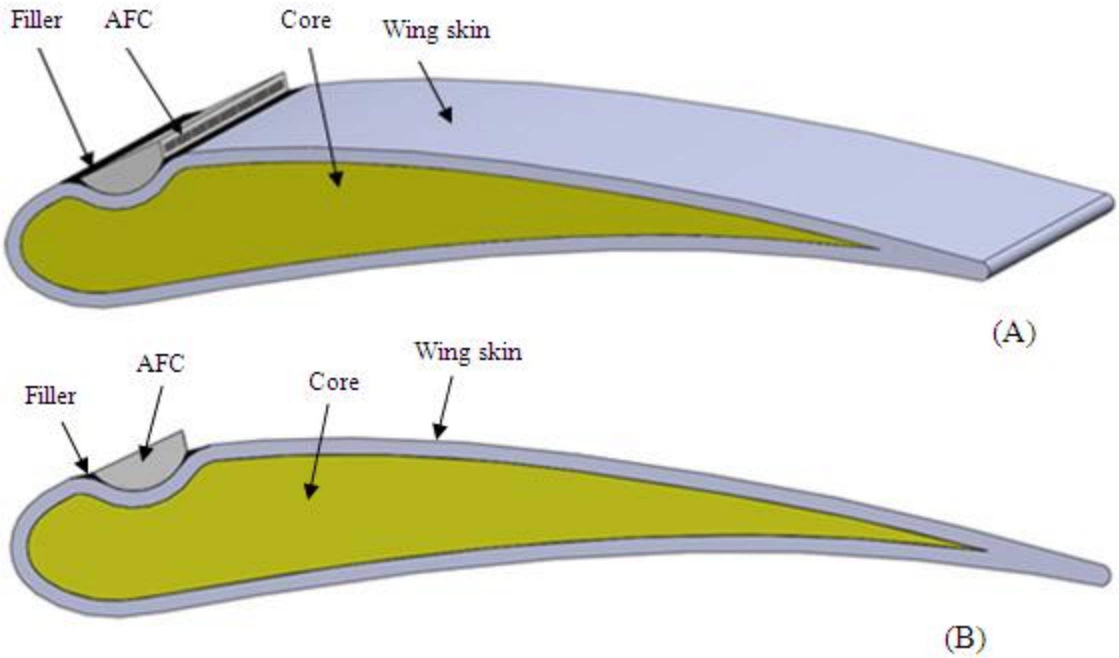


Figure 3.35: Semi-circular groove tilted AFC design
(A) Isometric view
(B) Side view

The semi-circular groove designs are similar to the rounded groove designs in both location and appearance. Instead of rounding the corners of the AFC, the semi-circular designs round the entire bottom surface of the AFC. This rounding allows an even smoother path for stresses to be transmitted around the AFC. The downside to rounding the entire bottom surface is that there is no built-in positioning guide. The AFC must be oriented manually to ensure that the exit ports are tangential to the wing skin surface. As before, the design with the straight AFC has a slightly tilted groove so that the skin surface on the inactive side is flush with the upper AFC surface. The tilted AFC design does not have a tilted groove because the AFC was designed to meet the skin at the same height on both the active and inactive sides. Both designs require that the AFC protrude above the top surface of the wing. As with the rounded groove designs, the difference between a foam cores or ribbed designs requires no modifications other than the manufacturing process.

This section discusses the grooved integration designs. These designs are based primarily on the manufacturing design specification. The groove on the exterior surface of the wing for the AFC allows for an easy manufacturing process. Because there are no holes in the wing skin, the wing flap can be laid up as a single piece on either a mandrel or the foam core. The structural design specification is not adversely affected by the integration of the AFC device. The skin is continuous throughout and the corners have been rounded to limit stress concentrations. The aerodynamics specification is not optimized for the external designs because a section of the AFC devices protrude above the surface of the wing flap. The AFC in the airflow could cause turbulence and affect the flight characteristics of the airfoil. The operation of the AFC could minimize these effects but the advantages that the AFC delivers would be hindered. The maintenance for the AFC also is not ideal because the AFC devices are co-cured, which may cause damage to the device or the flap during removal.

3.3 Internal AFC Integration

The idea of integrating the AFC device inside the wing flap is based almost exclusively on the aerodynamics design specification. In order for the air exiting the AFC devices in the grooved designs to be tangential to the wing flap surface, the exit ports of the AFC must be above the flap; hence, the top surface of the AFC must also be above the skin. By placing the AFC inside the wing skin, the aerodynamics of the wing flap are no longer hindered by an object in the airflow, but the ease of manufacturing experienced in the grooved designs is no longer a possibility. The other benefits of placing the AFC inside the wing skin are protection and location security. The internal mounting of the device is ideal because of the protection from aerodynamic stresses and other potential risk factors, such as foreign object debris. The location of the AFC is more secure such that the AFC will not be knocked off the wing flap or blown away. There are three major design branches that are considered internal AFC integration designs: the side inserted AFC, top inserted AFC, and the attached AFC. Each design branch has a ribbed and foam core variant.

3.3.1 Wing Flap Modifications

The tangential airflow from the AFC over the wing skin is a critical requirement for the functionality of the assembly. To facilitate the air exiting the wing skin in the proper direction, a slot is used to guide the air from inside the wing skin to the upper surface. Figure 3.36 shows the AFC slot in the wing skin. The exit ports of the AFC must be above the top surface of the AFC slot ramp in order for the air exiting the AFC to interact with the boundary layer.

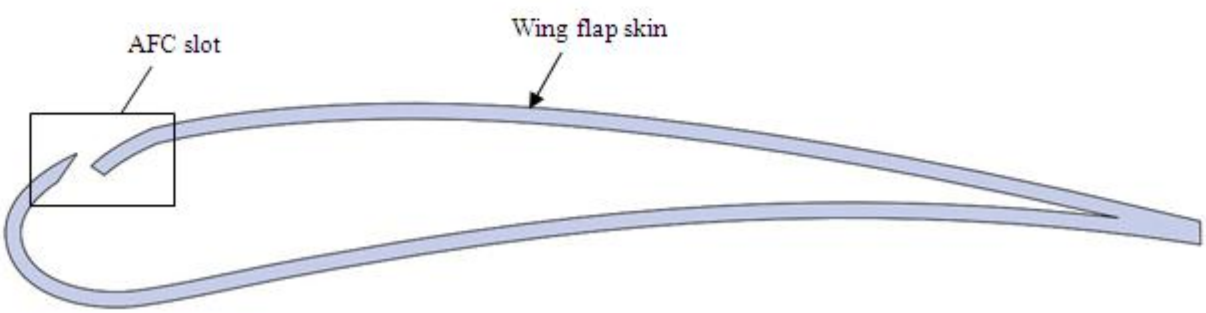


Figure 3.36: Wing flap skin modified with AFC slot

A slot is used in all of the three internal designs. The ramp of the AFC exit slot is used to redirect the air exiting the AFC to the tangential direction required by the design. Although the AFC slot corrects the aerodynamic problems, the addition of the slot severs the continuity of the wing skin and causes a serious structural issue which must be addressed.

The discontinuity of the wing flap causes problems with strength, torsional properties, overall rigidity of the wing, and stress concentrations. The composite material of the wing flap is designed to carry and transmit stresses within in it. By opening the cross section, the stresses normally transmitted by the skin must be transferred to the core to flow through the AFC slot. Those conditions would most likely damage the core and cause failure under fatigue loading. Any torsional load that the wing flap will encounter during flight will cause the gap to enlarge and to damage the core or the AFC components inside. External forces in tension, compression, or torsion will cause the opening to expand or contract limiting the structural rigidity of the wing flap. The abrupt geometry change of the slot could generate large stress concentrations that may lead to premature failure of the flap.

To minimize the negative effects of an open airfoil structure, the AFC slot is divided into sections leaving continuous wing skin in between. Figure 3.37 shows the AFC slots and the continuous skin connection pieces. The continuous skin connection pieces will allow some stress to flow directly across the AFC slot instead of transferring into the core material. The slot still will be inclined to open during torsion, but it will be much more limited by the continuous skin as will the effects of tensile or compressive loading.

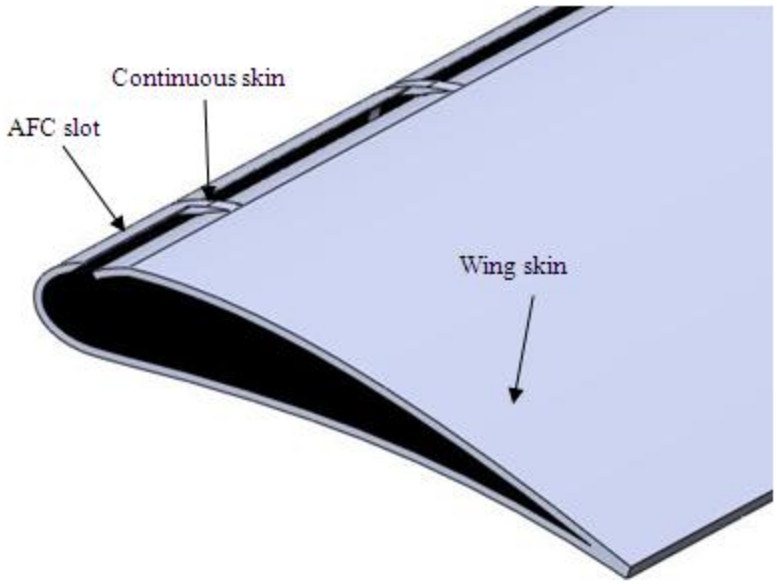


Figure 3.37: Isometric view of wing flap with AFC openings

The continuous skin can be as wide or narrow as is needed by the application, which affords a high level of variability for the structural design criteria. The wing flap will still have a strength reduction due to the openings for the AFC slots and the reduced area for the continuous skin, so the connecting skin and the ramp of the AFC slot are structurally reinforced to reduce the possibility of failure. The reinforcement also will assist in reducing the stress concentrations, and the increased strength should minimize the potential for failure. This helps to minimize the slot's negative impact on the structural strength of the wing flap as well as to increase the rigidity. This conclusion will need to be assessed in future work when determining the structural stability of the wing flap.

The internal AFC integration designs also strive to accommodate the maintenance design criteria. The placement of the AFC inside the wing skin does not allow for easy repair or replacement. There are two major questions that these designs need to answer to be viable. The first is: how will the AFC fit inside the wing? The second question is: how can it be made removable? Each of the designs in this section will discuss the modifications made to the AFC and AFC slot, how those apply to the four main design criteria, and how the AFC fits and functions within the wing skin.

3.3.2 Side Inserted AFC

The side inserted AFC design is relatively self explanatory when it comes to the insertion location of the AFC. The AFC device is inserted from the side of the wing flap to avoid any modifications to the wing skin previously displayed. To satisfy the maintenance requirement, the AFC needs to be able to be inserted, located into place, remain fixed, and removed when damaged. Before satisfying the maintenance requirement, the original AFC must be modified to fit within the size constraints of the wing flap.

To reduce the AFC size, all excess material around the main air chamber is removed, thereby leaving only what is structurally required for the AFC to function. The reservoir tube is moved toward the active side of the AFC reducing the width of the device. The inlet tube is identical in diameter to the original AFC inlet tube but its length is longer in order to pass through the continuous connecting skin. The finalized side inserted AFC is shown in Figure 3.38. Although the exterior of the AFC is different, the internal geometry remains the same as the original AFC.

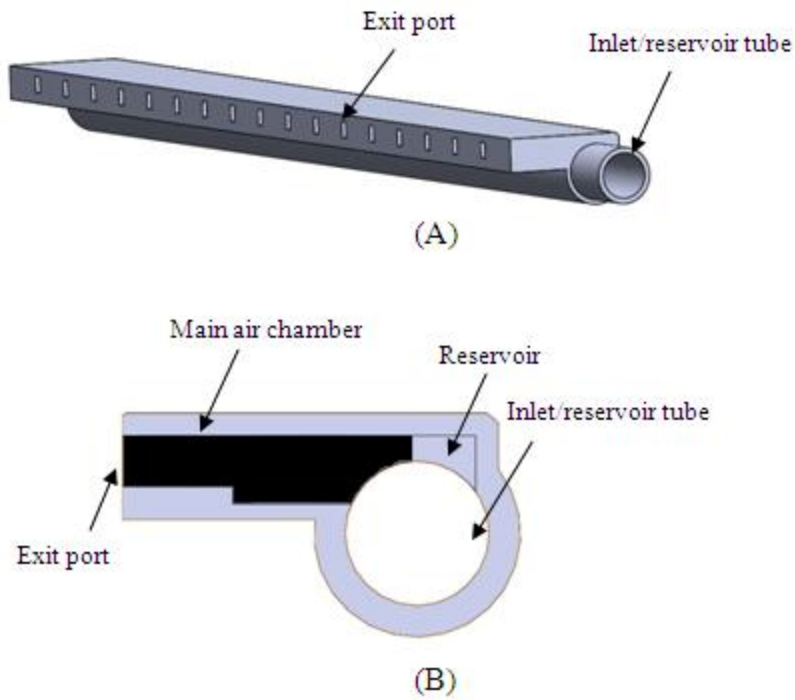


Figure 3.38: Side inserted AFC device
(A) Isometric view of side inserted AFC
(B) Side view of side inserted AFC

The AFC device needs to be capable of spanning the wing flap to provide airflow to the entire wing surface. To allow for maintenance, the AFC device is not created as a single piece that spans the wing flap, it is chained together so that if a piece becomes damaged, it can be changed without replacing the entire structure. The use of multiple AFC devices will also provide the spaces required to create the continuous skin connection pieces in between the AFC slots. Based on the final location of the AFC shown in Figure 3.39, the continuous connecting pieces of wing skin will interfere with the AFC placement outside the AFC slots. In order to avoid those areas, the AFC device's length is made to correspond to that of the AFC slots, which are predetermined based on the performance needs of the wing flap. To connect the devices, the AFC's geometry is reduced only to its reservoir tube which passes through the width of the continuous skin, connecting to another AFC device on the other side.

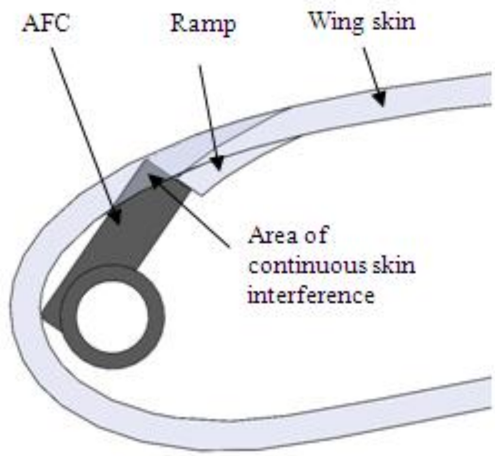


Figure 3.39: Placement for side inserted AFC

The AFC device needs to be able to be inserted and removed with relative ease in order to satisfy the maintenance design requirement. The AFC is inserted from the side of the wing flap through the entire wing flap length. Once the device is inserted, it is rotated into place until it is properly seated. A retaining piece is inserted to secure the AFC into place which is a pin style connection. The retaining piece's shape is based on the cut-out created for the AFC to slide and rotate within the core. The cut-out size and shape differ between the foam core and the ribbed design and each will be discussed in greater detail in that section. A story board of the assembly will also be depicted for each design variant.

3.3.2.1 Side Inserted Foam Core

The foam core, as stated previously, occupies the inside of the wing flap through the entire wingspan. Because of this, the AFC cut-out section, which will house the AFC and the retaining piece, must be large enough to accommodate the insertion of the AFC and the space required for the entire AFC body to rotate into place. The AFC is required to rotate into place because the continuous skin connecting pieces' bottom surfaces are lower than the AFC's final placement. The foam core with the AFC cut-out is shown in Figure 3.40. It can be seen that the foam core has a geometry change between the area of the connecting wing skin pieces and the area of the AFC slot, which accommodates the AFC slot ramp.

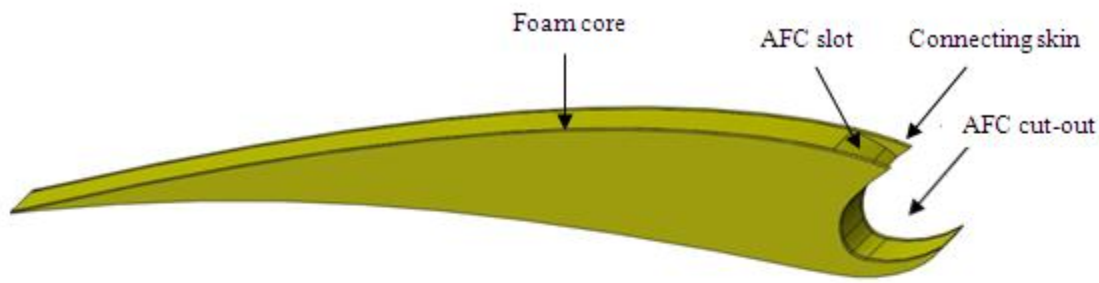


Figure 3.40: Foam core with AFC cut-out for side inserted AFC design

The retaining piece is designed to occupy the space left in the foam core once the AFC has been inserted and rotated into place. The retaining piece slides into the foam core locking the AFC into place through the entire span of the flap. The retaining piece for the foam core, shown in Figure 3.41, uses the wing skin to lock the back of the AFC into place while keeping the AFC from rotating. The retaining piece only fixes the AFC through the AFC slot because in the area through the connecting skin thickness; no part of the AFC is in contact with the wing skin due to the reduction of the AFC's geometry for chaining. The figure has the foam core through the width of the continuous skin piece hidden so that all the internal components can be seen.

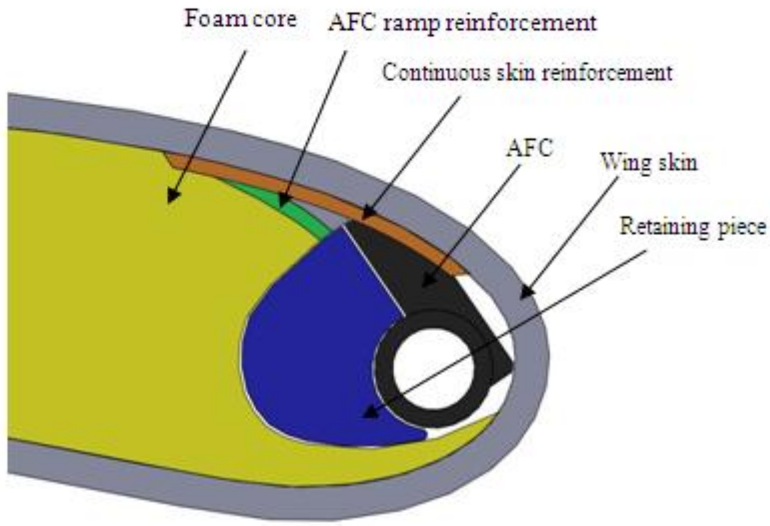


Figure 3.41: Assembly of side inserted AFC foam core design

The fabrication of the side inserted AFC design wing flap with foam core uses seven of the eight manufacturing steps outlined at the beginning of the chapter. The only step not utilized is step seven, "insert ribs." Even though this design has a foam core, it requires removable mandrels to fabricate the carbon fiber wing flap. The mandrels are required for this design to seal the AFC cut-out, as well as to create the ramp of the AFC slot. Figure 3.42 shows the removable mandrel pieces and the way that they are oriented. The outer, middle, and inner mandrel pieces are all the length of the AFC slot while the length of the base mandrel piece encompasses the span of the wing flap. Each individual AFC slot requires all three of the outer, middle, and inner pieces to form the ramp for the AFC slot. A single base mandrel piece is required per wing flap.

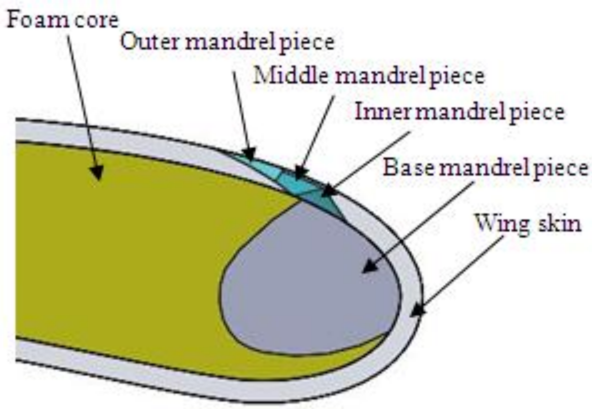


Figure 3.42: Mandrel pieces for side inserted AFC foam core design

The second step of the manufacturing process, “create foam core,” is completed using the configuration that was shown in Figure 3.40. After the foam core is fabricated, the layer cuts must be completed. In addition to the cuts required to form the exterior profile of the carbon fiber layers, the side inserted AFC designs require internal cuts to form the AFC slot. Each layer of carbon fibers is cut so that it wraps around the core and mandrels starting at the trailing edge of the upper surface and ending at the trailing edge of the lower surface. The wing skin for both the foam core and ribbed designs are identical so the carbon layers created to manufacture the wing skins are identical. A series of cuts are made into a carbon sheet so that the carbon will form the AFC slot as well as the continuous skin connecting pieces between slots. Figure 3.43 shows the cuts made in each layer of carbon fiber and what component each cut forms. The extra material has been removed to show the detail of the AFC slot cuts but a single piece of carbon encircles the entire wing flap to preserve the continuity.

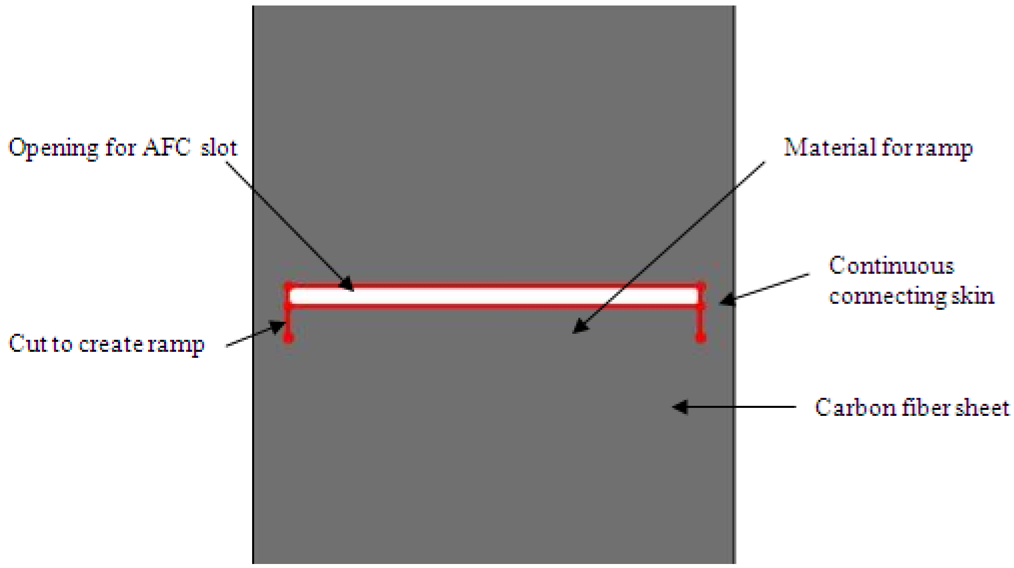


Figure 3.43: Carbon fiber layer for side inserted AFC design

The layup process for the side inserted AFC designs can be difficult. Each layer has identical cuts made in it to create the AFC slot, which need to be aligned to create an acceptable part. Once all of the carbon fiber layers have been placed and aligned correctly, the bagging and resin infusing step can be completed. Upon the successful completion of the curing cycle for the wing flap, the mandrels must be removed. The outer mandrel piece is the first piece to be removed and the only piece removed from the top surface of the wing. All the other mandrel pieces are removed from the side using the AFC cut-out. The base mandrel must be removed before either the inner mandrel or middle mandrel can be removed. If removed correctly, all of the mandrel pieces can be utilized for multiple layup operations.

The seventh step for the manufacturing process is skipped because there is no need for ribs in the foam core variant of the side inserted AFC design. The final manufacturing step is the insertion of the AFC. This step covers the final assembly of both the AFC device and its retaining piece. The AFC is inserted through the side of the wing flap in the AFC cutout in the foam core, Figure 3.44: (A). The AFC is inserted in such an orientation that the flat top surface faces downward and is horizontal to the ground. The exit ports of the AFC are facing the leading edge of the flap, and the reservoir tube is the upper-most feature. The AFC is then rotated into place, sliding towards the leading edge, seen in Figure 3.44: (B)-(E). The AFC will stop its rotation once the final placement has been reached. Once the AFC is located, the retaining piece is inserted, locking the AFC into place, seen in Figure 3.44: (F).

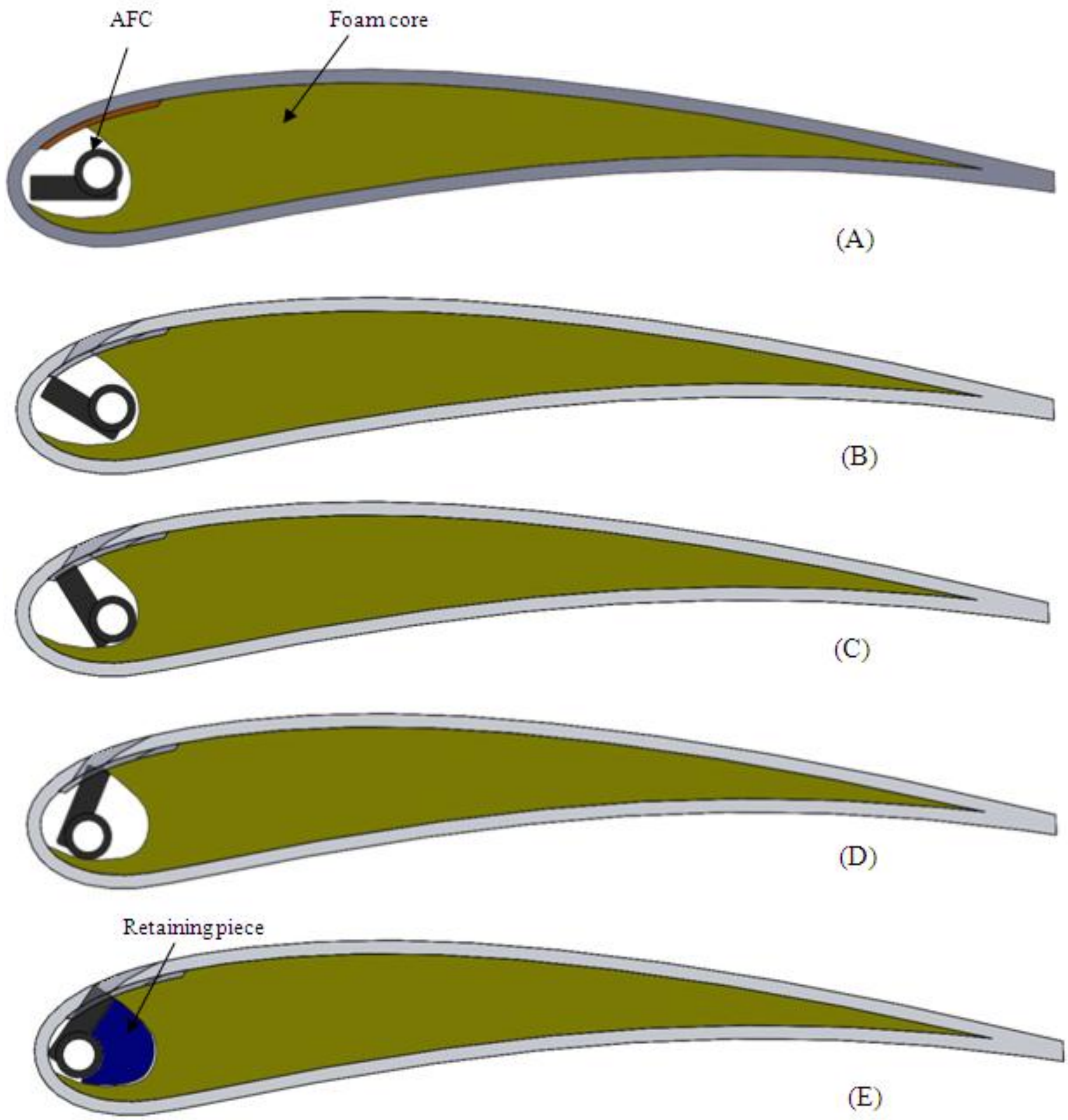


Figure 3.44: Side inserted AFC foam core insertion storyboard

The assembly is completed once the AFC is located in place and the retaining piece has been inserted. Figure 3.45 shows the assembly of the side inserted AFC with foam core design. The configuration shown has only one AFC slot with continuous connecting skin on either side. The AFC shape reduction can be seen as only the reservoir tube protrudes from the side of the wing flap. The length of the AFC slot and its number of occurrences can be modified before manufacturing allowing for custom arrangements based on specific wing flap needs.

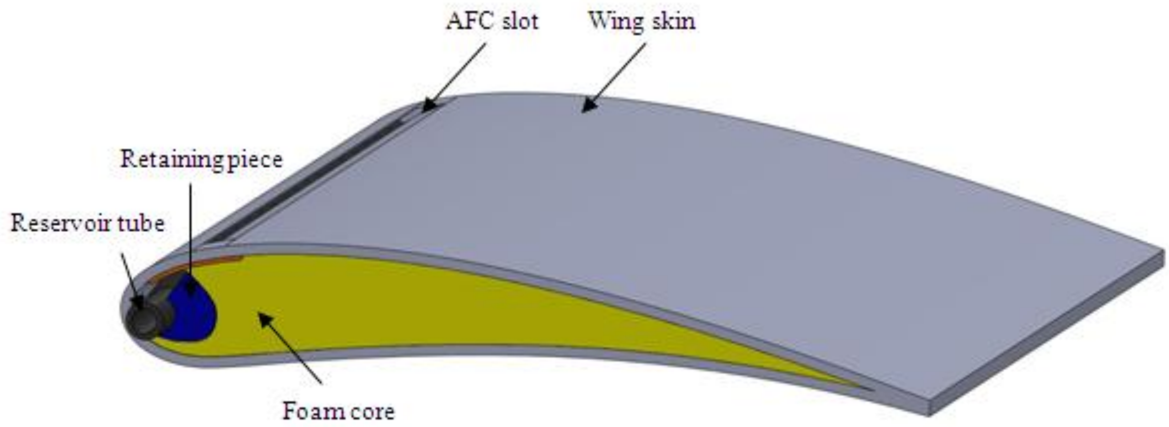


Figure 3.45: Side inserted AFC foam core design

3.3.2.2 Side Inserted Ribbed

The ribbed design variation does not support the wing skin through the entire span of the wing; instead it has empty space between each of the ribs. With the foam core, the cut-out for the AFC had to be large enough for the entire AFC body to rotate into place. Because there is no material between the ribs, the AFC cut-out for the ribbed design only has to be large enough for the insertion of the AFC into the wing flap and the path the reservoir tube takes when the AFC is rotated into place. This means that the area removed from the rib for AFC insertion, shown in Figure 3.46, is smaller than the AFC cut-out for the foam core. As with the foam core design, the AFC must rotate into place because the continuous skin on either side of the AFC slot would interfere if the AFC was inserted directly into its final location. There is no geometry change through the thickness of the ribs because the rib is located outside the geometry of the AFC slot.

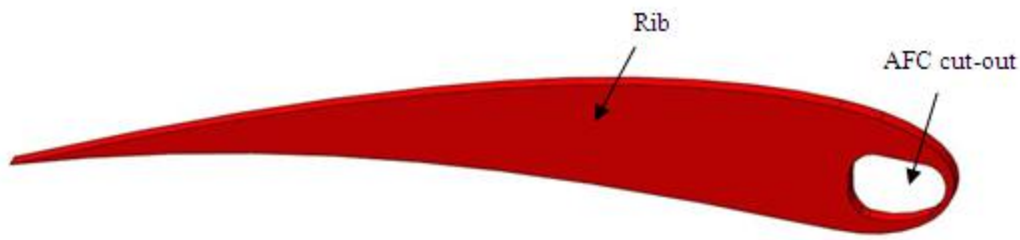


Figure 3.46: Rib with AFC cut-out for side inserted AFC design

The retaining piece for the ribbed design was created based on the remaining space in the AFC cut-out once the shape was determined by the insertion and rotation of the AFC. As with the foam core retaining piece, the ribbed core retaining piece is the same length as the wingspan of the flap so that it is in continuous contact with the AFC. The ribbed retaining piece fixes the AFC in place not only through the area of the AFC slot but also through the continuous skin areas. Figure 3.47 shows how the retaining piece locks the AFC into place by using the back of the AFC and the wing skin through the area between ribs. Through the rib thickness, the contact between the rib and the AFC reservoir tube is what allows the retaining piece to fix the AFC in place. The closest rib has been removed in order to show the detailed interior of the wing.

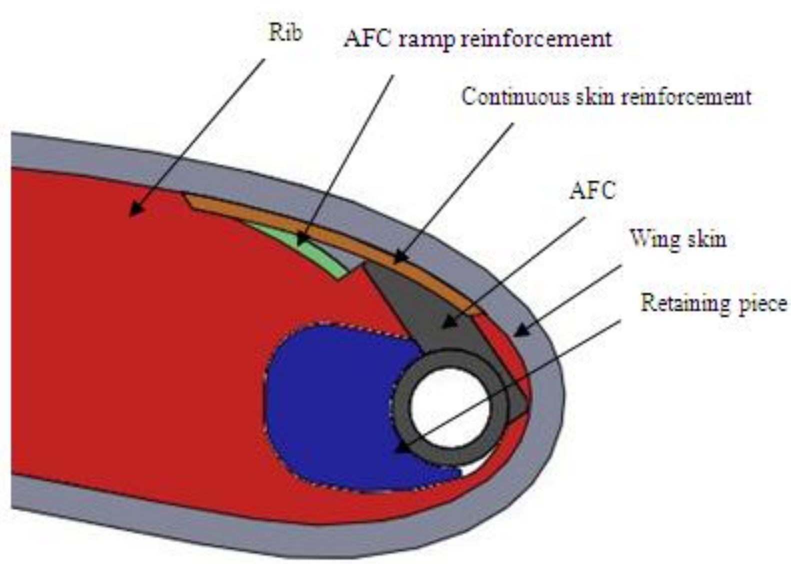


Figure 3.47: Assembly of side inserted AFC ribbed design

The fabrication of the wing skin for the side inserted AFC with ribbed design utilizes all eight manufacturing steps. A completely removable set of mandrels is required for the manufacturing process. The base mandrel shown in Figure 3.48:(A) is composed of two pieces with one side being removable so that the mandrel can easily slide out of the wing skin once the curing process has ended. The removable side is connected to the base mandrel with a very mild adhesive than can be broken with pressure. The side is removed because its exterior profile is higher than the AFC slot and would damage the AFC ramp if pulled through its thickness. The base mandrel forms the inside of the wing flap as well as the AFC slot ramp. The outer, middle, and inner mandrel pieces, shown in Figure 3.48: (B), are identical in geometry to that of the foam core. Each AFC slot is required to have its own set of the three removable mandrel pieces as well as the base mandrel piece.

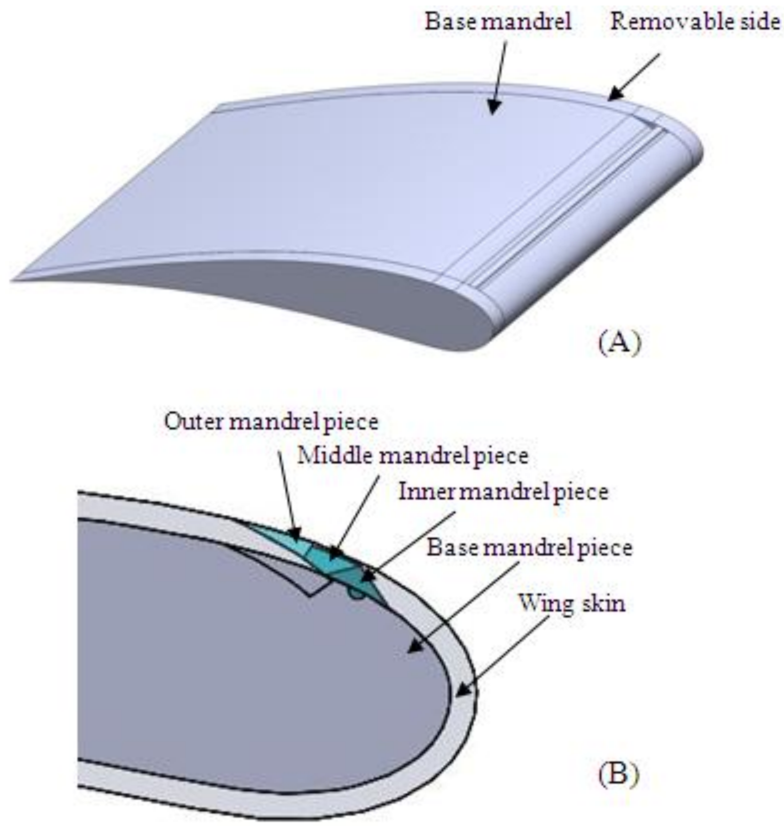


Figure 3.48: Mandrel pieces for side inserted AFC ribbed design
(A) Base mandrel and the removable side
(B) Base, Inner, Middle, and Outer mandrel pieces

The ribs for the side inserted AFC design are manufactured from a carbon fiber epoxy plate. The ribs are cut out in the geometry that was shown in Figure 3.46. The rib is cut from the carbon fiber plate and the AFC cut-out section is also removed at that time. Once the ribs are created, the carbon fiber layers are cut into the correct geometry. The layer cuts for the side inserted ribbed AFC design are identical to the layer cuts for the side inserted foam core AFC design.

The process for laying up the carbon fiber layers is identical to the foam core variant. The AFC slot must still be properly aligned through all of the layers before the vacuum bagging and infusing step can take place. Once the wing flap has cured, the mandrels must be removed. The outer mandrel piece is the first piece to be removed and the only piece removed from the top surface of the wing flap. The second mandrel piece to be removed is the base mandrel. The base mandrel is removed from both sides of the wing flap because of the removable side. By removing one side of the mandrel, the AFC slot is not damaged by the geometry of the continuous skin section be pulled through. The inner mandrel piece and the middle mandrel piece are also removed from the side of the wing flap after the base mandrel has been removed.

The seventh manufacturing step is the insertion of the ribs. The ribs must be inserted, located, and permanently fixed into place individually, Figure 3.49: (A). The final manufacturing step is the insertion of the AFC. This step covers the final assembly of the AFC device and the retaining piece. The AFC is inserted through the side of the wing flap in the AFC cutout in the rib. The insertion orientation of the AFC for the ribbed variant is identical to the foam core, shown in Figure 3.49: (B)-(E). The AFC is then rotated into place, sliding towards the leading edge. The AFC will stop its rotation once the final placement has been reached. Once the AFC is located, the retaining piece is inserted, locking the AFC into place, Figure 3.49: (F).

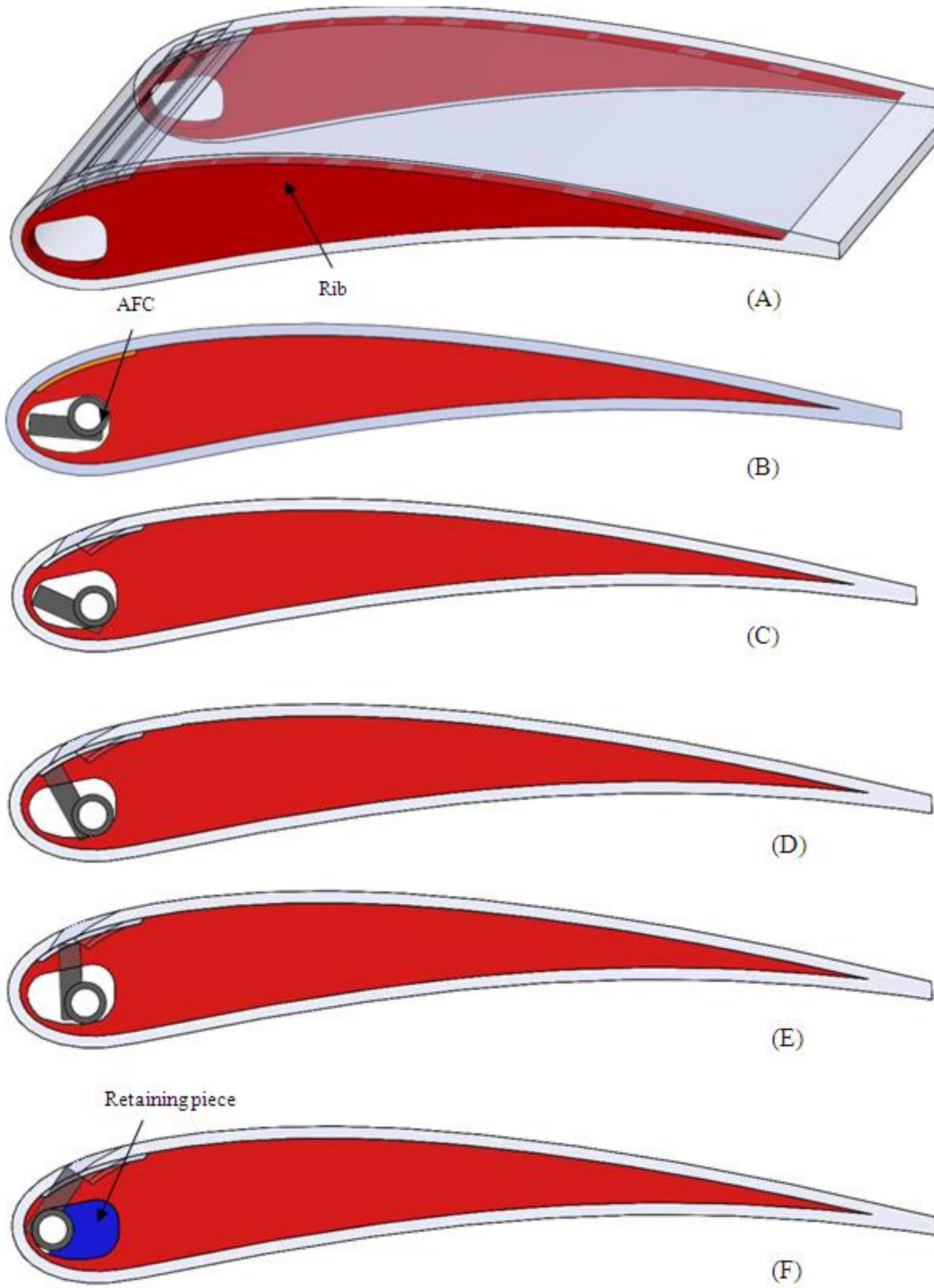


Figure 3.49: Side inserted AFC ribbed insertion storyboard

The assembly is completed once the AFC is located in place and the retaining piece has been inserted. The final assembly of the side inserted ribbed AFC design is shown in Figure 3.50. This assembly is an example of a single AFC assembly with continuous connecting material on either side of the AFC slot. The reservoir tube can be seen protruding through the rib thickness which allows for the addition of more AFC devices.

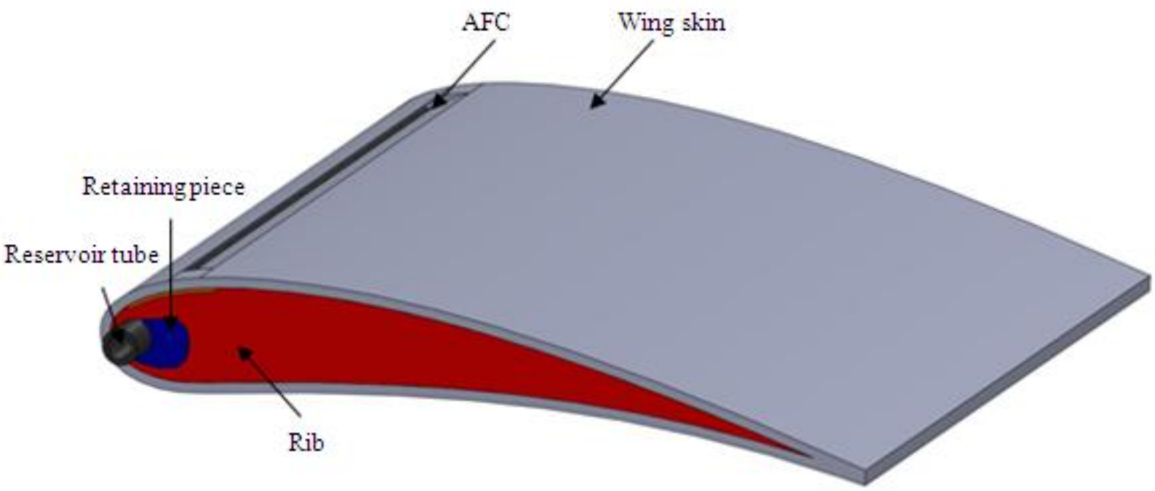


Figure 3.50: Side inserted AFC ribbed design

The side inserted designs were created to maintain the aerodynamic benefits of having a smooth airfoil surface while enabling the AFC devices to be repaired or replaced if necessary. The ability to replace an AFC device is important over the life of the wing flap. By inserting the AFC in the side of the wing flap and using a retaining piece instead of a permanent housing, a damaged unit can be replaced rather than losing performance or having to replace the entire wing flap. The two design variants within the side inserted design are the foam core and ribbed designs. The differences between these two designs are the size of the AFC cut-out, which affects the retaining piece, and the manufacturing method. For the foam core, the AFC cut-out is determined by the area needed to insert the AFC and rotate the entire body into place. The manufacturing for the foam core design requires four removable mandrels and the foam core which remains imbedded in the wing skin. The ribbed core AFC cut-out requires space for the insertion of the AFC and the path that the reservoir tube takes as the AFC is rotated into place. The manufacturing of the ribbed design requires a set of six mandrels, all of which are removed before the ribs can be put into place. Both of these variants accomplish the task of finding a way to have an internal AFC that can be easily removed for maintenance.

3.3.3 Vertically Inserted AFC

The AFC for this design is integrated into the wing skin from the top surface of the wing flap. This type of insertion allows the sides of the wing flap to be permanently sealed while still allowing the AFC devices to be accessed. This design, as with all the internal AFC integration designs, focuses on the aerodynamics of the wing flap with the other three design criteria being secondary. The structural criterion remains the same as with the side inserted AFC designs where a piece of skin in between the AFC devices is left uninterrupted to aid in the stress transfer across the AFC slot. The maintenance requirement has the same goal which is to be able to remove the AFC device for repair if necessary. The differences between this design and the side inserted AFC design are the direction that the AFC is installed and removed, as well as the method of securing the AFC.

In order to allow the removal of the AFC after integration, it needs to be fixed in such a way that it will be secured during operation but is not permanent. A stud connection similar to LEGO® blocks is a simplistic yet functional method of securing the AFC device within the wing. For this method to work both the AFC and the permanent AFC base need to be outfitted with studs and sockets respectively. The permanent AFC base is the component to which the AFC will be anchored. The base is made of the same material as the AFC and is unique to the AFC and its insertion angle.

The wing flap for this design is identical to the side inserted design once assembled. The wing skins for the vertically inserted designs require modifications because most of the AFC slot is directly attached to the AFC. Instead of a slot, a much larger hole is created to accommodate the size of the new AFC during its placement into the wing. Figure 3.51: (A) shows the modified wing flap for the vertically inserted AFC designs. A section of the original AFC slot ramp remains on the wing flap to assist in the location of the permanent AFC base. Once the AFC device has been inserted, the original AFC slot discussed at the beginning of the internal integration section is recreated. The recreated AFC slot as well as the final location of the AFC and the permanent AFC base can be seen in Figure 3.51: (B). Although not shown here, the continuous skin section is reinforced similarly to the side inserted AFC design to reduce the structural impact of the AFC hole. Unlike the side inserted AFC design, the ramp for the vertically inserted AFC design does not need to be reinforced because a majority of the ramp section rests atop the AFC device while the other section of the ramp is supported directly by the permanent AFC base.

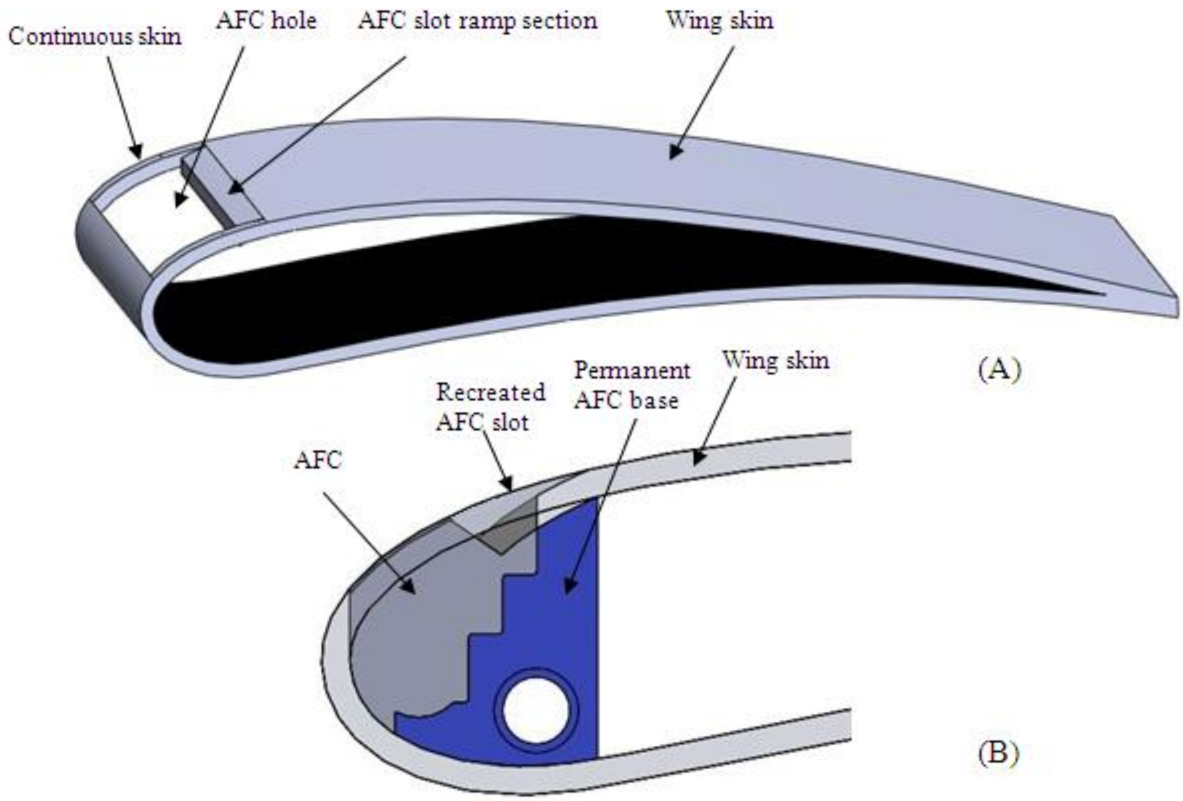


Figure 3.51: Wing flap skin modifications for vertically inserted AFC design
(A) Vertically inserted AFC wing flap
(B) Placement for vertically inserted AFC components

Unlike all the previous designs where the AFC units are chained together with a single air inlet, the vertically inserted AFC devices are all independent of each other. This division, shown in Figure 3.52, is necessary because of the continuous connecting skin that surrounds the AFC slot in the wing flap. There is no way to maintain the continuous skin pieces and still have the AFC devices touch each other when being inserted from the top of the flap. Instead of feeding all the AFC devices independently with tubing, the permanent AFC base is employed as the AFC supply tube. This restores the capability of the wing flap to have a single air inlet source and allows the permanent base to chain together through the thickness of the connecting skin instead of the AFC. Both the foam core and ribbed design variants will have material through the thickness of the connecting skin which will need cut-outs to allow the permanent base to connect to the adjacent permanent bases.

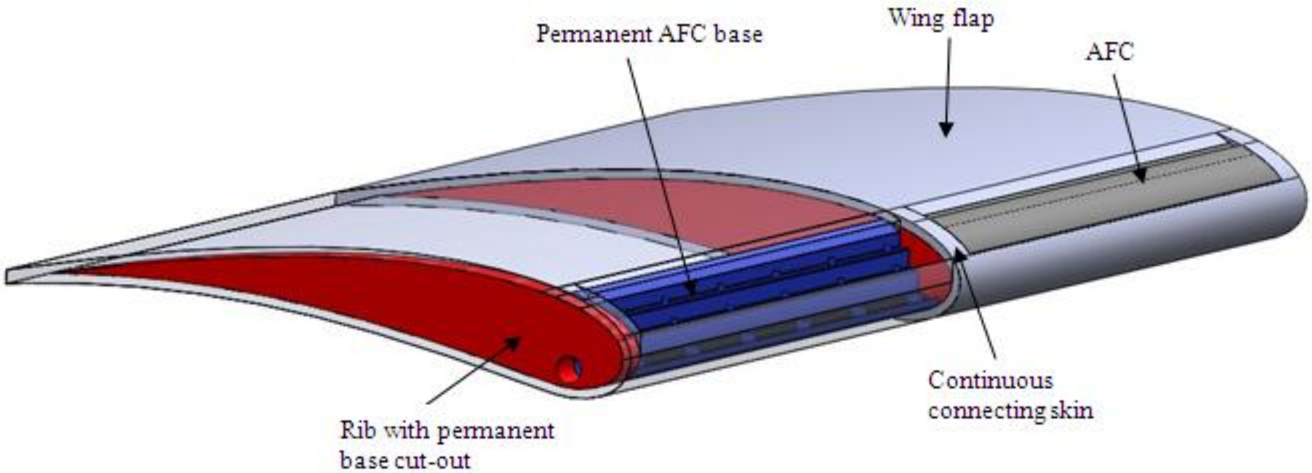


Figure 3.52: Required independence of the AFC devices

The vertically inserted AFC device is modified to employ the stud connection method with an upright installation angle. Instead of modifying the original AFC device, the side inserted AFC is used as the base for the vertically inserted AFC modifications. Material is added to create the vertical sides and stepped areas for the stud connections. The section of the ramp of the AFC slot is integrated into the AFC device to facilitate removal. The carbon fiber material used to create the AFC ramp is attached directly to the AFC device shown in Figure 3.53: (A). There is a layer of carbon fiber that covers the entire top surface of the AFC device so that it may protect the device from debris or incidental contact. A section of the ramp component of the AFC slot is supported by the AFC to allow insertion and removal of the device. The bottom of the device is equipped with a series of inlet ports and socket connections running along its length shown in Figure 3.53: (B). The inlet ports feed directly into the reservoir pipe, supplying the AFC with air. The socket connectors correspond to studs located on the permanent AFC base. The sockets enable the AFC to be fixed in place easily and without concern for the correct positioning of the exit ports.

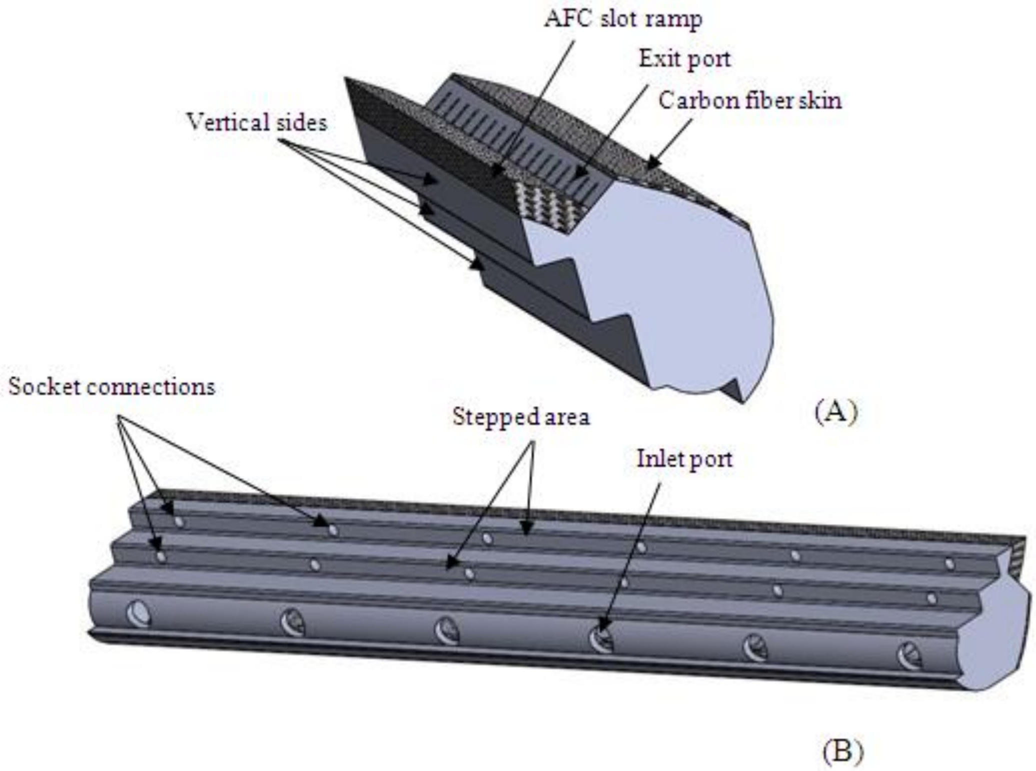


Figure 3.53: Vertically inserted AFC device
(A) Vertically inserted AFC
(B) Bottom view of vertically inserted AFC

The AFC device connects to the vertically inserted permanent AFC base which secures the AFC and houses the air supply for AFC devices. The connector protruding from the side of the base, shown in Figure 3.54: (A), is what allows the chaining through the thickness of the connecting skin. The protruding studs on the stepped area coincide with the sockets on the AFC, which secure the device in place. The feeding tube connects the permanent base internal air chamber to the reservoir pipe of the AFC allowing all of the AFC devices to be fed from a single inlet on the side of the wing flap. The gasket will seal the surface below the feeding tubes to the bottom of the AFC preventing air from escaping between the base and the AFC. Figure 3.54: (B) shows the side view of the permanent base. The side wall has been hidden to display the internal air chamber which feeds both the AFC device and the chained permanent AFC bases.

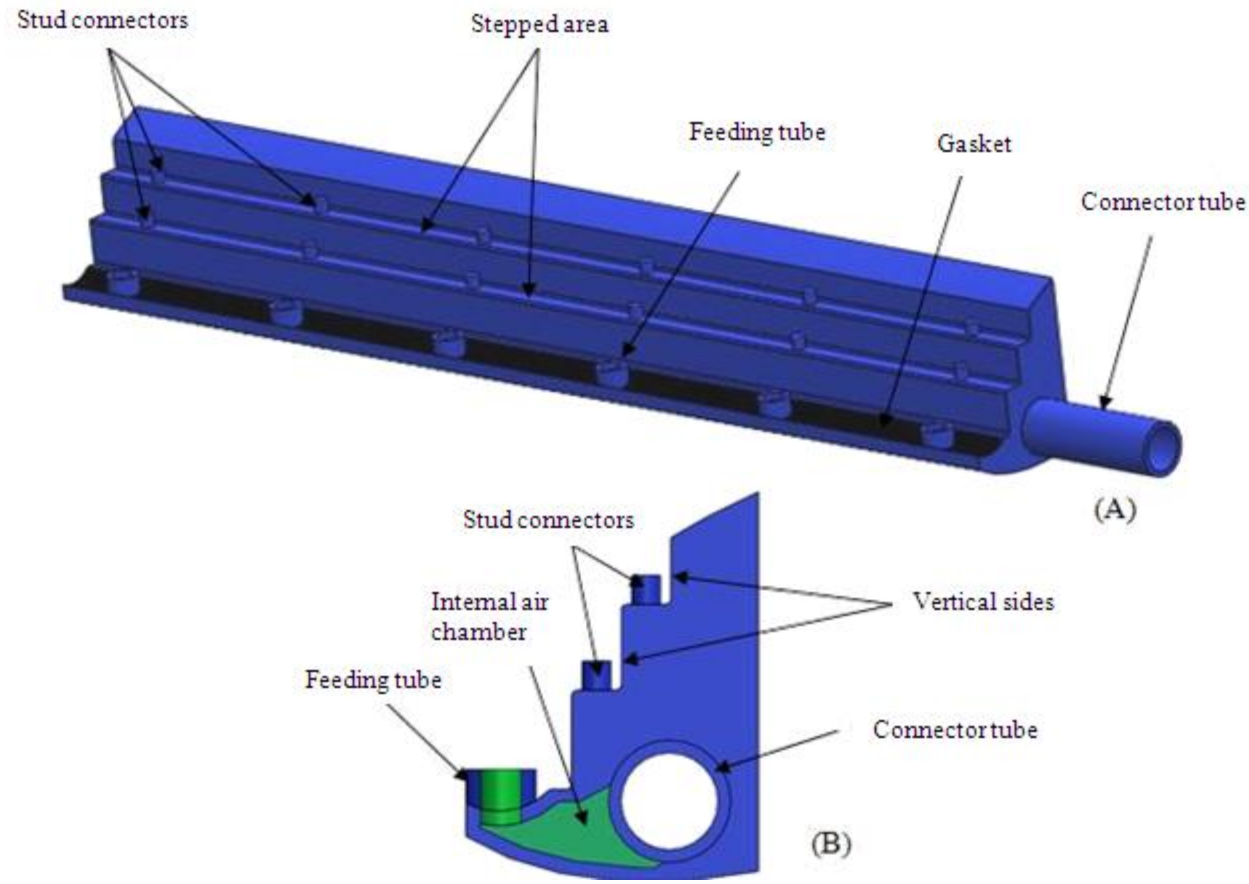


Figure 3.54: Vertically inserted permanent AFC base
(A) Isometric view of permanent AFC base
(B) Side view of permanent AFC base

The two variants within the vertically inserted AFC design are the foam core and ribbed designs. The permanent AFC base and the AFC device are the same for both the foam core and ribbed designs which gives no advantage to either in the maintenance requirement because both AFC devices are inserted and removed identically. Although foam cores and ribbed designs have different structural and weight benefits, the major difference between the two variants falls under the manufacturing design consideration. Both types of wing flaps are created using the VARTM process of composites lay-up using an arrangement of removable mandrels. The number of mandrels required to fabricate the wing flaps are unique to the specific variant as is the assembly procedure.

3.3.3.1 Vertically Inserted Foam Core

The foam core for the vertically inserted AFC design occupies all of the remaining space behind the permanent AFC base and all of the space through the connected skin from the leading edge to the trailing edge. The only space that will not be composed of foam or the permanent AFC base will be the area designated for the AFC device. Figure 3.55 shows the foam core for the vertically inserted AFC design. To accommodate the permanent base, the foam core has been divided into two pieces per AFC device. The first piece is the rear foam core which is located behind the permanent AFC base. The second piece is the continuous skin foam core piece which has the permanent base connector cut-out removed. The figure below shows two separate continuous skin foam core pieces because it depicts the area in which the permanent AFC base will reside.

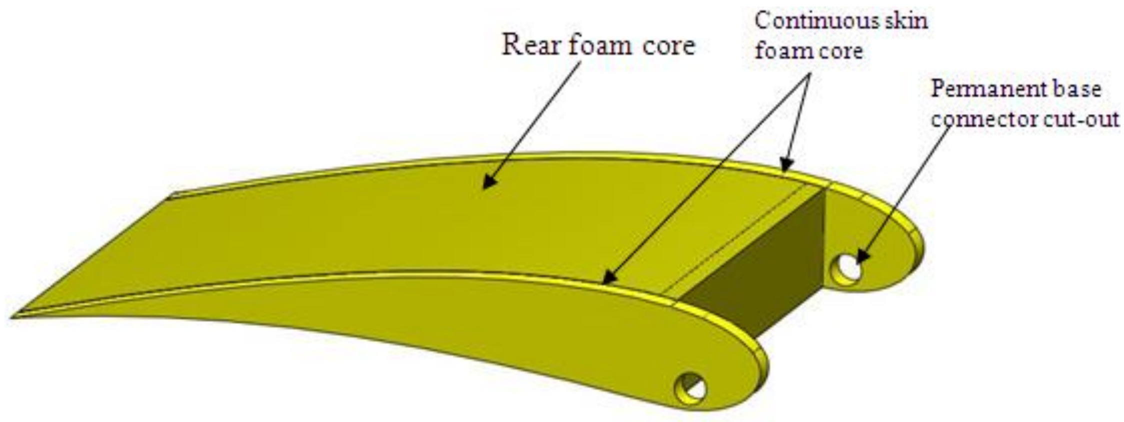


Figure 3.55: Foam core pieces for vertically inserted AFC design

The final orientation of the AFC device and the permanent AFC base are shown in Figure 3.56. The AFC is secured by pressing down on the upper surface of the AFC and having it snap into the permanent base. The continuous skin foam core has been removed to reveal the wing flap assembly. The continuous skin reinforcement is visible and is substantially larger than the reinforcement used for the side inserted AFC design. The extra reinforcement is required because the continuous connecting skin must span the AFC hole.

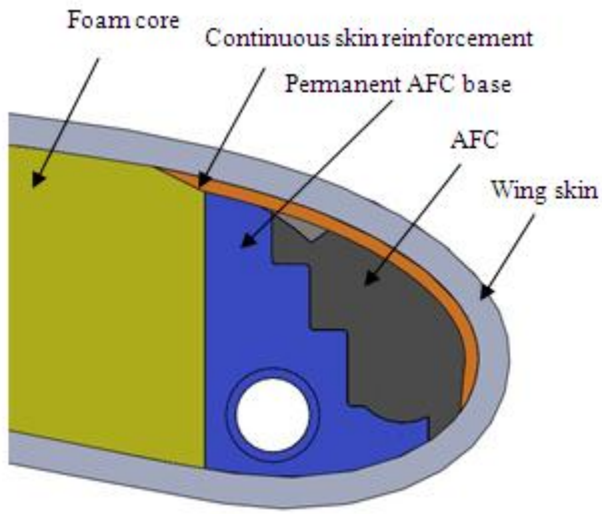


Figure 3.56: Assembly of vertically inserted AFC foam core design

The manufacturing process for the vertically inserted AFC design with a foam core requires seven of the eight manufacturing steps. The only step not utilized is step seven, "insert ribs." Even though this design has a foam core, it requires removable mandrels and the permanent AFC base to fabricate the carbon fiber wing flap. A removable mandrel is required for the foam core design to seal the AFC hole and simultaneously seal the feeding tubes of the permanent AFC base. Figure 3.57 shows the removable mandrel piece and how it is oriented. It can be seen that the mandrel fills the interior cavity for the AFC and it also completes the exterior contour of the wing flap.

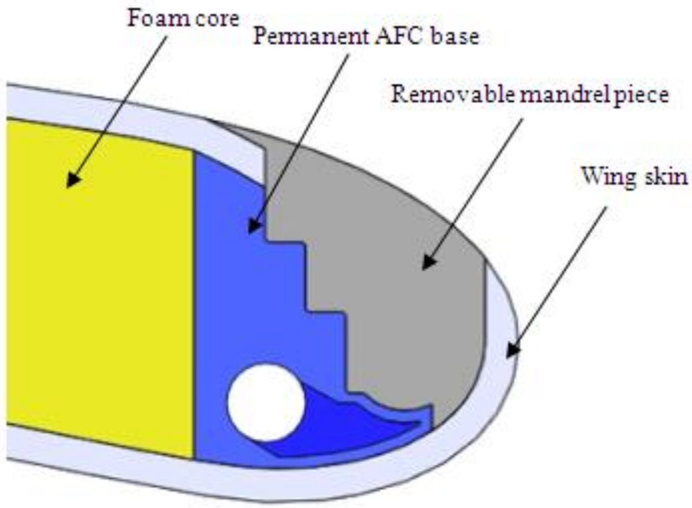


Figure 3.57: Mandrel piece for vertically inserted AFC foam core design

The second step of the manufacturing process, "create foam core," is completed using the configuration that was shown in Figure 3.55. As stated previously, the foam core must be created in pieces to allow for the insertion of the permanent AFC base prior to the carbon fiber layup process. The assembled foam core and permanent AFC base can be seen in Figure 3.58. The foam core components and the permanent AFC base are cured with epoxy before the layup process so that they remain properly located during the layup.

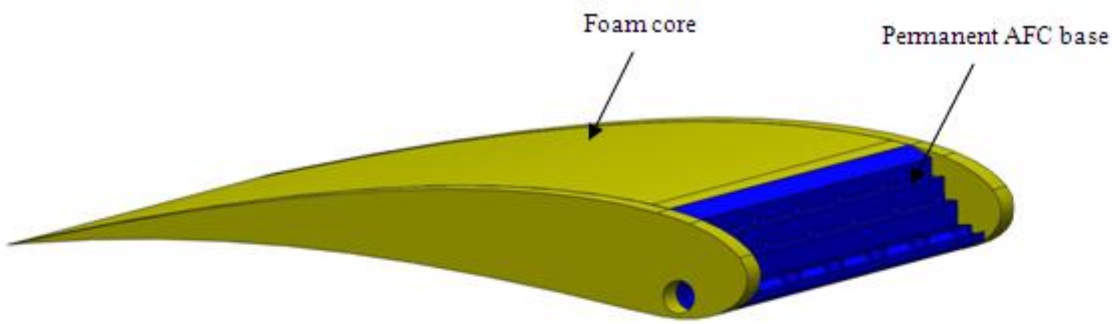


Figure 3.58: Assembled foam core and permanent AFC base for vertically inserted AFC design

After the foam core is fabricated, the layer cuts must be completed. In addition to the cuts required to form the exterior profile of the carbon fiber layer, the vertically inserted AFC design requires internal cuts to form the AFC hole. Each layer of carbon fibers is cut so that it wraps around the core, permanent AFC base, and mandrels starting at the trailing edge of the upper surface and ending at the trailing edge of the lower surface. The wing skin for both the foam core and ribbed designs are identical so the carbon layers created to manufacture the wing skins are also identical. A series of cuts are made into the carbon sheet to create the AFC hole as well as the continuous skin connecting pieces between slots. Figure 3.59 shows the cuts made in each layer of carbon fiber and what component each cut forms. The extra material has been removed to show the detail of the AFC hole cuts, but a single piece of carbon encircles the entire wing flap to preserve the continuity.

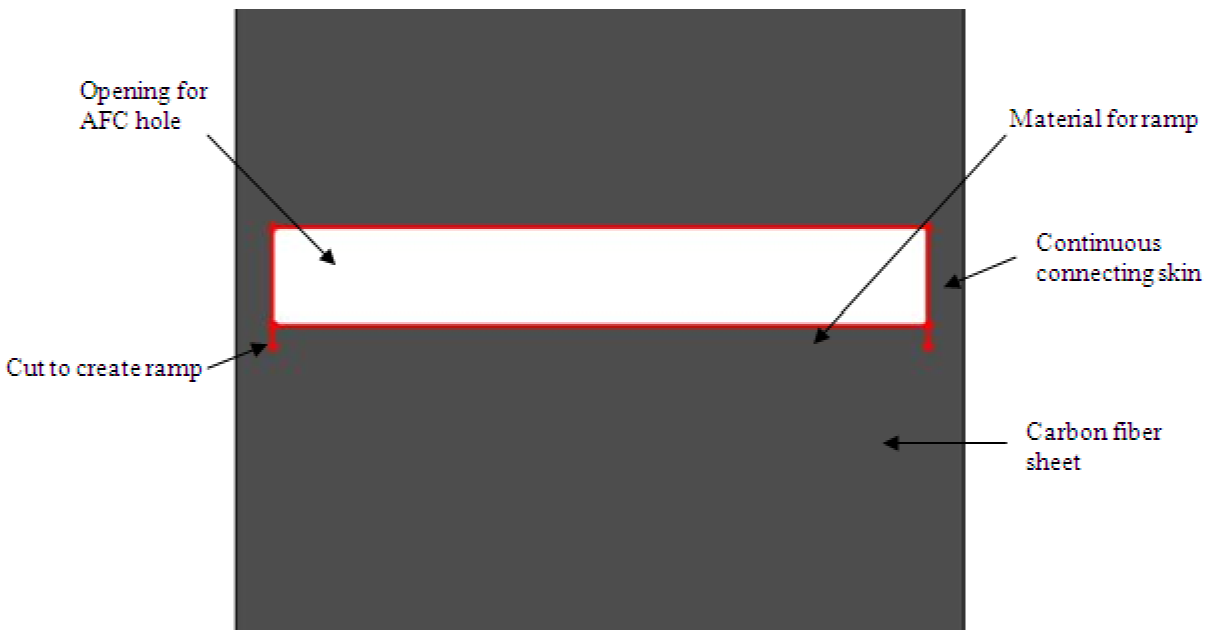


Figure 3.59: Carbon Fiber layer for vertically inserted AFC designs

The layup process for the vertically inserted AFC designs can be difficult. Each layer has identical cuts made in it to create the AFC hole, which need to be aligned to create an acceptable part just as with the side inserted AFC design. Another difficulty encountered with the vertically inserted AFC design layup is keeping the layers on the leading edge of the wing from deforming. The fibers on either side of the AFC hole will try to return to their original flat state instead of remaining attached to the leading edge contour. Once all of the carbon fiber layers have been placed and aligned correctly, the bagging and infusing step can be completed for the wing flap. A simultaneous layup process is being completed for the AFC device. The upper surface of the AFC devices is covered by carbon fiber to ensure that it remains protected during operation. Upon the successful completion of the curing cycle for the wing flap, the mandrel is removed. The mandrel is removed vertically through the AFC hole leaving the area for the AFC device. If removed correctly, the mandrel piece can be used for multiple layup operations.

The seventh step for the manufacturing process is skipped because there is no need for ribs in the foam core variant of the vertically inserted AFC design. The final manufacturing step is the insertion of the AFC. This step is simple for the vertically inserted AFC device. The AFC is inserted vertically into the AFC hole coming to rest on the permanent AFC base, Figure 3.60: (A)-(C). There is only one orientation that will allow the AFC to enter the AFC hole. Once inserted, a small vertical force is applied to the upper surface of the AFC to snap it into place; locking it with the permanent AFC base.

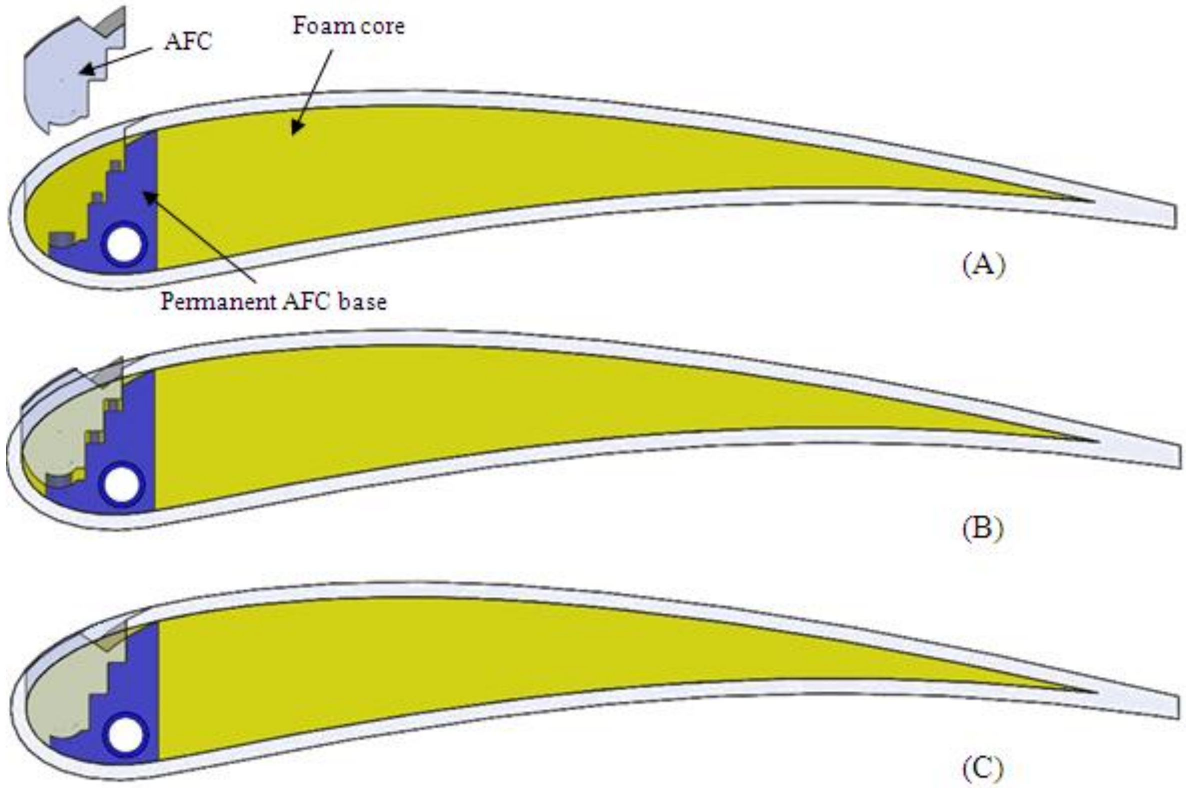


Figure 3.60: Vertically inserted afc foam core insertion storyboard

The final vertically inserted AFC foam core wing is shown in Figure 3.61. Only one AFC device has been depicted for clarity. The finalized wing is smooth through the AFC hole section because the composite pieces attached to the AFC recreate the AFC slot. The permanent AFC base connector can be seen protruding from the side of the wing. In a full wing flap, the connector will be either attached to another base or it will be the inlet tube for the entire system.

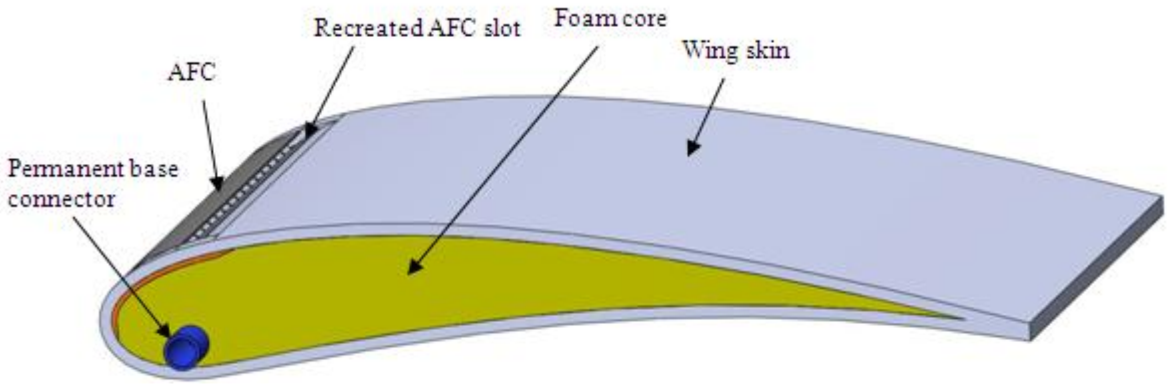


Figure 3.61: Vertically inserted AFC foam core design

3.3.3.2 Vertically Inserted Ribbed

The ribbed design, as stated previously, does not occupy all the space within the wing flap. In the ribbed design, there is no material behind the permanent AFC base as there was with the foam core design. The rib, shown in Figure 3.62, is identical in geometry to the continuous skin foam core piece in every way except thickness. The location of the rib is determined by the orientation of the AFC devices and the continuous skin that surrounds it because the rib must be contained within the width of the continuous skin. The maximum rib thickness corresponds to the width of the continuous skin but the rib can be thinner than the continuous skin if necessary. Just as with the continuous skin foam core pieces, the rib contains a permanent base connector cut-out that allows chaining between the permanent bases.

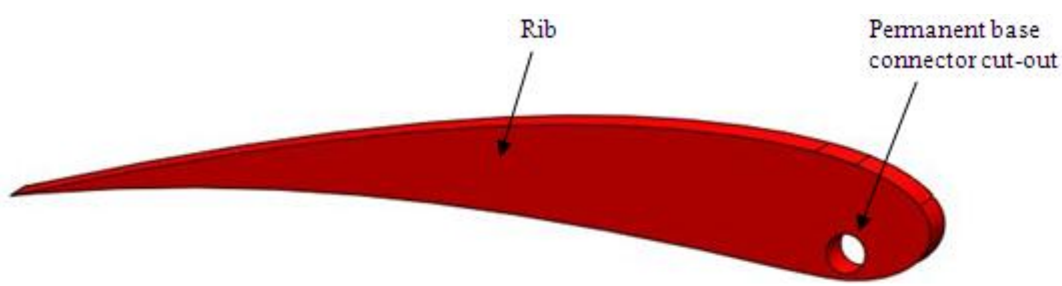


Figure 3.62: Rib for vertically inserted AFC design

The assembled attached AFC ribbed design is very similar in appearance to the foam core version. Figure 3.63 shows all of the components and their relative locations. The closest rib has been removed so that the interior of the wing can be seen. As previously stated, the continuous skin reinforcement bridges the entire AFC hole distance to limit the possibility of failure due to structural limitations.

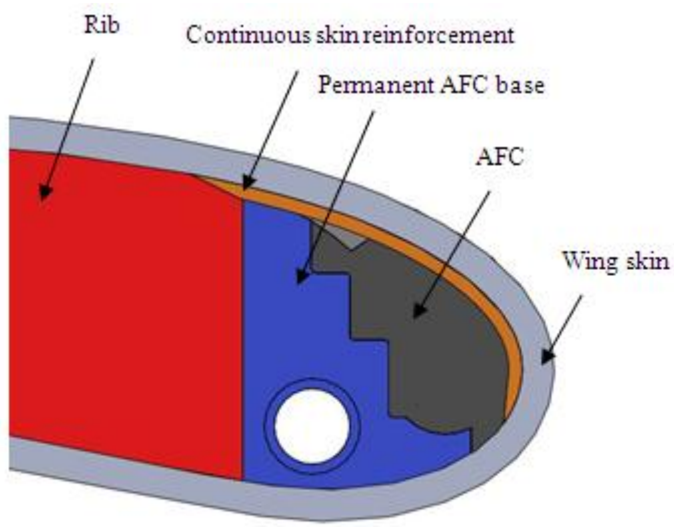


Figure 3.63: Assembly of vertically inserted AFC ribbed design

The fabrication of the wing skin for the vertically inserted AFC with ribbed design utilizes all eight manufacturing steps. A completely removable set of mandrels is required for the manufacturing process. The base mandrel shown in Figure 3.64:(A) is composed of two pieces with one side being removable so that it can easily slide out of the wing skin once the curing process has ended. The top mandrel piece shown in Figure 3.64: (B) is only required through the area of the AFC hole. The top mandrel piece fills the remaining area of the AFC hole ensuring that no resin enters. Each AFC hole is required to have its own top mandrel piece as well as base mandrel piece.

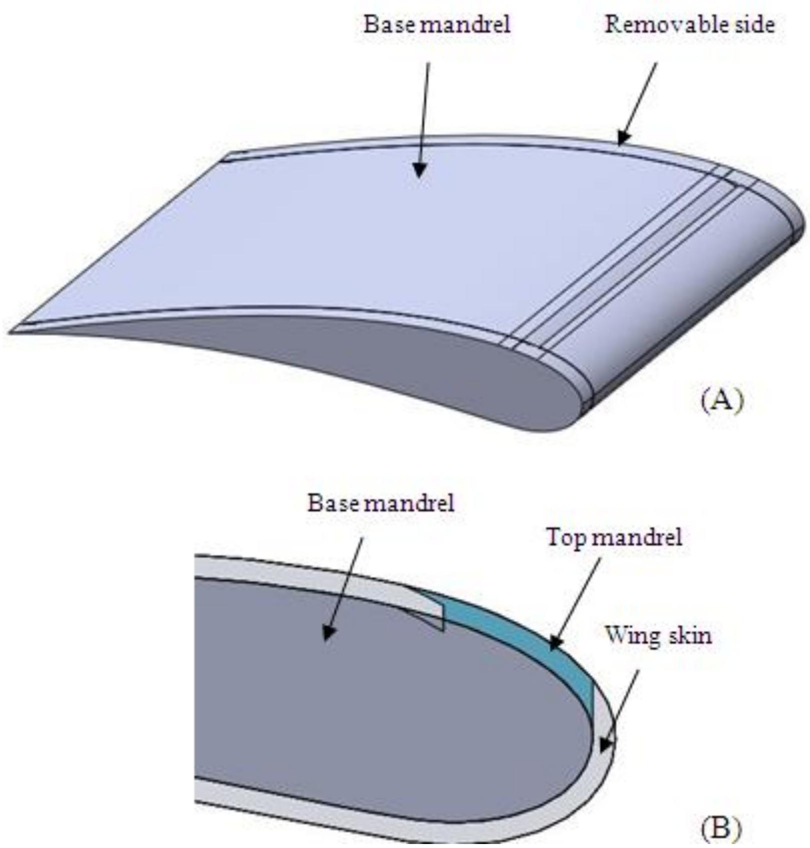


Figure 3.64: Mandrels for vertically inserted AFC ribbed design
(A) Base mandrel and the removable side
(B) Base mandrel and the top mandrel

The ribs for the side inserted AFC design are manufactured from a carbon fiber-epoxy plate. The ribs are cut out in the geometry that was shown in Figure 3.62. The rib is cut from the carbon fiber plate and the permanent base connector cut-out is also removed. Once the ribs are created, the carbon fiber layers are cut into the correct geometry. The layer cuts for the vertically inserted AFC ribbed design are identical to the layer cuts for the vertically inserted AFC foam core design.

The process for laying up the carbon fiber layers is also identical to the foam core variant. The AFC hole must still be properly aligned through all of the layers before the vacuum bagging and infusing step can take place. Once the wing flap has cured, the mandrels must be removed. The top mandrel piece is the first piece to be removed and only piece removed from the top surface of the wing. The base mandrel is removed from both sides of the wing flap because of the removable side. By removing one side of the mandrel, the flap in the AFC hole is not damaged by the geometry of the continuous skin section be pulled through.

The seventh manufacturing step is the insertion of the ribs. Before the ribs can be inserted into the wing flap, they must be combined with the permanent AFC bases. Figure 3.65: (A) shows two permanent AFC bases combined with three ribs. The bases and ribs must be assembled before the ribs are inserted because the chained bases pass through each of the ribs. The ribs and permanent AFC bases are located within the wing flap and permanently cured into place shown in Figure 3.65: (B).

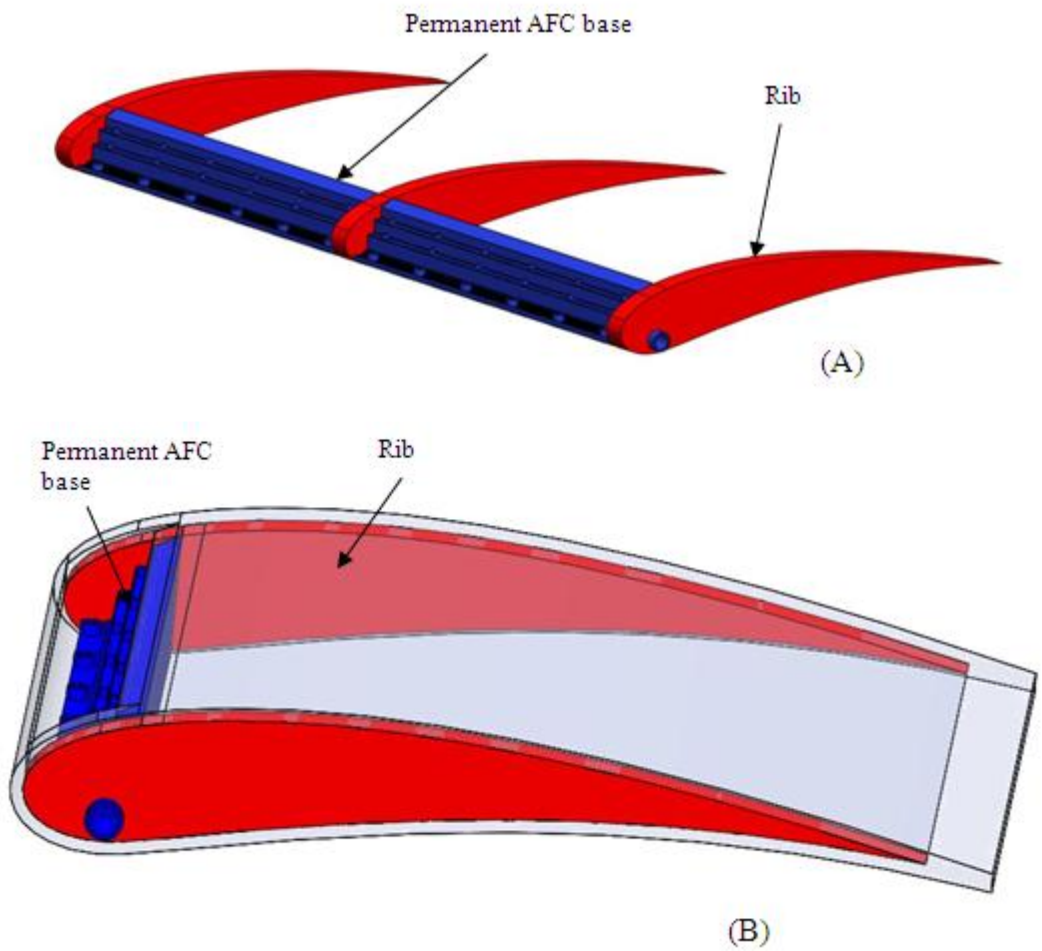


Figure 3.65: Assembled ribs and permanent AFC base for vertically inserted AFC design

The final manufacturing step is the insertion of the AFC. This step is identical to the assembly of the foam core variant. The device is vertically inserted into the AFC hole. There is only one orientation that will allow the AFC to enter the AFC hole. Once inserted, a small vertical force is applied to the upper surface of the AFC to snap it into place; locking it with the permanent AFC base shown in Figure 3.66: (A)-(C).

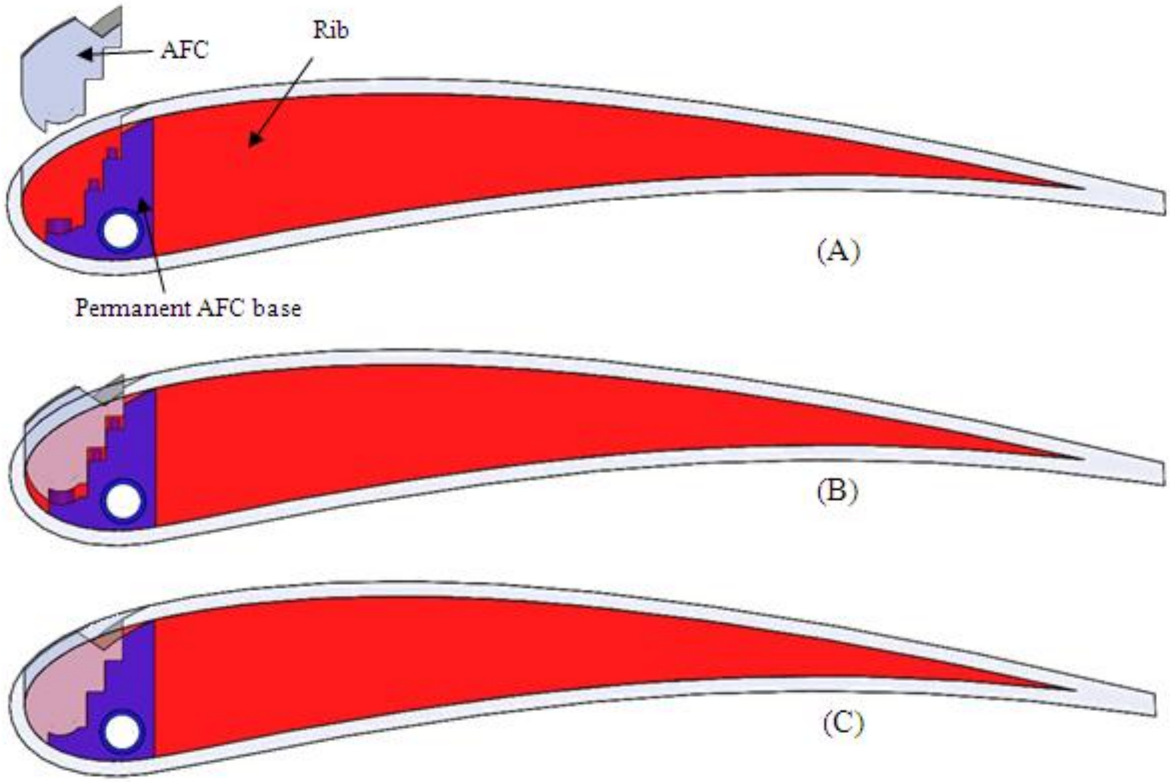


Figure 3.66: Vertically inserted AFC ribbed insertion storyboard

Once the AFC has been inserted and locked into place, the ribbed assembly is complete. Figure 3.67 shows the completed vertically inserted AFC ribbed design. The AFC slot has been recreated by inserting the AFC device into the AFC hole in the wing flap. The permanent base connector can be seen because this design only depicts a single AFC device. In a completed wing, the only permanent AFC base connector visible would be the one connected to the air source for all of the AFC devices.

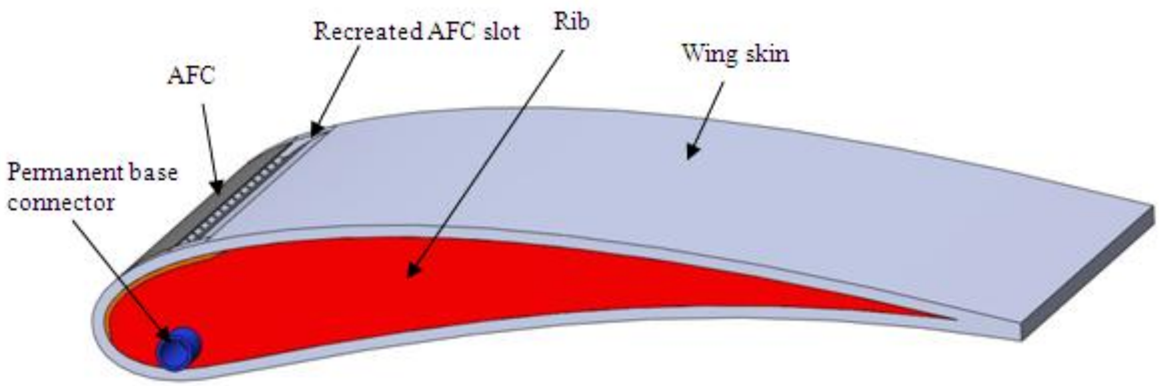


Figure 3.67: Vertically inserted AFC ribbed design

The most influential design requirement for the vertically inserted AFC design is aerodynamics. The AFC is located inside the wing flap surface to remove the negative effects of having an obstruction in the free stream air around the wing flap. The maintenance requirement is second in importance after the aerodynamics. The ability to repair or remove damaged AFC units is imperative to the functional life span of the wing flap. The vertically inserted AFC devices are fixed into place using a stud connection. This type of connection will allow the AFC devices to be removed when repair is necessary, but it is also secure enough that glues are not necessary to keep the AFC in place. The structural requirement of the design is weakened by the increased size of the AFC hole as opposed to the AFC slot from the side inserted design. To counteract the structural weakness, the continuous connecting skin that surrounds the AFC hole has been reinforced to allow stresses to be distributed around the hole instead of through the core or the AFC. The structure of the wing flap is also affected by the core selection. The two core choices are foam core and ribbed for the vertically inserted AFC design. The manufacturing for each design variant is unique in both the layup equipment and the final assembly process. The foam core variant requires one removable mandrel, the foam core, and the permanent AFC base to layup the carbon fiber layers. Once cured, the assembly is completed by removing the mandrel and inserting the AFC. The ribbed design variant requires six removable mandrels to layup the carbon fiber layers. Once cured, the mandrels must be removed and the permanent AFC bases and ribs are assembled and inserted into the wing flap. Both design variants offer solutions to the questions posed in the internal AFC integration introduction section. They both have an AFC device that fits inside the wing skin and can be easily removed for maintenance.

3.3.4 Attached AFC

The attached AFC design is the final design in the internal AFC designs category of the design tree. Instead of the AFC device being inserted from the side or the top of the wing flap, the attached AFC is placed on the front of the wing flap as a nose cone. The importance of the aerodynamics aspect of the internal AFC designs remains with the attached AFC design. The attachment method of the nose cone needs to ensure that there are no objects in the airflow in order to satisfy the aerodynamics requirement while also accommodating the maintenance requirement of removal and replacement of the AFC device. The attached AFC design is unique from both the side inserted and top inserted designs not only because of the insertion direction and the method of securing, but it does not require the same structural considerations across the AFC slot. The original internal design wing flap incorporated the AFC slot and continuous skin surrounding it. The attached AFC design eliminates the need for the continuous skin by utilizing an almost continuous base wing skin.

The attached AFC device is secured to the leading edge of the base wing flap. To accommodate the attachment of a nose cone, the wing flap chord length must be reduced in order to preserve the original wing flap profile once fully assembled. The profile of the leading edge of the original wing flap is shifted back towards the trailing edge until it surpasses the location of the AFC slot. Figure 3.68 shows the new base wing skin with an outline of the location of the original wing flap and AFC slot. The base wing flap has a similar profile to the original wing flap and can still function with the AFC nose cone removed, but the flight characteristics would differ between the two flaps. Two flange slots are removed from the leading edge of the base wing flap to accommodate the flanges that attach the AFC device. The flange slots are small and spaced far enough apart that serious stress issues should not arise within the base wing skin. Removing the AFC slot from the wing flap eliminates the need for there to be continuous connecting skin across the slot.

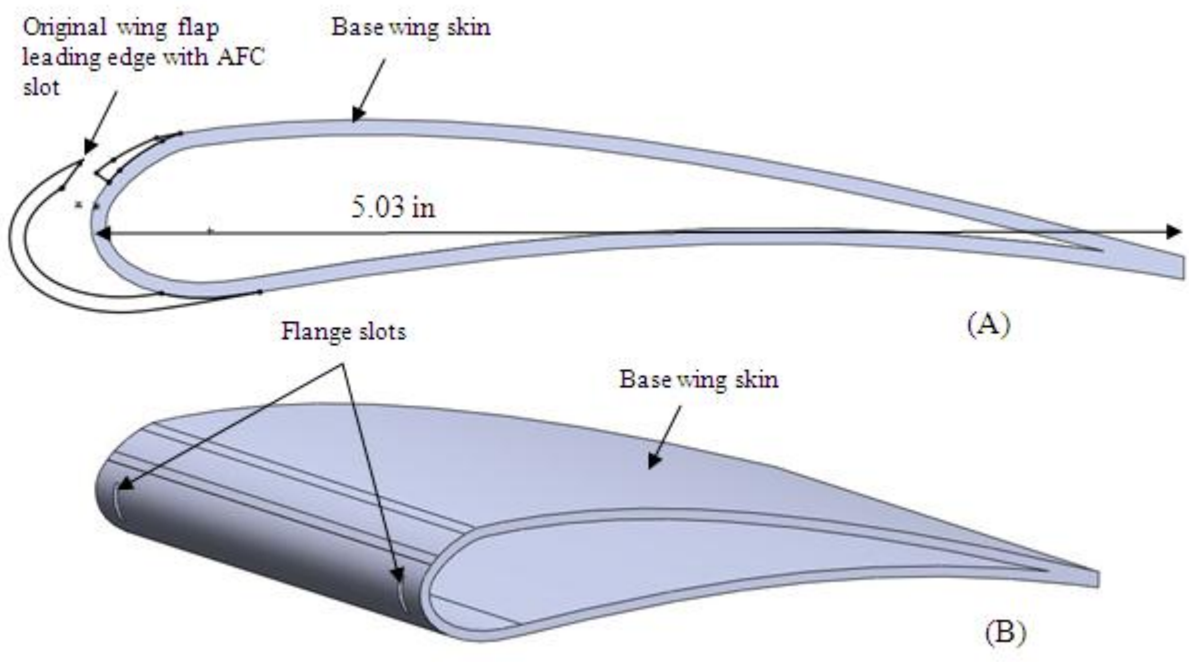


Figure 3.68: Wing flap skin modifications for attached AFC design
(A) Base wing skin for attached AFC design
(B) Base wing skin with flange slots

The attachment method for the attached AFC design is a pin connection. The AFC device is equipped with flanges that correspond to the flange slots located in the base wing flap. The addition of the flanges is only one of the modifications required for the AFC device, shown in Figure 3.69. The base AFC for these modifications is the side inserted AFC. Material is added to the side inserted AFC so that it mirrors the contour of the leading edge of the base wing flap. The AFC slot is recreated on the AFC device so that the air exiting the AFC will flow tangentially onto the base wing flap. Flanges are added as the attachment method between the AFC and the base wing flap at the leading edge. The flanges are equipped with a cut-out for the securing pin. The square shape of the cut-out will limit the AFC device's ability to rotate around the leading edge of the base wing flap. The composite layers of the nose cone assembly encase the leading edge of the AFC. The skin offers the AFC device protection from the free stream air and any debris that accompanies it. The AFC slot ramp also is covered in a protective carbon fiber skin for the same reasons. The AFC devices for this design will be chained together before they are attached to the base wing skin. This chaining allows a single air inlet source at the side of the wing flap.

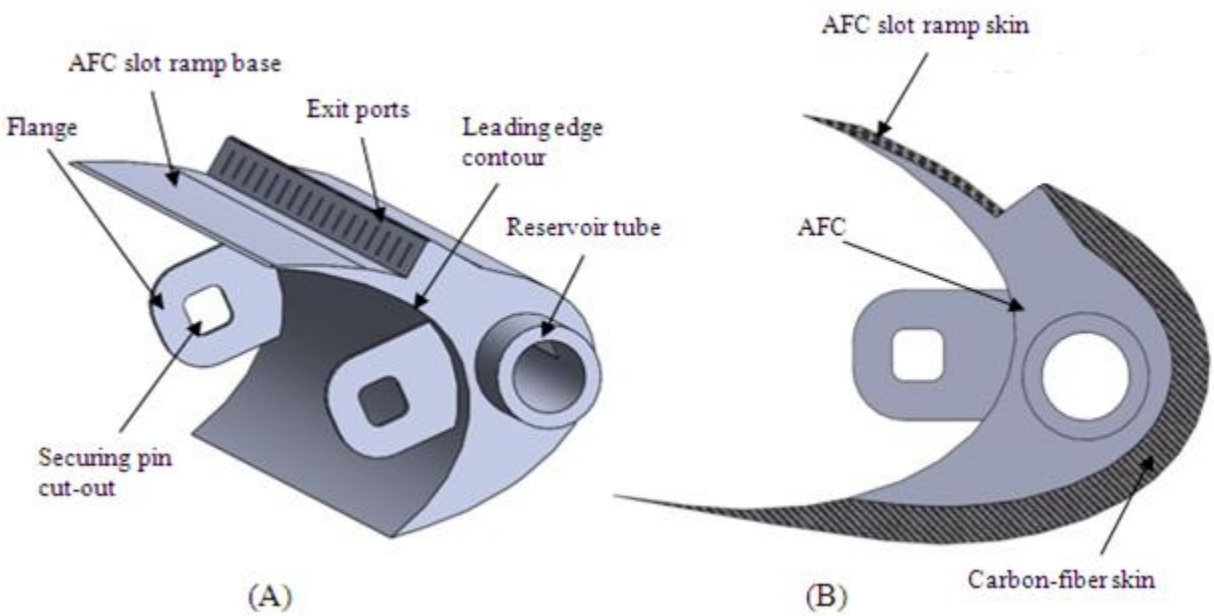


Figure 3.69: Attached AFC device
(A) Base AFC device
(B) Nose cone sub-assembly

3.3.4.1 Attached Foam Core

The foam core variation of the attached AFC design utilizes a permanent foam core that encompasses all of the space inside the base wing flap except for the area needed to place the attachment anchors and the securing pin. The foam core variant requires attachment anchors to ensure that the foam core is not damaged if the AFC flanges exert forces on the securing pin. Figure 3.70 shows the foam core for the attached AFC design. There is no need to divide the foam core into pieces as with the top inserted AFC design because the attachment anchors slide in from the front.

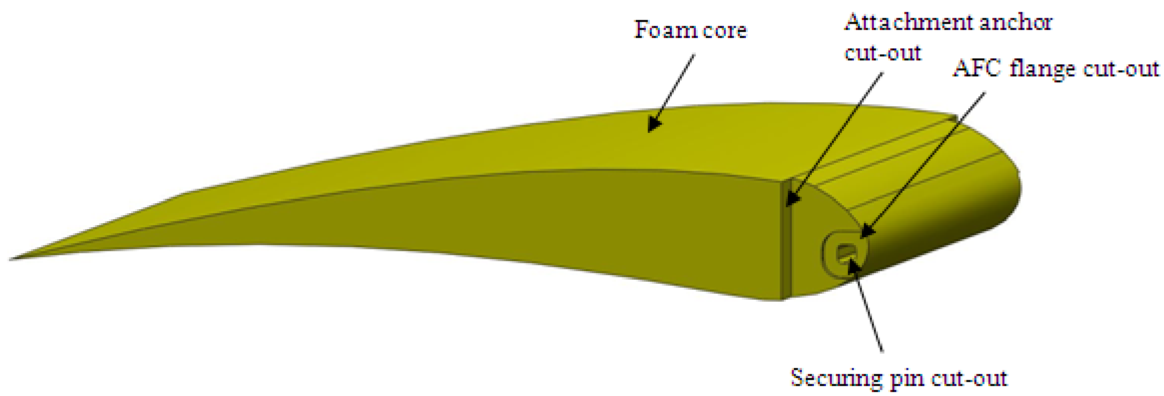


Figure 3.70: Foam core for attached AFC design

The attachment anchor is necessary for the attached AFC foam core design because of the forces that could be put on the securing pin by the nose cone assembly. The foam core might not be structurally robust enough to withstand the forces generated when the nose cone assembly is being pulled by aerodynamic forces. The attachment anchor shown in Figure 3.71 is made of the same material as the securing pin. The contour on the front edge will seat against the carbon fiber skin of the leading edge of the base wing. The flat back side will seat against the foam core. There will be two attachment anchors per AFC nose cone to ensure that they remain attached.

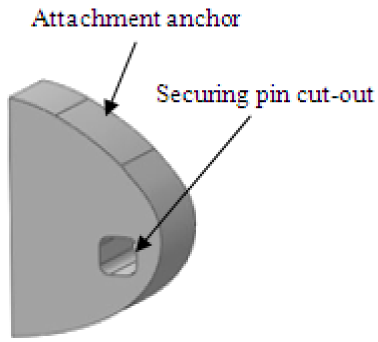


Figure 3.71: Attachment anchor for attached AFC foam core design

The securing pin has two primary functions: to attach the AFC nose cone and to prevent it from moving. The securing pin has a square shape because this will keep the AFC nose cone flanges from trying to rotate within the base wing. Once the AFC nose cone flanges have been inserted into the base wing flap, the securing pin is inserted which locks everything into place. Figure 3.72 shows the final assembly with the base wing skin and foam core transparent so that the flanges, securing pin, and attachment anchors can be seen.

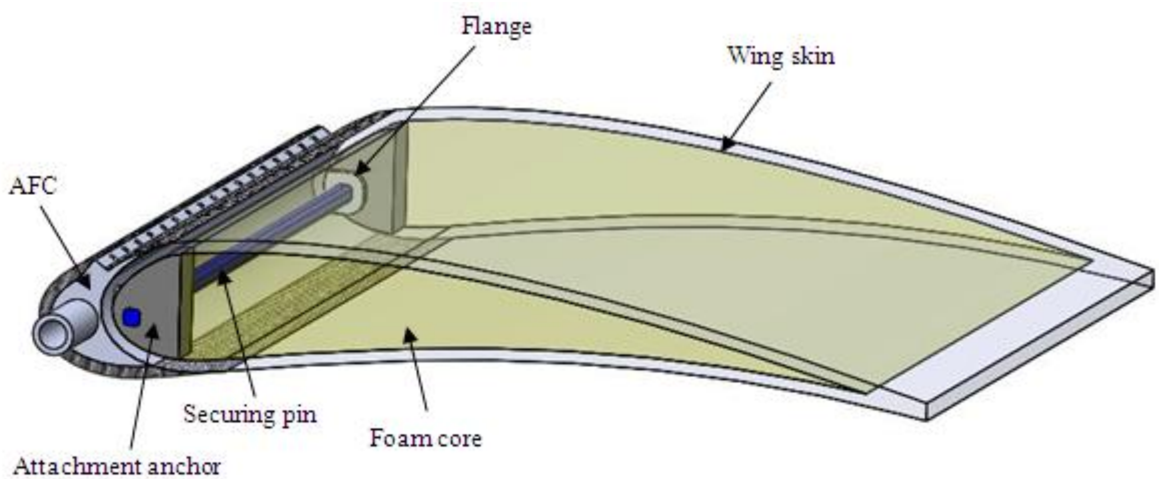


Figure 3.72: Assembly of attached AFC foam core design

The manufacturing process for the attached AFC foam core design again requires seven of the eight manufacturing steps. The only step not utilized is step seven, “insert ribs.” Even though this design has a foam core, it requires three removable mandrels and the attachment anchor to fabricate the carbon fiber wing flap. Two removable mandrels are required for the foam core design to seal the flange slots and the flange locations within the foam core. The third mandrel is identical in geometry to the securing pin which keeps the flange mandrels in place as well as keeping the resin out of the area reserved for the securing pin. Figure 3.73 shows the removable mandrel pieces and anchor pieces within the foam core.

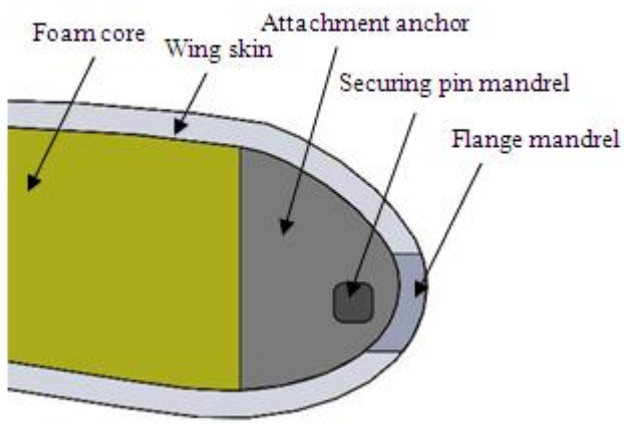


Figure 3.73: Mandrel pieces for attached AFC foam core design

The second step of the manufacturing process, "creating the foam core," is completed using the configuration which was shown in Figure 3.70. The cut-outs in the leading edge of the foam core are spaces left for the incorporation of the attachment anchors. The attachment anchors are used to negate the possibility of the securing pin pulling through the foam. The attachment anchors are cured into the foam core with epoxy prior to layup so their orientation is assured. The assembled foam core and attachment anchors can be seen in Figure 3.74.

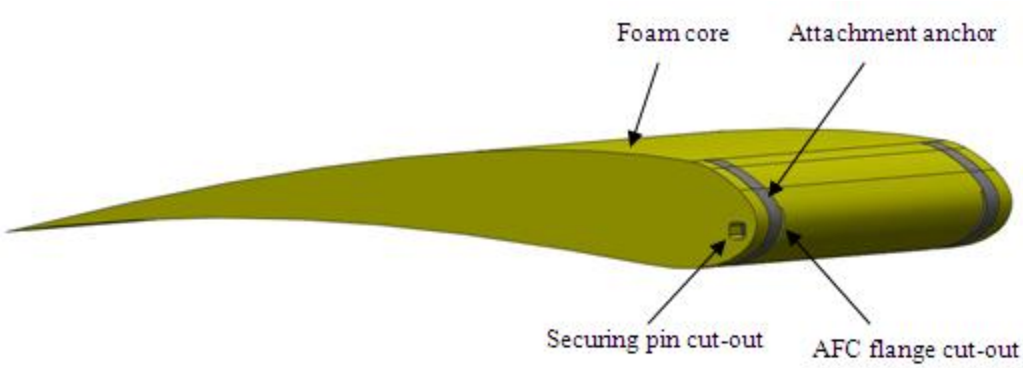


Figure 3.74: Assembled foam core and attachment anchors for attached AFC design

After the foam core is fabricated, the cuts for the carbon fiber layers must be completed. As with all the previous designs, cuts around the exterior of the layer are required to form the width of the wing flap. Along with the exterior cuts, the attached AFC designs require internal cuts to form the flange slots. The wing skin for both the foam core and ribbed designs are identical so the carbon layers created to manufacture the wing skins are also identical. A series of small cuts are made into a carbon fiber sheet to create the flange slots. Figure 3.75 shows the cuts made in each layer of carbon fiber and the component each forms. The extra material has been removed to show the detail of the flange slot cuts, but a single piece of carbon encircles the entire wing flap to preserve the continuity.

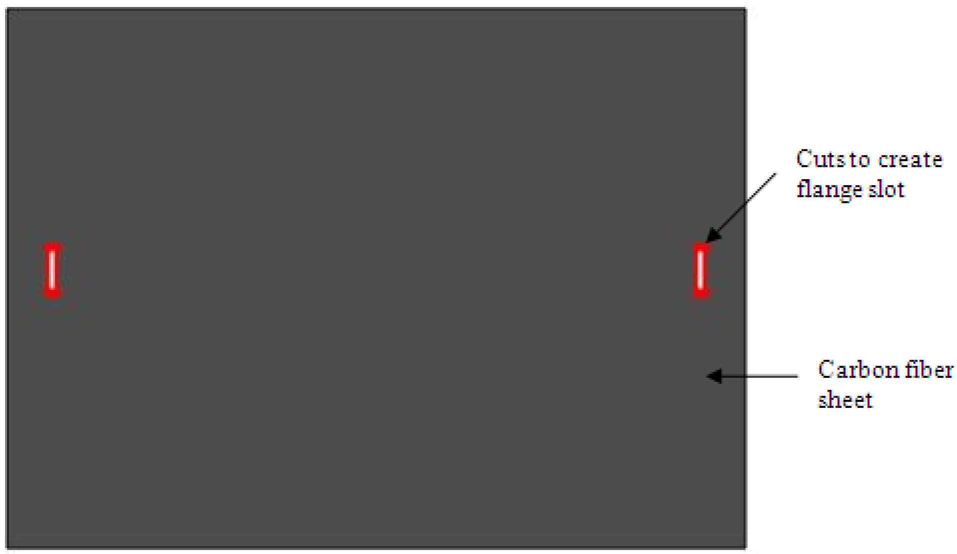


Figure 3.75: Carbon fiber layer for attached AFC designs

The layup process for the attached AFC designs is the simplest of the internal designs. Each layer has identical cuts to create the flange slots, which are aligned around the flange slot mandrels. The mandrels for the flange slots protrude giving the carbon layers something to grip as they are formed around the rest of the wing flap. Once all of the carbon fiber layers have been placed and aligned correctly, the bagging and infusing step can be completed for the wing flap. A simultaneous layup process is being completed for the AFC device. The leading edge surface of the AFC devices is covered by carbon fiber to ensure that it remains protected during operation. The completed layup of the AFC creates the nose cone sub assembly. Upon the successful completion of the curing cycle for the wing flap, the mandrels are removed. The securing pin mandrel is removed first from the side of the wing flap. Once the securing pin mandrel is removed, the flange mandrels are free to be removed from the leading edge of the base wing flap. If removed correctly, the mandrel pieces can be used for multiple layup operations.

The seventh step for the manufacturing process is not necessary because there are no ribs in the foam core variant of the attached AFC design. The final manufacturing step is the insertion of the AFC. This step is relatively simple for the attached AFC nose cone. The flanges on the nose cone sub-assembly are inserted into the flange slots until the contour of the AFC rests on the leading edge contour of the base wing flap, shown in Figure 3.76: (A)-(B). The securing pin is situated through the cut-out in the attachment anchors, locking the nose cone into place shown in Figure 3.76: (C).

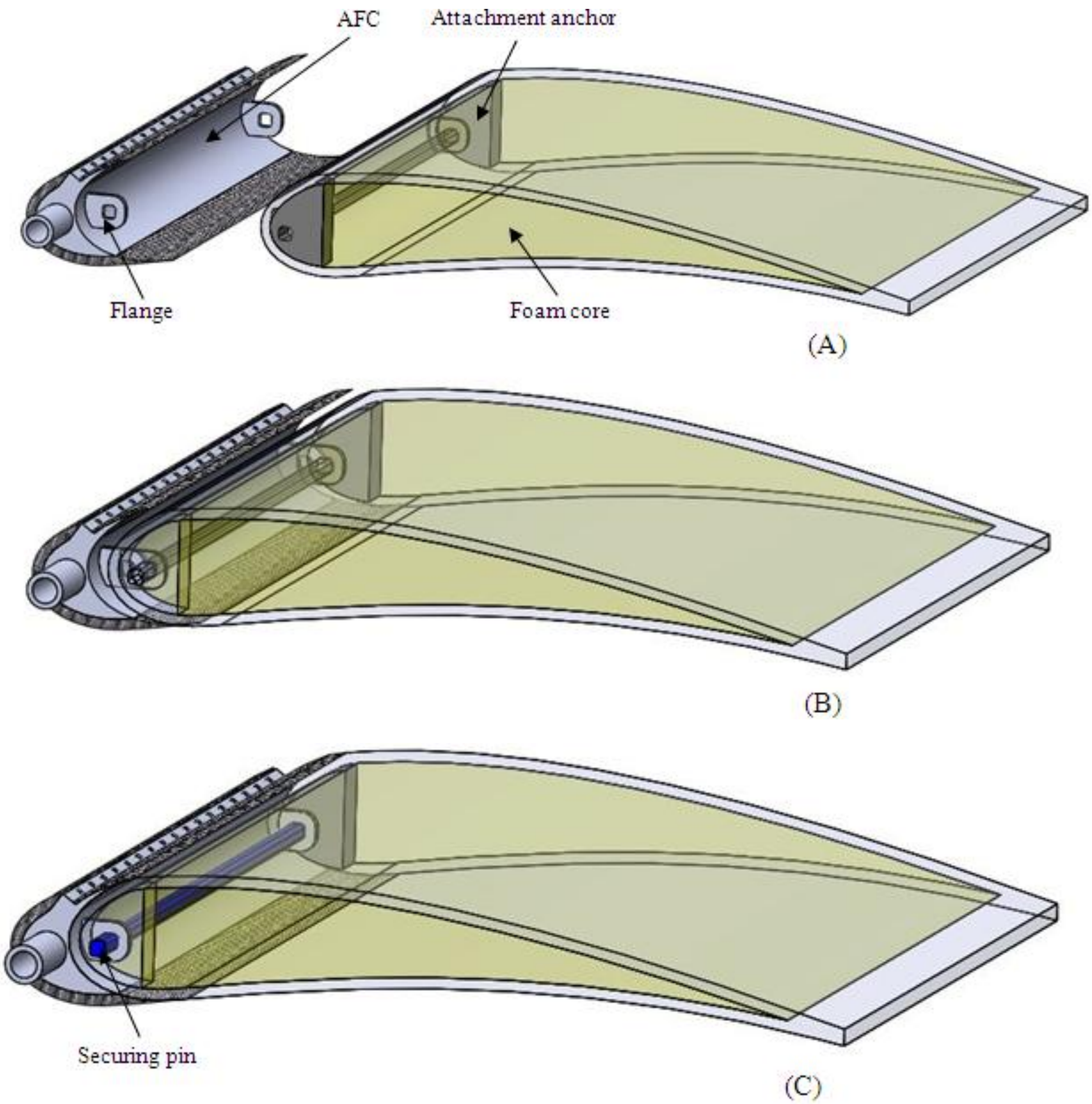


Figure 3.76: Attached AFC foam core insertion storyboard

The final attached AFC foam core design is shown in Figure 3.77. The wing flap appears similar to both the side inserted and top inserted designs except for the removal of the continuous connecting skin for the attached design. The continuous skin pieces are not necessary for the attached AFC design because stresses and strains in the base wing skin will not transfer across the AFC slot. The locations on the top and bottom surface of the base wing skin where the nose cone sub-assembly skin merges requires a sealant to ensure that no air from the free stream is able to enter the area between the nose cone assembly and the base wing flap. The final wing flap will appear as a single piece instead of the two clearly identifiable sections shown in Figure 3.77.

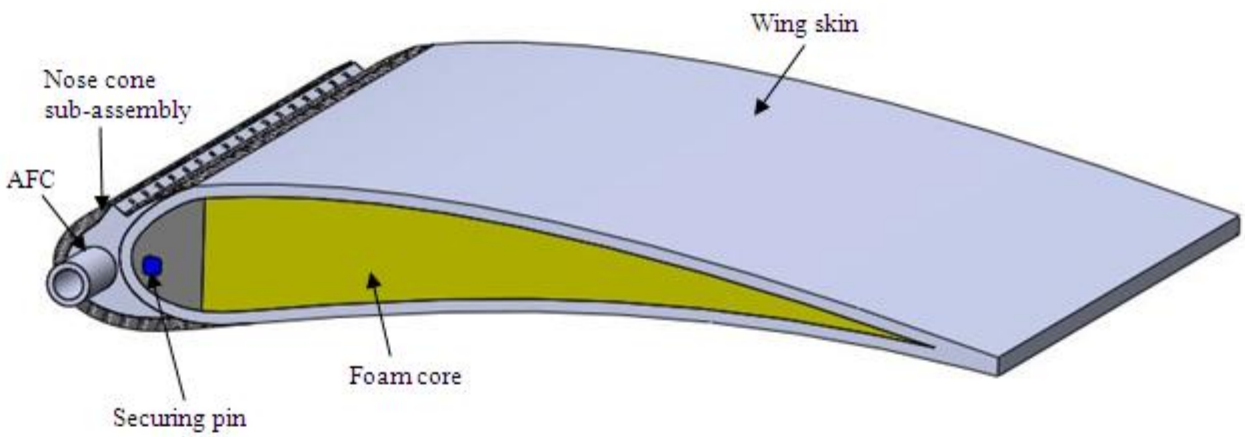


Figure 3.77: Attached AFC foam core design

3.3.4.2 Attached Ribbed

The ribbed variant of the attached design does not have the same rib location constraints as previous internal AFC designs. With both the side inserted and vertically inserted designs, the locations of the ribs are restricted to the area of the continuous connecting skin pieces. The continuity of the base wing skin allows the ribs to be placed almost anywhere within the base wing skin, with the exception of the flange slot locations. It is ideal for the ribs to be placed directly adjacent to a flange slots because the ribbed design variant does not incorporate an attachment anchor like the foam core variant. The rib, shown in Figure 3.78, acts not only as the primary support for the base wing skin but also as the attachment anchor for the nose cone sub-assembly. The rib has a cut-out for the securing pin which facilitates the rib's function as the attachment anchor.

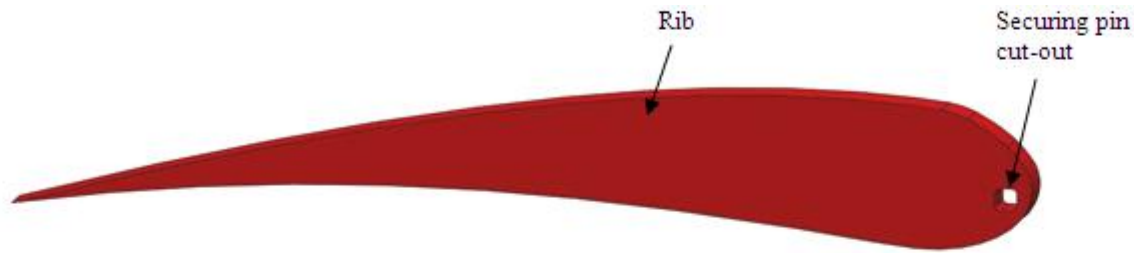


Figure 3.78: Rib for attached AFC design

The assembly of the attached AFC ribbed design is almost identical to the foam core variant. The major difference between the two is the lack of attachment anchors for the ribbed version. The ribs are made from carbon fiber and are therefore much more adept at handling the loads that the securing pin will encounter. The attached AFC ribbed assembly, shown in Figure 3.79, is completed once the securing pin is in place. The skin and closest rib are transparent to show the flanges and securing pin.

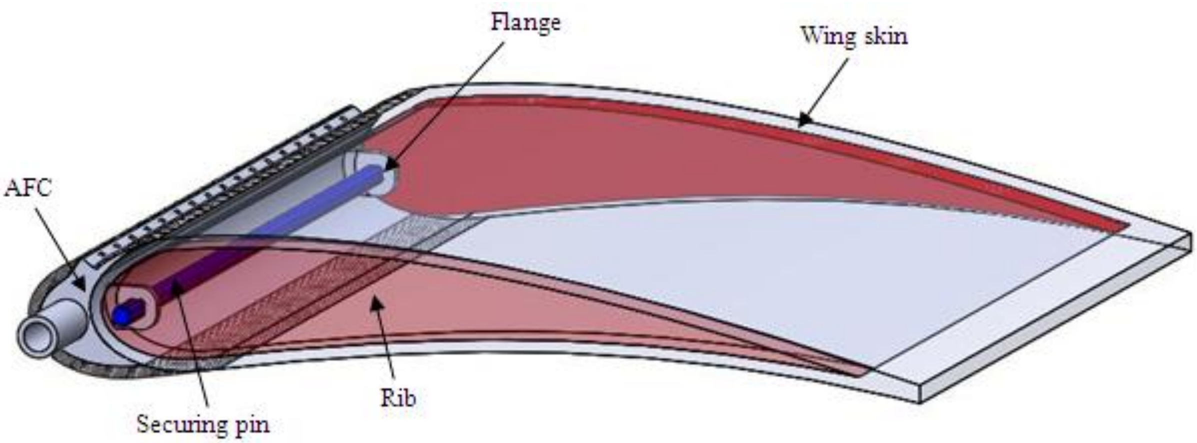


Figure 3.79: Assembly of attached AFC ribbed design

The fabrication of the wing skin for the attached AFC ribbed design utilizes all eight manufacturing steps. A removable set of mandrels is required to manufacture the base wing flap. The base mandrel and the flange slot mandrels are shown in Figure 3.80. Unlike the other internal AFC designs; the base mandrel is a single piece. The flange slot mandrels attach to the leading edge of the base mandrel to provide the openings for the flange slots.

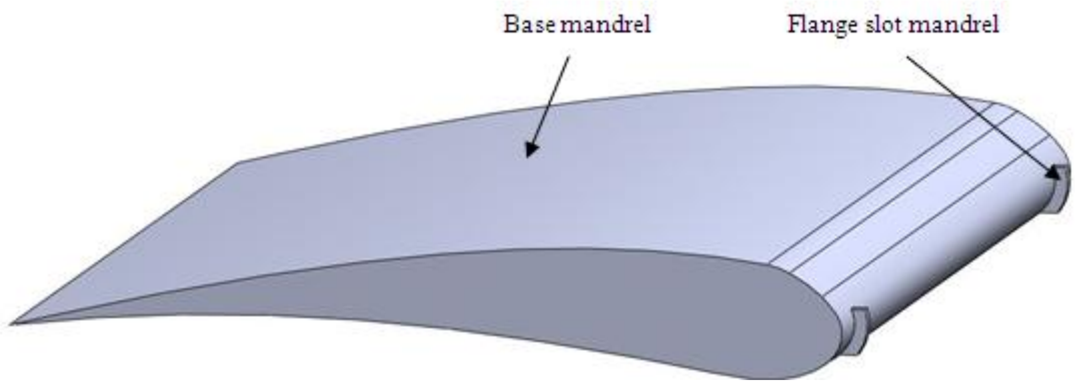


Figure 3.80: Mandrel pieces for attached AFC ribbed layup

The second manufacturing step is the fabrication of the ribs. The ribs for the attached AFC design are manufactured in the same way as the ribs previously described. The ribs are cut out of a carbon fiber plate in the geometry shown in Figure 3.78. Once the ribs are created, the carbon fiber layers are cut into their correct geometry, which is identical to the foam core variant of the attached AFC design.

The process for laying up the carbon fiber layers is also the same as the foam core variant. The flange slot mandrel pieces assist in the layup by giving the carbon fiber layers something to grip while being wrapped around the base mandrel. When all of the layers are lined up properly, the wing flap is vacuum bagged and infused. As stated previously, the carbon fiber skin pieces for the nose cone sub-assembly and the base wing skin are created simultaneously. Once the wing flap has cured, the mandrels can be removed. The order of mandrel removal is not important for the ribbed variant of the attached AFC design. The easiest method of removal would be to extract the base mandrel piece first and then pop out the flange slot mandrels.

The seventh manufacturing step is the insertion of the ribs. The ribs are positioned inside the base wing skin and cured into place using epoxy, preferably close to the flange slots. The location close to the flange slot will reduce the bending moment put onto the securing pin. The final manufacturing step is the attachment of the AFC nose cone. The nose cone is attached by inserting the flanges through the flange slots until the contour of the AFC rests against the contour of the leading edge of the base wing skin, Figure 3.81: (A)-(B). Once located, the securing pin is inserted through the entire assembly, locking the nose cone in place, Figure 3.81: (C).

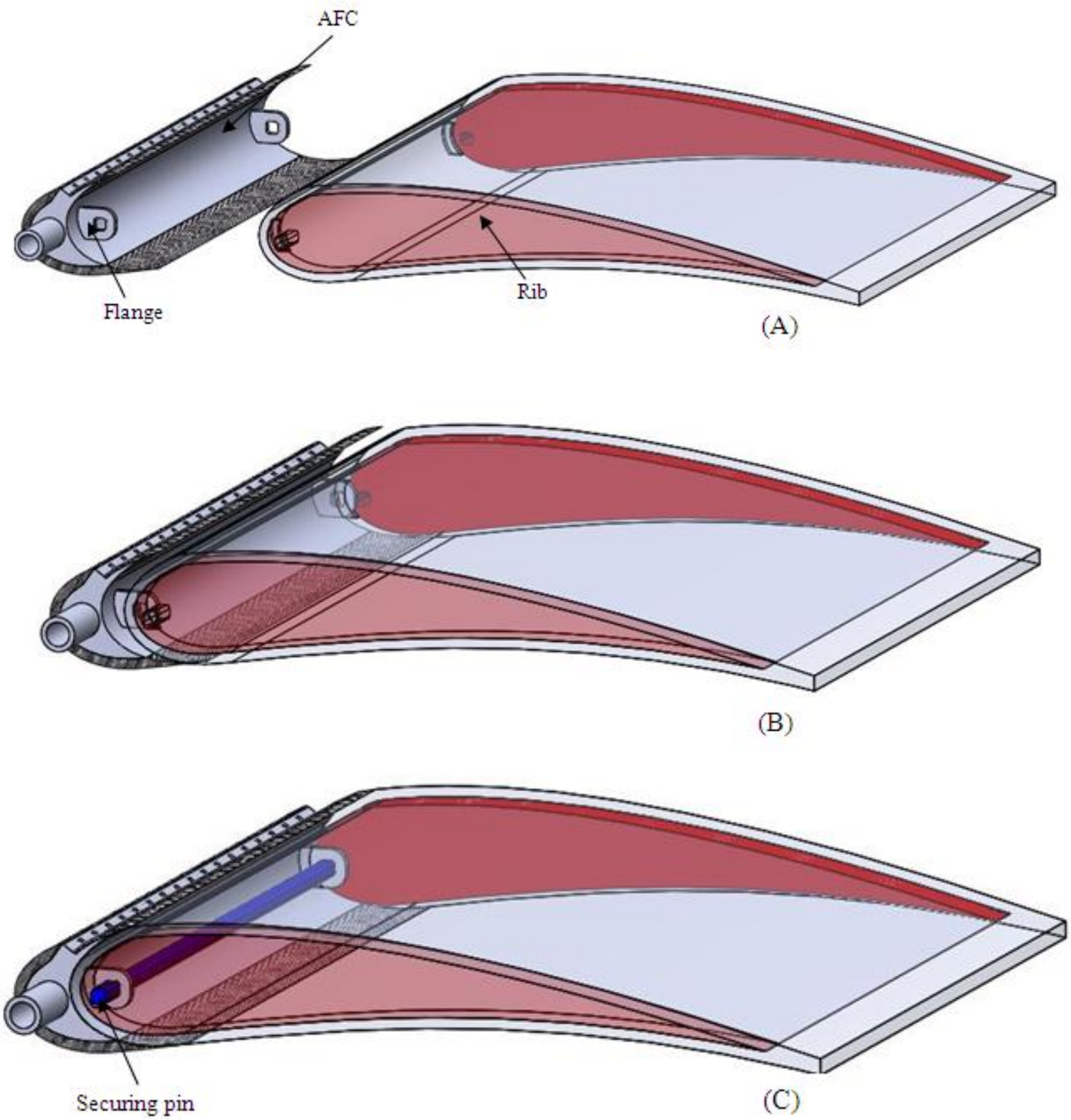


Figure 3.81: Attached AFC ribbed insertion storyboard

The finalized attached AFC ribbed design is identical to the attached AFC foam core design in external geometry. Figure 3.82 shows the finalized attached AFC ribbed design. There is no need for the continuous connecting skin because the base wing skin is considered continuous. As with the foam core variant, the ribbed assembly requires that the locations of contact between the nose cone skin and the base wing skin be sealed to prevent airflow between the two surfaces. The final wing flap will appear as a single piece instead of the two clearly identifiable sections shown.

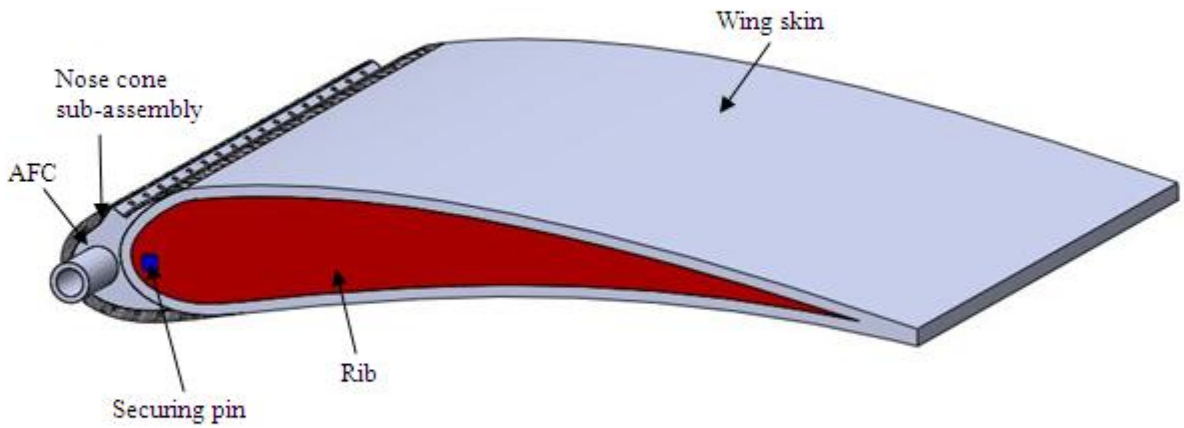


Figure 3.82: Attached AFC ribbed design

The attached AFC designs focus on maintaining similar aerodynamic qualities to the wing flap without an AFC, as well as making the AFC device accessible for any maintenance that may be required through its life span. The AFC is attached to the leading edge of the base wing skin; the concept of which is created by moving the original leading edge backwards behind the location of the original AFC slot. By using an almost continuous base wing skin, the necessity of the continuous connecting skin pieces seen in both the side inserted and vertically inserted designs is no longer needed. The AFC is surrounded by a carbon fiber skin for protection from the free stream air and debris. The AFC is attached with flanges and a securing pin that passes through them. The two design variants differ in manufacturing, assembly, and attachment pieces. The foam core variant requires a set of attachment anchors for each AFC device. The attachment anchors are made of the same material as the AFC and are integrated into the foam core prior to the layup process. The layup process for the foam core requires the use of three removable mandrel pieces. The two flange mandrels occupy the space within the foam core where the AFC flanges will rest when fully assembled. The flange mandrels also occupy the area for the flange slots in the base wing skin. The securing pin mandrel secures both of the flange mandrels as well as preserves the empty space that the securing pin will take up in the final assembly. Upon the removal of the mandrels, the AFC is located properly and the locked into place with the securing pin, completing the assembly process. The ribbed variant of the attached AFC design does not require attachment anchors because the rib doubles as the support for the wing flap and the securing points for the AFC flanges. The layup process for the ribbed design requires three mandrel pieces. The base mandrel piece takes up the entire interior of the base wing flap. The two flange slot mandrels, that create the flange slots, are attached to the base mandrel with a mild adhesive. Once the mandrels are removed, the ribs are inserted and cured into place. The final assembly is complete when the AFC is placed correctly and the securing pin is inserted. Both of the design variants accomplish the goals of maintaining similar aerodynamic qualities to a wing flap without an AFC and making the AFC accessible for maintenance.

This section examined the internal integration designs and how they apply to the aerodynamic, manufacturing, maintenance, and structural design requirements. All of the internal designs focused mainly on the aerodynamics requirement but the maintenance requirement was also necessary. To fulfill the aerodynamics aspect, the AFC devices were placed inside the wing skin. This internal placement not only accomplished the aerodynamics requirement, it also protected the devices from damage which benefitted the structural design requirement. Each internal design implemented the maintenance requirement in a unique way. The side inserted design placed the AFC in the side of the wing flap, the AFC rotated into place, and a retaining piece secured it. The vertically inserted design slides the AFC into the wing flap from the top, locking it into place on the permanent AFC base with studs. The attached design connects the

AFC from the leading edge and it is locked into place with a securing pin. Each design has a foam core and a ribbed variant that differ almost exclusively in the manufacturing.

3.4 Chapter Summary

This chapter details two major design categories for the integration of an AFC into a composite wing flap; the external designs and the internal designs. The external design category places the AFC outside of the wing skin in a groove. The two types of grooves are the rounded groove and the semi-circular groove. Both grooves place the active side of the AFC at the point of highest curvature of the wing flap. The rounded groove has a flat bottom to assist in the placement of the AFC device. The semi-circular groove rounds the entire bottom of the groove to reduce the possibility of stress concentrations. The rounded bottom requires that the AFC be oriented correctly by hand because the AFC does not properly locate on its own. Within each of the groove types, two AFC variants were created. The straight AFC does not modify the AFC device anywhere but the bottom surface to match the groove. Instead of modifying the straight AFC, the groove surface on the inactive side of the AFC is raised until it meets the level of the top surface of the AFC. In order to compensate for the elevation change, the groove for the straight AFC is tilted. The second type of AFC that was created was the tilted AFC. This AFC was developed to eliminate the necessity for an elevation change within the wing skin. Instead of changing the elevation of the skin, the elevation of the inactive side of the AFC was lowered to meet the original elevation of the wing flap. All of the external designs secure the AFC device with epoxy. The AFC devices also protrude from the surface of the wing flap for all external designs.

The second design category is internal designs. This category places the AFC devices within the wing skin so that the location of the air exiting the wing flap is at the point of highest curvature. To allow the AFC to be removed, three designs were created: the side inserted design, the vertically inserted design, and the attached design. The side inserted design requires that the AFC enter and exit the side of the wing flap. It is fixed by a retaining piece that also slides in the side of the wing. The vertically inserted design allows the AFC to enter and exit the wing skin vertically. It locks into place on the permanent AFC base with studs. The attached design places the AFC on the front of a base wing flap as a nose cone. It is secured with flanges and a securing pin.

All of the design concepts have two variants within them. The core selection, either ribbed or foam, does not affect the aerodynamics of the wing because they are located within the skin. With the grooved designs, the only difference between the two variants is the manufacturing method. The side inserted design also differs in manufacturing between the cores, but the retaining piece and the retaining piece cut-out are unique between the cores. The top inserted design differs in manufacturing and the assembly procedure between the two variants, while the attached design varies in both manufacturing and the required components. With the ribbed attached design, there is no need for an attachment anchor because the rib is sturdy enough to handle forces put on it.

In order to determine if the proposed designs are feasible, prototypes must be created. These prototypes are used to asses and refine the designs of the AFC devices, wing flaps, and final assemblies. The prototypes are fabricated on a limited scale so that their manufacturing techniques may be directly applied to the continued research of creating wind tunnel test models.

Chapter 4:

PROTOTYPE EVALUATION

Prototypes for some of the integration techniques for placing an AFC into a composite wing flap designs were created to help assess the manufacturing process for each design and to assist in further design refinement. The first designs to be prototyped were the external designs. An AFC from each design was created and wing flaps for the rounded and semi-circular straight AFC designs were created. The creation of the external prototypes assisted in refining the designs for the internal designs. The side inserted AFC design was the only internal design to be prototyped. The vertically inserted AFC designs and the attached AFC designs were not been prototyped because their designs and manufacturing processes are based upon the side inserted AFC designs.

4.1 AFC Prototypes

Prototypes of the AFC devices for the external designs and the side inserted AFC design were created using stereolithography (SLA), a 3D printing process using plastics. The material used was WaterShed XC 11122 which had material properties comparable to ABS plastic (Fineline Prototyping Inc, 2012). The external design AFC devices were the first to be prototyped because they were the first finalized design. Following analysis of these prototypes, the side inserted AFC device was prototyped. The prototypes for the AFC devices are surrogate actuators for the real AFC devices. The production AFC devices are to be made of different materials but will maintain the same geometry as the SLA prototypes. The production AFC devices are to be injection molded using an engineering thermoplastic polymer such as PEEK reinforced with carbon fibers.

A single AFC device was prototyped for each of the external designs. Each AFC was one foot in length with fifty-five exit ports. These devices were created with a single inlet tube on one end with the other end sealed. The fabrication of the AFC devices highlighted design and manufacturing problems that needed correction before further prototypes could be made. Each AFC was designed to have an inlet tube that would fit inside the rubber air source tubing. The AFC inlet tube was designed with a thickness below the 0.022 inch minimum thickness required for SLA manufacturing. The inlet tubes did not have enough structural strength to withstand the insertion into the rubber air source tubing and collapsed in on themselves or broke off. This issue would also affect the production AFC devices so the inlet tubes are redesigned with a larger thickness.

Another problem seen by all of the external AFC devices is skewed main air chambers. The main air chambers and exit ports in the center of the AFC device are oriented correctly, which is perpendicular to the active side of the AFC. As the distance from the center line of the device increases, the main air chambers begin to twist towards the center line of the device. This problem should only be encountered with the SLA prototypes due to the fabrication process and not with the production AFC devices; so no redesign of the AFC devices is required.

The final two problems seen with the external AFC devices did not immediately manifest themselves. A yellowing of the plastic can be seen in the external AFC devices. This yellowing, shown in Figure 4.1, is caused by exposure to UV light. The data sheets for the WaterShed plastic do not indicate if the yellowing will have any effect on the structural properties of the AFC device. The second problem only occurred in the semi-circular groove AFC devices. After five months, the semi-circular AFC devices, shown in Figure 4.2, have bowed toward the upper surface of the devices. It is not known what caused the bowing because all of the external AFC devices were stored in the same conditions. The discoloration of the AFC prototypes is not a concern for the production AFC devices. The production devices will most likely be coated with a protective material like paint, which will limit the UV light exposure or will contain a UV stabilizer additive. As stated previously, the deformation of the AFC prototypes should not affect the production AFC devices due to the different manufacturing processes, but one does need to be aware of the possibility of warpage.

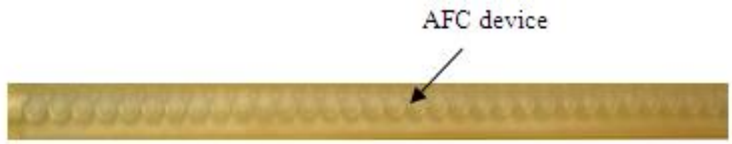


Figure 4.1: Yellowed AFC device

Figure 4.2: Semi-circular AFC device curvature

The side inserted AFC prototypes corrected many of the problems encountered with the external AFC prototypes. The body of the side inserted AFC device is 4.5 inches with 17 exit ports. The device has a 0.5 inch inlet tube on either side of the main body extending the total length of the device to 5.5 inches. The minimum thickness design problem seen in the external AFC devices' inlet tubes was fixed before the side inserted AFC devices were fabricated by increasing the thickness above the 0.022 inch minimum. Figure 4.3 shows the side inserted AFC device with inlet tubes.

Figure 4.3: Side inserted AFC

The reduced length of the AFC device eliminated the skewing of the main air chambers that was seen in the external AFC prototypes. There is also no bowing of the side inserted AFC device. It is not known if this lack of deformation is due to the reduction in length or the change in geometry between the two designs. The side inserted AFC prototype, seen in Figure 4.3, did not turn yellow because the devices were protected from UV light exposure. Because they are made of the same material as the external AFC prototypes, it can be inferred that they too would yellow if exposed to UV light.

Along with the side inserted AFC devices, the retaining pieces for the side inserted AFC designs were created. They are fabricated from the same material as the AFC prototype and are 5 inches in length. These retaining pieces, shown in Figure 4.4, like the side inserted AFC prototypes, were protected from UV light to reduce discoloration. All of the corners on the retaining pieces were rounded to avoid any thicknesses less than 0.022 inches. These pieces were designed to allow a snug fit within the AFC cut-out in both the foam core and ribbed designs.

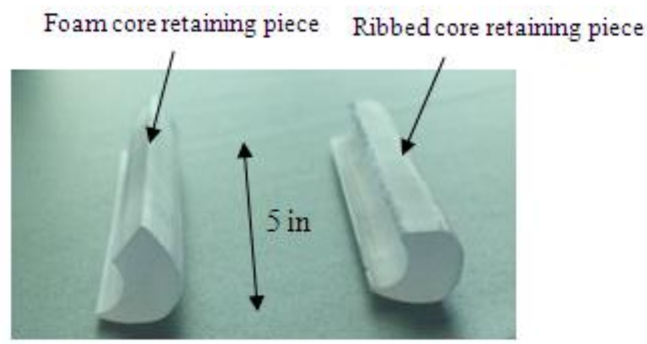


Figure 4.4: AFC retaining pieces

The first AFC devices to be prototyped were the external AFC designs. From these prototypes, it was learned that: a minimum thickness of 0.022 inches must be maintained, the main air chambers of the prototype can distort with length, UV light will discolor the plastic, and the semi-circular AFC devices bow over time. These problems experienced with the first prototypes were corrected before the side inserted AFC devices and the retaining pieces were created. Testing and the fabrication of more prototypes will be needed to determine the length a device can be before deformation and if the effects of the UV light are cosmetic or structurally damaging.

AFC devices were not fabricated for the vertically inserted AFC designs or the attached AFC designs. Both of the AFC devices have been designed with a length under 5 inches and with thicknesses greater than 0.022 inches everywhere. Because of these design considerations, it is assumed that prototypes of the remaining two designs and their accessories, such as the permanent AFC base and the attachment anchors, would function as effectively as the side inserted AFC devices and their retaining pieces.

4.2 Wing Flap Prototypes

Prototypes of the wing flaps for the external AFC designs and the side inserted AFC design were created to determine the manufacturing feasibility and the final fitment of the prototyped AFC devices. Unlike the AFC prototypes, only the straight AFC versions of the external groove design wing flaps were prototyped. The straight AFC groove designs were selected to be prototyped first because the required tilt in the groove would theoretically make them harder to fabricate. It was thought that if the straight AFC grooved wing flaps could be successfully fabricated, the tilted AFC grooved wing flaps could also be fabricated. Three generations of wing flaps were created for the external AFC designs and a single prototype generation was fabricated for the side inserted AFC wing flap.

All of the prototypes were created using the VARTM process for composite manufacturing with carbon fiber-epoxy. This manufacturing process was performed to determine a reliable hand layup technique that could be utilized to create a single piece wing flap for testing in the laboratory. Because the actual materials fabrication techniques used in the aerospace industry are not known, several generations of wing flap were created until a viable prototype was created.

The first two generations of external AFC wing flap prototypes were manufactured using non-dense foam as their cores. These cores were created using the water-jet cutting machine to create core sections 2.25 inches in depth. The core pieces were hung from a bar so that the carbon fiber layers and vacuum bagging material could be draped over it. This layup process was used to fabricate the external AFC design wing flap prototypes. Figure 4.5: (A) depicts a vertical VARTM process using the plastic core from the third generation prototype because no photographs were taken of the first and second generation layups. Figure 4.5: (B) shows the wing flap vacuum bagged, ready for resin infusion.

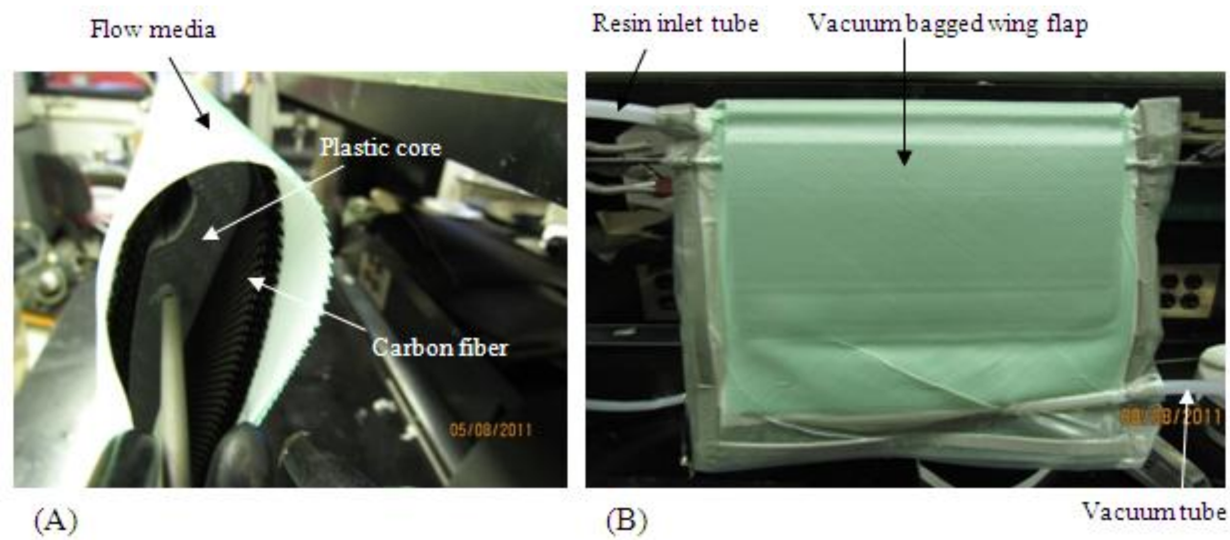


Figure 4.5: Vertical VARTM process
(A) Vertical VARTM layup
(B) Wing flap with vacuum bag

Figure 4.6 shows the rounded straight AFC wing flap and the semi-circular straight AFC wing flap prototypes. There are two main problems with these prototypes. The first problem is that the fibers did not completely wet. Two explanations for the dry fibers are: the resin began to flow into the air pockets within the foam core, or not enough resin was infused into the wing flap. The second problem seen in the prototype is that the carbon fiber fabric within the groove did not properly contour. It is believed that the thickness and stiffness of the fabric and bagging material reduced the vacuum's ability to shape the carbon fiber to the foam core.

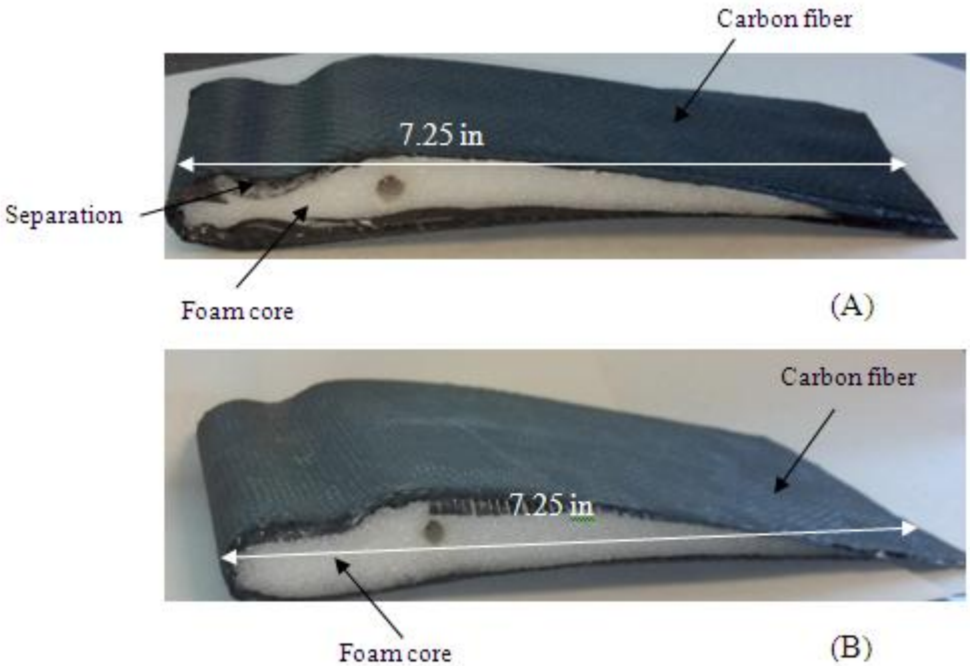


Figure 4.6: First generation wing flap prototype
(A) Semi-circular groove with straight AFC wing flap
(B) Rounded groove with straight AFC wing flap

To counteract the carbon fiber contouring problem, the next prototype was hung vertically during the bagging process. It was laid horizontally on a table during the infusion and curing. To fix the wetting issue, more epoxy was introduced to the system with a slower curing time allowing a larger volume of resin to enter into the wing flap. Figure 4.7 shows the second generation prototype of the rounded groove with straight AFC wing flap. Although the problems from the first generation prototypes are fixed, the second generation wing flap has other problems. It can be seen in Figure 4.7 that the surface of the wing flap has flaws due to the foam core. These bumps were caused because the foam core for this wing flap consisted of three 2.25 inch thick pieces. The connection locations of these pieces are clearly visible in the wing flap skin. The foam core also compressed under the vacuum for this wing flap, which changed its external height dimension.

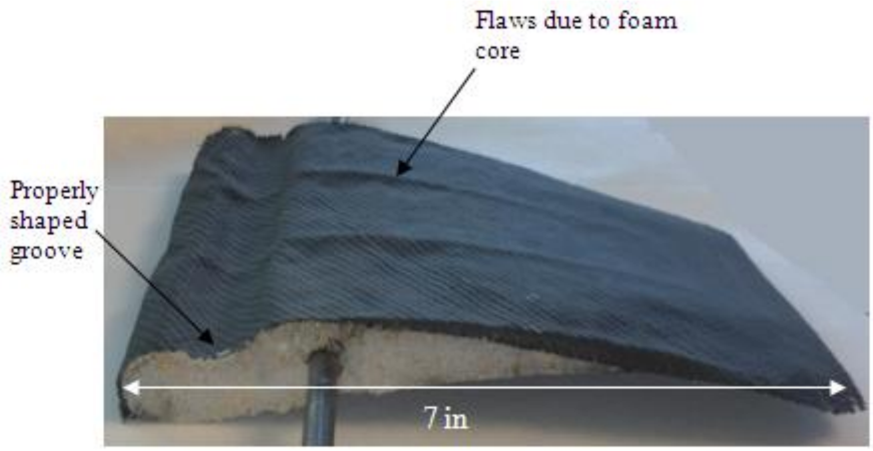
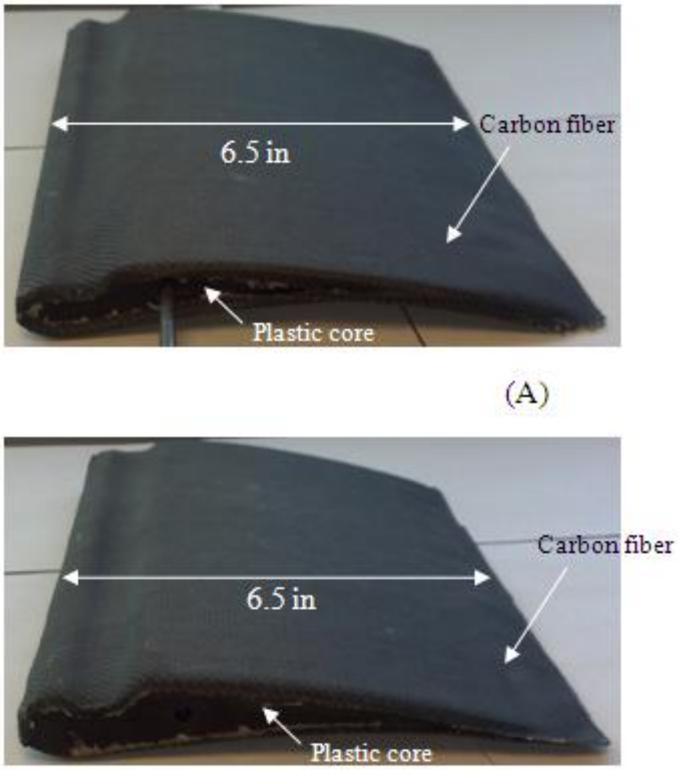


Figure 4.7: Second generation wing flap prototype

The third generation external wing flap prototype removed the foam core and replaced it with a rapid prototyped, fused deposition modeling (FDM), plastic core. The goal of the solid core was to eliminate the excess resin used in the second generation models and the deformation of the core due to the vacuum. The same manufacturing procedure, used for the second generation prototype, was again used for the third generation. Figure 4.8 shows both the rounded and semi-circular grooves for the straight AFC wing flap prototypes. Both of these wing flaps eliminated the flaws from the compression of the foam core. The only problem with the carbon fiber skin is a small separation gap between the plastic core and the carbon fiber layers within the groove. Other than the separation, both wing flaps are considered functional prototypes. A new problem discovered with these prototypes is that the plastic core is heavy and cannot be removed without damaging the wing flap. In order to remove the plastic core, more preparation work is required prior to the composite layup. The FDM wing flap core has a textured surface due to the manufacturing process. This texture must be removed because resin bonds to the textured surface during the infusion and curing process. Removal of the textured surface and the addition of a releasing agent will assist in the future removal of the plastic core.



(A)

(B)

Figure 4.8: Third generation wing flap prototype
(A) Semi-circular groove with straight AFC wing flap
(B) Rounded groove with straight AFC wing flap

The third generation wing flaps were combined with the AFC prototypes to determine the quality of the wing flap grooves. The AFC devices were laid into place without the use of adhesives and the fitment between the AFC and the wing flap were investigated. It was determined as previously noted, that the wing flap skin did not completely contour to the core's groove. This contour problem left space below the rounded AFC where the flat bottom of the device should seat flush against the flat bottom of the groove. The semi-circular device seated smoothly but the groove is larger than the design proposed. It is thought that this size variation is caused by an incorrect thickness calculation for the carbon fiber skin.

The prototypes for the side inserted AFC design wing flap have only one generation. Multiple wing flaps were fabricated for the side inserted AFC wing flap but the manufacturing process was unchanged between the models. Using the knowledge gained from the external AFC wing flap prototypes, denser foam was used for the foam core designs and a set of plastic and metal removable mandrels were used for the ribbed designs. The foam core shown in Figure 4.9: (A) was fabricated using a hot wire cutting machine. The aluminum mandrel, Figure 4.9: (B), was created using the water-jet and the pink and yellow plastic mandrel were rapid prototyped using fused deposition modeling (FDM). The textured surface of the plastic mandrel was removed by sanding and the use of filling putty. The mandrels were also coated with release agent prior to the composite layup process.

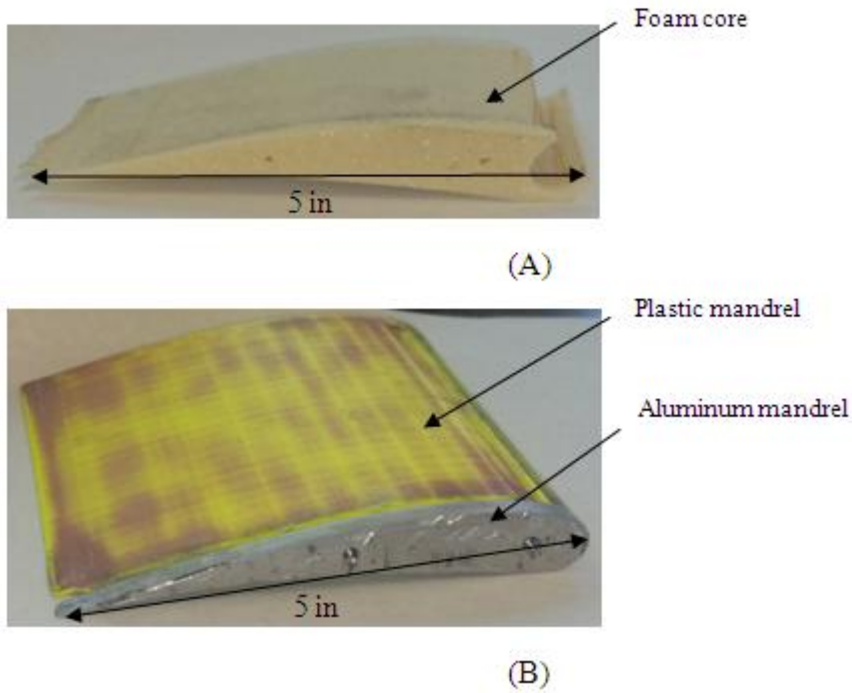


Figure 4.9: Layup apparatus for side inserted AFC wing flap
(A) Foam core
(B) Removable mandrels

The side inserted AFC wing flap prototype was not suspended vertically like with the external groove prototypes. The carbon fiber layers were wrapped around the core or mandrel and vacuum bagged in a horizontal position. The side inserted AFC wing flap prototype can be seen in Figure 4.10. This particular wing flap was created with the removable mandrels, the design of which was seen in Figure 3.48, so that ribs may later be inserted. Figure 4.10 shows that there is leading edge deformation. This deformation resulted from the wrinkles created by the bagging material. The trailing edge of the wing flap will be cut off in post processing so that deformation is considered acceptable.

Figure 4.10: Side inserted AFC wing flap prototype

A proposed method for eliminating the leading edge deformations is to modify a traditional prepreg layup. Instead of starting with pre-impregnated carbon layers, dry carbon layers are wet with resin as they are being placed onto the foam core or mandrels. The theory is that the bleeder layer of the prepreg layup will smoothly contour to the leading edge of the wing flap eliminating the leading edge deformations. It is not know if this method will work consistently, further testing needs to be conducted.

The side inserted AFC device and its retaining pieces were combined with the wing flap prototypes to determine fitment. The devices had better fitment than with the external prototypes because special attention was paid during the layup to properly represent the design's wing skin thickness with the prototype. Both the ribbed and foam core versions of the side inserted wing flap prototype fit together smoothly and in the proper locations.

The wing flap prototypes described all utilized the VARTM layup process. The external groove designs went through three generations of prototyping before an acceptable product was produced. It was learned that hanging the wing vertically while infusing the resin caused separation between the wing skin and the core. The non-dense foam core was eliminated in the third generation prototype because of its compressibility under vacuum and the excess resin it might retain. The use of a plastic core in the third generation was a success for the wing skin layup but it must be removable to eliminate its heavy weight. Using the information gathered from the external prototypes, the side inserted AFC wing flap prototype was created in a single generation. Although functional, the side inserted AFC wing flap prototype requires post processing to smooth the defects on the leading edge. A modified manufacturing method has been proposed to reduce the necessity for post processing. The flaws in the prototype wing flaps were experienced while trying to determine an effective hand layup technique. Once the layup process is finalized, the quality of the wing flap will remain constant. If the quality of the wing flap is high enough, the process may be utilized for production versions of the prototyped wing flaps.

The external grooved wings for the tilted AFC devices, the vertically inserted AFC design, and the attached AFC design did not have wing flap prototypes created. The external prototypes for the tilted AFC devices were determined to be simpler to fabricate and their success was to be based on the outcome of the proposed manufacturing method for the straight AFC device grooved wing flaps. The vertically inserted AFC design and attached AFC design wing flaps are similar in construction to the side inserted wing flap. Their prototyping was deemed secondary because the successful manufacturing techniques used in the side inserted wing flaps could be directly applied to the other two designs.

4.3 Chapter Summary

This chapter described the prototypes created for the external AFC devices, the side inserted AFC devices and retaining pieces, and the wing flaps for the external groove with straight AFC devices and the side inserted AFC variants. These prototypes were used to determine the manufacturing process and to assist in further design refinements.

All of the AFC device prototypes were created by SLA with WaterShed XC 11122 plastic which has material properties comparable to ABS plastic (Fineline Prototyping Inc, 2012). The external AFC devices were the first pieces prototyped. A single device was created for each external design at a length of 12 inches. The external AFC devices had a few major problems which were: not enough thickness on the inlet tubes, warping down the length of the devices, sensitivity to UV light, and warping in the semi-circular devices. These problems were observed and corrected before the fabrication of the side inserted AFC device and its retaining pieces. All of the device thicknesses were designed to be greater than 0.022 inches which is the minimum thickness for SLA. The side inserted AFC devices were created at 4.5 inches in length which eliminated the warping of the main air chambers and the devices were stored away from UV light eliminating the yellowing. The vertically inserted AFC device and the attached AFC device were not prototyped because their dimensions and fabrication are based on the success of the side inserted AFC device. It is assumed that prototypes of the remaining two designs and their accessories, such as the permanent AFC base and the attachment anchors, would function as effectively as the side inserted AFC devices and their retaining pieces.

The wing flap prototypes were created for the rounded groove with straight AFC, the semi-circular groove with straight AFC, and the side inserted AFC designs. The wing flaps were created using the VARTM process with a vertical layup for the external designs. The rounded groove and semi-circular groove prototypes each went through three generations of prototypes until an acceptable wing flap was created. The first and second generations used low density foam as the core for the wing flaps. In the first generation, the wings were left hanging vertically while curing and that caused separation between the foam core and the wing flap skin, and the fibers did not completely wet with resin. Both of these problems were fixed in the second generation by laying the wing flap horizontally while curing and infusing more resin into the system. The second generation wing flap compressed the foam core and surface flaws were created. To fix this, the third generation used a rigid plastic core to lay the wing flap skin on. This core fixed the surface flaws but there was still separation between the skin and the core in the groove of the wing flap. It was also determined that the core was too heavy and needed to be removed in future prototypes. The side inserted AFC design used the idea of the removable core for its ribbed variation and used denser foam for its foam core variant. Both of these core methods were successful in creating the side inserted wing flap prototype. The only flaws were seen on the leading edge where the bagging material had wrinkled. An alternate layup method was proposed which utilized a wet layup and breather cloth which would help eliminate wrinkles caused by the vacuum bag.

This chapter showed the prototypes created to integrate an AFC into a composite wing flap. The creation of the external AFC prototypes led to design changes for both the external designs and the subsequent internal designs. The fabrication of the wing flap prototypes assisted in the manufacturing steps and equipment required to create a consistently viable wing flap. The lessons learned through the prototyping relate directly to the selection of the final design. To determine the most fitting design, all of the concepts need to be compared and ranked on the four main design requirements. The design requirements and the specific criteria within each will be discussed as will each design’s ranking. The evaluation process will eliminate designs until only the most appropriate design remains.

Chapter 5:

DESIGN EVALUATION

The design concepts, described in Chapter 3, are split into two categories for evaluation. The foam core designs and the ribbed designs will be evaluated independently yielding two designs from each, which then will be compared to determine the final design. The evaluation uses two types of evaluation matrices. The base evaluation matrix, derived from the "second-level evaluation matrix" (Singhose & Donnell, 2011), is the first level of assessment for these designs. The second level of assessment, the "third-level evaluation matrix" (Singhose & Donnell, 2011), uses a weighted importance column, which increases the resolution of the results. The top two designs from the weighted evaluation matrices will be compared in a final weighted evaluation matrix. The criteria that the designs will be ranked against are all within the four major design specification categories.

The designs are rated by four main design specification categories: aerodynamics, manufacturing, maintenance, and structure. Each of the four design categories has unique design criteria within it to determine the functionality of each design. The first design category is aerodynamics. The general aerodynamics objective is that the integration of the AFC must not detrimentally impact the flight characteristics of the flap. The second area is manufacturing which should be of the same difficulty when integrating the AFC as without. The third specification pertains to maintenance. The objective for maintenance is that the AFC device should be able to be removed or replaced if it becomes damaged during its operation. The last area corresponds to the wing flap structural requirements, which should not be greatly reduced by integrating the AFC. The criteria within each of the design categories, shown in Table 5.1, highlight a specific aspect of each broad category stated above.

Table 5.1: Design criteria

	Criteria
Aerodynamics	Similarity to original wing flap
	Functional flap with AFC inactive
	Obstructions in the airflow
Manufacturing	Mandrels
	Layer cuts
	Fiber Layup
	Assembly pieces
	Self aligning AFC
Maintenance	Accessible AFC
	Removable AFC
	Modular AFC
Structure	Continuous skin
	AFC detachment
	Stress concentrations
	Protected components

The criteria within the aerodynamics category are: "similarity to original wing flap," "functional flap with AFC inactive," and "obstructions in the airflow." The "similarity to original wing flap" is selected as a criterion because the original flap was chosen and incorporated to perform a specific role in the aerodynamic performance of the entire wing. If the wing flap is changed greatly, its performance during flight will be altered. The functionality of the wing flap is important during all phases of flight, which is why similarity to the original wing flap is necessary as well as having a flap that functions with the AFC inactive. The AFC devices may only be utilized during portions of the flight so the wing flap must function as designed when the AFC is not active. The final aerodynamics criterion is "obstructions in the air flow." The attachment of the boundary layer around a wing generates lift. When the boundary layer separates from the wing, stall begins and lift decreases. If there is a protrusion from the surface of the wing, the boundary layer is more likely to be disrupted and separate prematurely. This would reduce the maximum lift that the wing can achieve, hence negating the positive effects of the AFC. All of the aerodynamics criteria directly relate to the functionality of the wing flap with the integrated AFC device.

The criteria within the manufacturing category are: “mandrels,” “layer cuts,” “fiber layup,” “assembly pieces,” and “self aligning AFC.” These criteria are created using the steps and equipment necessary to manufacture and assemble all of the AFC integration design prototypes and models. The first manufacturing step is to create the mandrels, which are used during the layup process as part of a male mold that the carbon-fiber is laid on. The mandrels are created before the layup using either metal or plastic and can be reused until they become damaged. The number of mandrels and their complexity affect the ease of fabrication of the wing flap. The layer cuts for the manufacturing also are created prior to laying up the fibers. For many of the designs, the wing flap skin has sections removed, which are required for every layer of carbon-fiber. Each design has a different number and difficulty of cuts, which changes the amount of preparation time required for each flap. Once the carbon layers are prepared, they are laid on the mandrels, the foam cores, or a combination of the two. The “fiber layup” criterion assesses the difficulty of placing and aligning all of the dry carbon-fiber layers that are required for the wing flap. After the fabrication of the wing flap, the system must be assembled. The number of assembly pieces and the difficulty of assembling them are the specifications that make up the “assembly pieces” criterion. The final manufacturing criterion is the “self aligning AFC.” The placement of the AFC is critical to the proper function of the device. By having a device that automatically fits in the proper place, its alignment is assured. The manufacturing criteria assess the difficulty of the manufacturing process from pre-layup through final assembly.

The criteria within the maintenance category are: “accessible AFC,” “removable AFC,” and “modular AFC.” These criteria are based on the steps required to maintain the functionality of the AFC devices. The accessibility of the AFC allows the device to be inspected easily, which helps determine if repairs are necessary. When a repair is required, the AFC device must be removed. The removal of the AFC needs to be easy and should not damage the wing flap or the AFC. The ease of AFC removal depends on the process required to unseat the device. After the removal of the AFC, only the damaged section of the device needs to be replaced. In order for that to happen, the AFC devices must be modular. The ability of the devices to separate allows the damaged section to be repaired, thereby allowing the reuse of the other device sections. All of the maintenance criteria pertain to the steps required to assess damage, extract the part, and replace the damaged section without damaging the wing flap or the AFC devices.

The criteria within the structure category are: “continuous skin,” “AFC detachment,” “stress concentrations,” and “protected components.” The “continuous skin” criterion assesses the problems that might be caused by having an open skin structure for the wing flap. An open structure will require that the stresses flowing through the skin divert and take a new path around the opening. The openings also can cause larger part deformation when loads are applied than with a closed structure. The “AFC detachment” criterion addresses the structure that will keep the AFC from detaching from the aircraft if it becomes loose. The detachment of anything from an aircraft during flight is a large safety risk. If the part that detaches is on the outer surface of the craft, it becomes a safety risk not only for the aircraft but also for anyone below it. If the AFC device were to be jostled loose, it would be ideal that it not become a projectile that might cause damage or injury. The third criterion for the stress category is “stress concentrations.” An abrupt geometry change can disrupt the original stress pattern causing stress concentrations. The concentrations can cause high stresses in small areas of the wing flap which may exceed the limits of the wing skin material. To reduce the possibility of the wing flap failing, potential stress concentration areas are predetermined and smoothed or reinforced. The “protected components” criterion is one of the most important criteria. In order for the AFC device to function for the maximum amount of time, it must be protected. If the device becomes damaged too easily, it will not be able to perform properly. It will waste time and money to repair the device, which would limit its appeal to the user. The structural category criteria deal with stresses and damage that the wing flap assembly will encounter during its working lifespan.

5.1 First-Level Evaluation

The first-level of evaluation will use a base evaluation matrix, which uses an absolute scale of 0-4 to rank each design concept against the design criteria. The scale is as follows: 4 = very good, 3 = good, 2 = satisfactory, 1 = tolerable, and 0 = unacceptable. Once the concept designs have been compared to all of the design criteria, the values are summed yielding a total. The total is then divided by the maximum possible score to produce a relative total for success. The relative total for success is the percentage of criteria that each design concept satisfies. The base matrix reveals a general idea of which designs will succeed based on the fulfillment of all criteria.

5.1.1 Foam Core Evaluation

The base evaluation matrix for the foam core design concepts is shown in Table 5.1. The concept rankings totaled at the bottom show that the internal designs outscore all of the external designs by at least eight points. The vertically inserted AFC design has the highest total with 46 points and a relative success total of 0.82. The side inserted AFC design has the second highest total with 44 points and a relative success total of 0.79. The explanations for each score can be found at the bottom of the table.

Table 5.1: Foam core base evaluation matrix

	Concept	**External Designs**				**Internal Designs**			
	Criteria	Rounded groove straight AFC	Rounded groove tilted AFC	Semi-circular groove straight AFC	Semi-circular groove tilted AFC	Side inserted AFC	Vertically inserted AFC	Attached AFC	Max Score
Aerodynamics	Similarity to original wing flap	2	2	2	2	3	3	3	4
	Functional flap with AFC inactive	1	1	1	1	3	3	3	4
	Obstructions in the airflow	2	2	2	2	4	4	4	4
Manufacturing	Mandrels	4	4	4	4	2	3	2	4
	Layer cuts	4	4	4	4	3	3	2	4
	Fiber Layup	2	2	2	2	2	2	3	4
	Assembly pieces	4	4	4	4	3	4	3	4
	Self aligning AFC	4	4	2	2	4	4	4	4
Maintenance	Accessible AFC	4	4	4	4	2	2	2	4
	Removable AFC	1	1	1	1	4	3	4	4
	Modular AFC	3	3	3	3	3	4	3	4
Structure	Continuous skin	4	4	4	4	2	2	3	4
	AFC detachment	0	0	0	0	4	4	0	4
	Stress concentrations	2	2	3	3	1	1	3	4
	Protected components	0	0	0	0	4	4	4	4
	TOTAL	**37**	**37**	**36**	**36**	**44**	**46**	**43**	**60**
	Relative Success Total	**0.66**	**0.66**	**0.64**	**0.64**	**0.79**	**0.82**	**0.77**	**1**

4=Very good **2= Satisfactory** **0= Unacceptable**
3= Good **1= Tolerable**

Within the aerodynamics category, none of the external designs are ranked higher than a 2 for any of the criteria while all of the internal designs are ranked with a score of 3 or above. The external designs receive a score of 2 for the “similarity to original wing flap” criterion because of the location of the AFC on the outer surface of the wing flap. The profile of the flap is altered both with the AFC installed and without. The alterations to the wing flap may negatively impact the flight characteristics. The internal designs all have a ranking of 3 for the "similarity to original wing flap" criterion because the addition of the AFC slot only alters the flap geometry in a small section of the profile. For the "functional flap with AFC inactive" criterion, the external designs all have a ranking of 1. The negative effects of the profile change from the last criterion may be counteracted by a functioning AFC, but when inactive, the negative effects become a problem during flight. When the AFC devices are inactive for the internal designs, the wing flap should function similarly to the original flap. The internal designs all receive a score of 3 for the "functional flap with AFC inactive" criterion. The final aerodynamic criterion is "obstructions in the airflow." The elevated AFC location required for the air exiting the external AFC devices places the device directly into the airflow. All of the external designs receive a ranking of 2. The AFC slot for the internal designs allows the air exiting the AFC to be tangential to the wing flap without the exit ports being above the flap surface. The internal designs have a ranking of 4 for the "obstructions in the airflow" criterion. In the aerodynamics category, the internal designs outscore the external designs 2 to 1.

Unlike the aerodynamics category, the manufacturing category favors the external designs in a majority of the criteria. For the first manufacturing criterion, all of the external designs receive the highest rank of 4 because they require no mandrels for the composite fabrication process. The side inserted AFC design and the attached AFC design both have a ranking of 2 because they require four and three mandrels respectively for fabrication. The vertically inserted AFC design receives a score of 3 because it only requires a single mandrel for the composite fabrication. The external designs again receive the highest score for the "layer cuts" criterion. None of the external designs require any pre-fabrication alterations to the carbon-fiber layers. The side inserted AFC design and the vertically inserted AFC design have a score of

3 for the “layer cuts” criterion, with each design requiring four cuts per carbon-fiber layer. The attached AFC design requires eight small cuts per layer giving it a ranking of 2. The “fiber layup” criterion has similar scores between all the designs. All of the designs, except the attached AFC design, have a score of 2. The external designs all score a 2 because of the difficulty of keeping the dry fiber layers in the grooves while laying it up. The side inserted AFC design and the vertically inserted design receive 2’s because of the necessity of lining up the layers perfectly to create the AFC slot and AFC hole. The attached AFC design, scoring a 3, is easier to layup than the other designs because the slots cut into the layers are aligned around the protruding mandrels. For the “assembly pieces” criterion, all of the external designs have a ranking of 4. Each design requires a single assembly piece which is the AFC itself. The side inserted AFC design and the attached AFC design both require the AFC device and some form of retaining feature, which is why they receive a score of 3. The vertically inserted AFC design has a single assembly piece, the AFC, earning it the rank of 4 for the “assembly pieces” criterion. The final design criterion in the manufacturing category is “self aligning AFC.” Both rounded groove designs have a ranking of 4 because the flat bottom of the groove matches the flat bottom of the AFC which properly aligns the device. The semi-circular designs do not have a flap portion in the groove, so the AFC must be held in place while being secured to ensure the proper location is attained. Both semi-circular designs have a score of 2 for this criterion. All of the internal designs have a ranking of 4 for the “self aligning AFC” criterion. The side inserted AFC design allows the AFC to be inserted and rotated in a single direction. The AFC device will stop its rotation automatically when the final location is reached. The top inserted AFC design only allows the AFC to be inserted in the proper orientation. It is locked into place by pressing down on the AFC. The attached AFC design slides the flanges on the AFC into the flange cut-outs on

the base flap properly aligning the nose cone assembly. The highest score totals in the manufacturing category belong to the rounded groove designs each with 18 points. The lowest total belongs to both the side inserted AFC design and the attached AFC design each with 14 points.

The first criterion in the maintenance category is “accessible AFC.” The accessibility of the AFC for the external designs is very good because of its location on the external surface of the wing flap, earning a value of 4. The internal designs all have satisfactory AFC accessibility because although the AFC devices can be inspected from the exterior of the wing flap, a thorough inspection requires the removal of the AFC which is why they received 2’s. The “removable AFC” criterion ranks very low for the external designs. Although the AFC is accessible, its location requires that the AFC be glued into place to prevent disassembly during flight. Removal of the AFC is difficult and may require machining or other post processing which is why each external design has a score of 1. The removal of the AFC devices from the side inserted and attached design requires the removal of a retaining piece and the extraction of the AFC. The removal does not damage the devices so both the side inserted AFC design and the attached AFC design have 4’s in the “removable AFC” criterion. The vertically inserted design requires the use of a tool to remove the AFC. The tool must be inserted into the exit ports of the AFC so that it may be lifted vertically. This removal may cause damage to the AFC which is why it received a score of 3. Once the AFC devices are removed, they can easily be disconnected from each other so that only a damaged section is replaced. The vertically inserted design is the only design concept to have a value of 4 in the “modular AFC” criterion. Unlike all the other designs where the AFC devices are chained and then integrated into the wing flap, the vertically inserted design chains the permanent AFC base instead. The AFC devices do not touch each other, so only the damaged device needs to be removed. All other designs receive a score of 3. All of the AFC devices can be disconnected from one another allowing the damaged piece to be the only thing replaced but the entire AFC assembly must be removed first. All of the internal designs outscored the external designs in the maintenance category by a single point. Each internal design received a score of 9 points while the external designs each received a total score of 8 points.

The structure category is the first category where any design receives a rank of 0. For the first criterion of “continuous skin,” all of the external designs receive a 4. The skin of the wing flap is shaped around the AFC to form the grooves, but the skin continuity is never severed. The “continuous skin” criterion has a ranking of 2 for the side inserted AFC and the vertically inserted AFC designs. Both designs have a section removed from the wing flap skin to create the AFC slot and AFC hole respectively. The attached AFC design has a score of 3 because there are only two small slots removed from the wing flap skin. The removed sections are much smaller than the surrounding area of connected skin. In the “AFC detachment" criterion, all the external designs are ranked with a 0. The exposed position of the AFC does not afford any fail-safes if the AFC was to detach in the middle of a flight. The projectile nature of an object detaching from an aircraft is a safety concern that cannot be ignored. The attached AFC design also has a score of 0 for the “AFC detachment” criterion because there is nothing to keeping it from flying off of the wing flap if the flanges fail. The side inserted design and the vertically inserted design score a 4 in the “AFC detachment” criterion. If the side inserted AFC came loose from is functioning position, it would be trapped within the wing flap which would prevent the AFC from becoming a projectile. The vertically inserted design would not trap the AFC in the same way as the side inserted AFC design, but the aerodynamic forces acting on the upper surface of the AFC would secure the device in place until the aircraft was no longer in motion. The “stress concentrations” criterion is still a concern for the external designs even though the wing flap skin is continuous through the grooves. The rounded designs have rounded corners reducing the stress concentrations at the groove but they still may occur, which is why they have a ranking of 2. The semi-circular grooves reduce the possibility of stress concentrations even farther than the rounded grooves by eliminating corners all together. The semi-circular groove designs have a score of 3 for the “stress concentrations” criterion. As previously stated, both the side inserted design and the vertically inserted design have sections removed from the wing flap skin. These abrupt changes in geometry will cause a certain amount of stress concentration even if there are reinforcements and continuous skin on either side of the holes. Both designs have a score of 1 for the “stress concentrations” criterion. The attached design receives a score of 3 because the continuous skin area surrounding the AFC flange cut-outs is much larger than the cut-outs themselves. The stresses are more likely to flow around the cut-outs reducing the possibility of stress concentrations at the point of the cut-outs. The final structural criterion is “protected components.” All of the external designs receive a 0 due to the exposed nature of the AFC devices. The potential for damage is high both while on the ground and in the air. All three internal designs score a 4 for having completely encased AFC devices. The devices are surrounded by multiple layers of carbon-fiber which will shield them from debris or other types of damage. The largest point total for the structure category is 11 produced by both the vertically inserted AFC design and the side inserted AFC design. The rounded groove designs scored lowest with totals of 6 points for the structure category.

The final totals at the bottom of the table show that there is a large difference between the external and internal designs in fulfilling the design criteria. The rounded groove designs both have a score of 37 points and the semi-circular designs both have a score of 36 points. These inferior totals are mainly caused by the 0 rankings received in both the "AFC detachment" and "protected components" criteria. The highest scoring design is the vertically inserted AFC design with 46 points. The differences between the vertically inserted AFC design's score and the side inserted AFC design score are in the "assembly pieces" and "modular AFC" criteria. Overall, the vertically inserted AFC design satisfied the most criteria followed closely by the side inserted AFC design and then the attached AFC design.

5.1.2 Ribbed Evaluation

The base evaluation matrix for the ribbed designs has many of the same rankings as the foam core base evaluation matrix. All of the scores for the aerodynamics, maintenance, and structure categories are identical between the two evaluation matrices because these categories pertain almost entirely to the wing flap skin and AFC placement which do not depend on the core selection. Table 5.2 shows the ribbed base evaluation matrix. As with the foam core matrix, the internal designs outscore the external designs by 7 points in this case. The vertically inserted AFC design has the highest total with 43 points and a relative success total of 0.77 followed closely by the side inserted AFC design and the attached AFC design both with a score of 42 points and a relative success total of 0.75.

Table 5.2: Ribbed base evaluation matrix

	Criteria \ Concept	External Designs				Internal Designs			
		Rounded groove straight AFC	Rounded groove tilted AFC	Semi-circular groove straight AFC	Semi-circular groove tilted AFC	Side inserted AFC	Vertically inserted AFC	Attached AFC	Max Score
Aerodynamics	Similarity to original wing flap	2	2	2	2	3	3	3	4
	Functional flap with AFC inactive	1	1	1	1	3	3	3	4
	Obstructions in the airflow	2	2	2	2	4	4	4	4
Manufacturing	Mandrels	3	3	3	3	1	2	2	4
	Layer cuts	4	4	4	4	3	3	2	4
	Fiber Layup	2	2	2	2	2	2	3	4
	Assembly pieces	3	3	3	3	2	2	2	4
	Self aligning AFC	4	4	2	2	4	4	4	4
Maintenance	Accessible AFC	4	4	4	4	2	2	2	4
	Removable AFC	1	1	1	1	4	3	4	4
	Modular AFC	3	3	3	3	3	4	3	4
Structure	Continuous skin	4	4	4	4	2	2	3	4
	AFC detachment	0	0	0	0	4	4	0	4
	Stress concentrations	2	2	3	3	1	1	3	4
	Protected components	0	0	0	0	4	4	4	4
	Total	**35**	**35**	**34**	**34**	**42**	**43**	**42**	**60**
	Relative Success Total	**0.63**	**0.63**	**0.61**	**0.61**	**0.75**	**0.77**	**0.75**	**1**

4=Very good **2= Satisfactory** **0= Unacceptable**
3= Good **1= Tolerable**

The differences between the ribbed and foam core base evaluation matrices occur within the manufacturing category. The two criteria that vary are “mandrels” and “assembly pieces.” The two other manufacturing criteria are identical between the core evaluations. In the “mandrels” criterion, the external designs all score 3 because they require a single mandrel. The external designs in the foam core evaluation matrix scored a 4 because there were no mandrels needed for the fabrication process. The side inserted AFC design receives a 1 as opposed to the previous score of 2 because the ribbed design requires an additional mandrel. The vertically inserted AFC design also loses a point because the ribbed design requires two additional mandrels which place its ranking at a 2. The attached AFC design does not have a score change between the two evaluations because both instances use three mandrels. The addition of ribs to the assembly process lowered almost every design's score by a point in the "assembly pieces" criterion. Except for the vertically inserted AFC design which lost two points, all of the external designs went from a 4 to a 3. The side inserted AFC design and the attached AFC design went from a 3 to a 2. The vertically inserted AFC design went from a 4 to a 2 because it required an additional assembly piece as well as the ribs. The highest scoring designs in the manufacturing category are both rounded groove designs with 16 points. The lowest scoring design is the side inserted AFC design with 13 points.

The totals at the bottom of the ribbed base evaluation matrix show that there is still a large difference between the external and internal designs. Also, it can be seen that the final totals for all the ribbed designs are lower than the foam core evaluation totals. The rounded groove designs both have a score of 35 points while the semi-circular designs both have a score of 34 points as opposed to the 37 points and the 36 points from the foam core evaluation. The internal designs' scores also drop with the largest difference being the vertically inserted AFC design which had a score of 46 points for the foam core evaluation now has a score of 43 points. The side inserted AFC design's score was reduce by two points between the core selection and the attached AFC design's score was reduced by a single point. Overall, the vertically inserted AFC design satisfied the most criteria for the ribbed evaluation followed closely by the side inserted AFC design and the attached AFC design.

It can be seen in both evaluation matrices that the internal designs have the largest totals and relative success totals. The vertically inserted AFC design receives the highest score overall for both the foam core and ribbed analysis with 47 points and 43 points respectively. They have a relative success total of 0.82 for the foam core and 0.77 for the ribbed. The side inserted AFC design is the next highest scoring in the foam core analysis followed by the attached AFC design. In the ribbed analysis, the side inserted AFC design and the attached AFC design have identical scores for the base evaluation. This base level evaluation shows that the three internal designs satisfy the most design criteria making them the best candidates for the final design.

4.1 Second-Level Evaluation

The weighted evaluation matrix is identical to the base evaluation matrix in the design criteria categories and each concept ranking. The weighted evaluation matrix increases the resolution of the evaluation by adding an importance column. The importance value is based on an absolute scale between 0-10 with 10 being extremely important and 0 being not important. Each concept ranking, which are identical to the base matrix concept rankings, is multiplied by the importance to create the weighted rankings. The weighted rankings are summed yielding the weighted total. The weighted total is divided by the maximum possible score giving the relative success total. The importance weight is determined by the critical nature of each criterion. Table 5.3 shows the importance weights of each design criterion.

Table 5.3: Importance Weights

	Criteria	Importance
Aerodynamics	Similarity to original wing flap	9
	Functional flap with AFC inactive	10
	Obstructions in the airflow	9
Manufacturing	Mandrels	5
	Layer cuts	6
	Fiber Layup	7
	Assembly pieces	9
	Self aligning AFC	9
Maintenance	Accessible AFC	6
	Removable AFC	10
	Modular AFC	7
Structure	Continuous skin	8
	AFC detachment	10
	Stress concentrations	8
	Protected components	10

The aerodynamics category has the highest importance values of any design category. The “similarity to original wing flap” and the “obstruction in the airflow” both have an importance value of 9. The similarity to the original wing flap is important because of the flight characteristics of the wing flap. If the wing flap geometry is altered greatly, the changed characteristics can be a large safety issue because of the wing’s unpredictability. The “obstructions in the airflow” criterion is important for many of the same reasons as the “similarity to original wing flap” criterion. The obstruction can actually cause the boundary layer to separate prematurely causing stall. The “functional flap with AFC inactive” criterion has an importance of 10. The AFC devices might only be utilized during takeoff and landing of the aircraft. In the time in-between, the wing flap needs to function properly and safely.

The manufacturing category has a broad level of importance. The "mandrels" criterion has an importance level of 5 because the mandrels are created before the wing flap fabrication, so they do not directly affect the composite layup process. The "layer cuts" criterion has an importance weight of 6. The importance is also low because it is a pre-layup process like the "mandrels." This cutting of the carbon-fiber layers can also be automated to simplify the manufacturing process. The "fiber layup" criterion has an importance level of 7. The ease of the layup process is essential to the manufacturing category but is not necessarily directly related to the flight performance of the wing flap. The "assembly pieces" criterion has an importance weight of 9 because the difficulty and number of part for the final assembly is important to the functionality of the total wing flap. The final manufacturing criterion is the "self aligning AFC." This has a high importance rating with a 9 because the correct alignment of the AFC directly affects its functionality. If not placed properly, the AFC device may not function correctly which may be more detrimental than having the AFC inactive.

The maintenance category has two low importance criteria and one very important criterion. The "accessible AFC" criterion has an importance of 6 because the accessibility is only important for the inspection of the devices. The accessibility of the AFC should not change the function or flight characteristics of the assembled system. The "removable AFC" is an extremely important criterion which is why it has a weight of 10. If the device is permanent, there is no possibility for removal or repair. If a large section of the AFC device were to fail, the entire wing flap would need to be replaced to fix the problem. The modularity of the AFC is important when it come to maintenance because once the device is removed, a modular AFC component can have the damaged section removed and replaced. The modularity does not affect the function of the AFC which is why it only receives a 7.

The structure category directly affects the function of the assembly, which is why it has high importance rankings. The “continuous skin” criterion has an importance of 8 because an open structure can be more susceptible to forces and can cause larger deformations. The “AFC detachment” criterion has an importance of 10 because the possibility of the AFC becoming separated from the wing during flight is a very serious safety concern. The “stress concentrations” criterion has an importance of 8 because the occurrence of stress concentrations can cause premature failure. The final criterion, “protected components,” has an importance value of 10. The protection of the AFC and its securing devices is one of the most important criteria because the more damage an AFC device takes, the more the aircraft will have to be repaired. The AFC needs to function as consistently as possible and protecting it is one of the best ways to ensure that occurs.

The results from the base level evaluation showed that the internal designs satisfied the design criteria more completely than the external designs. For this reason, the foam core weighted evaluation matrix, shown in Table 5.4, and the ribbed weighted evaluation matrix, shown in Table 5.5, only depict the internal designs. The complete foam core and ribbed weighted evaluation matrices, which include both the internal and external designs, can be found in Appendix A. The importance column is next to the criteria column depicting the importance weight for each. The weighted scores and totals are shown in bold.

5.2.1 Foam Core Evaluation

The foam core weighted evaluation matrix is shown in Table 5.4. The vertically inserted AFC design has the highest weighted total with 386 points and relative total of 0.785. The attached AFC design scored the lowest for the internal designs with 360 points and a relative total of 0.732.

Table 5.4: Foam core weighted evaluation matrix

	Concept		**Internal Designs**							
	Criteria	**Importance**	Side inserted AFC		Vertically inserted AFC		Attached AFC		Max Score	
Aerodynamics	Similarity to original wing flap	9	3	**27**	3	**27**	3	**27**	4	**36**
	Functional flap with AFC inactive	10	3	**30**	3	**30**	3	**30**	4	**40**
	Obstructions in the airflow	9	4	**36**	4	**36**	4	**36**	4	**36**
Manufacturing	Mandrels	5	2	**10**	3	**15**	2	**10**	4	**20**
	Layer cuts	6	3	**18**	3	**18**	2	**12**	4	**24**
	Fiber Layup	7	2	**14**	2	**14**	3	**21**	4	**28**
	Assembly pieces	9	3	**27**	4	**36**	3	**27**	4	**36**
	Self aligning AFC	9	4	**36**	4	**36**	4	**36**	4	**36**
Maintenance	Accessible AFC	6	2	**12**	2	**12**	2	**12**	4	**24**
	Removable AFC	10	4	**40**	3	**30**	4	**40**	4	**40**
	Modular AFC	7	3	**21**	4	**28**	3	**21**	4	**28**
Structure	Continuous skin	8	2	**16**	2	**16**	3	**24**	4	**32**
	AFC detachment	10	4	**40**	4	**40**	0	**0**	4	**40**
	Stress concentrations	8	1	**8**	1	**8**	3	**24**	4	**32**
	Protected components	10	4	**40**	4	**40**	4	**40**	4	**40**
	Weighted Total			**375**		**386**		**360**		**492**
	Relative Total			**0.762**		**0.785**		**0.732**		**1**

The vertically inserted AFC design and the side inserted AFC design have similar weighted totals and relative totals. The majority of the point difference between the two designs comes from the "assembly pieces" criterion which has an importance rating of 9. The point difference between the vertically inserted AFC design and the attached design is 26 points. The large difference comes from the "AFC detachment" criterion. The criterion has an importance weight of 10 points. The attached AFC design has a score of 0 points while the vertically inserted AFC design has a score of 40 points. The second place where the points differ is in the "assembly pieces" criterion. The "modular AFC" and the "layer cuts" criteria also have point differences between the designs, but the lower importance level impacts the weighted total less. The two designs that will go to the final evaluation are the side inserted AFC foam core design and the vertically inserted AFC foam core design.

5.2.2 Ribbed Evaluation

The ribbed weighted evaluation matrix is shown in Table 5.5. The vertically inserted AFC design has the highest weighted total with 372 points and a relative total of 0.756. The attached AFC design scored the lowest for the internal designs with 351 points and a relative total of 0.713.

Table 5.5: Ribbed weighted evaluation matrix

	Concept		**Internal Designs**							
	Criteria	**Importance**	Side inserted AFC		Vertically inserted AFC		Attached AFC		Max Score	
Aerodynamics	Similarity to original wing flap	9	3	**27**	3	**27**	3	**27**	4	**36**
Aerodynamics	Functional flap with AFC inactive	10	3	**30**	3	**30**	3	**30**	4	**40**
Aerodynamics	Obstructions in the airflow	9	4	**36**	4	**36**	4	**36**	4	**36**
Manufacturing	Mandrels	5	1	**5**	2	**10**	2	**10**	4	**20**
Manufacturing	Layer cuts	6	3	**18**	3	**18**	2	**12**	4	**24**
Manufacturing	Fiber Layup	7	2	**14**	2	**14**	3	**21**	4	**28**
Manufacturing	Assembly pieces	9	2	**18**	3	**27**	2	**18**	4	**36**
Manufacturing	Self aligning AFC	9	4	**36**	4	**36**	4	**36**	4	**36**
Maintenance	Accessible AFC	6	2	**12**	2	**12**	2	**12**	4	**24**
Maintenance	Removable AFC	10	4	**40**	3	**30**	4	**40**	4	**40**
Maintenance	Modular AFC	7	3	**21**	4	**28**	3	**21**	4	**28**
Structure	Continuous skin	8	2	**16**	2	**16**	3	**24**	4	**32**
Structure	AFC detachment	10	4	**40**	4	**40**	0	**0**	4	**40**
Structure	Stress concentrations	8	1	**8**	1	**8**	3	**24**	4	**32**
Structure	Protected components	10	4	**40**	4	**40**	4	**40**	4	**40**
	Weighted Total			**361**		**372**		**351**		**492**
	Relative Total			**0.734**		**0.756**		**0.713**		**1**

As with the base matrix, many of the scores are identical between the ribbed weighted evaluation matrix and the foam core weighted evaluation matrix. The differences occur in the manufacturing category. For the side inserted AFC design, a score of 5 points is achieved for the "mandrels" criterion. The vertically inserted AFC design has a score of 10 points and the attached AFC design also has a score of 10 points. The other difference happens in the "assembly pieces" criterion. The side inserted AFC design and the attached AFC design both score 18 points while the vertically inserted AFC design scores 27 points. Again, the highest scoring design is the vertically inserted AFC design with 372 points. The side inserted design places second with 361 points and the attached AFC ribbed design scores the lowest total of 351 points. As with the foam core weighted evaluation matrix, the largest point difference between the vertically inserted AFC ribbed design and the attached AFC ribbed design is in the "AFC detachment" criterion. The vertically inserted AFC design has a score of 40 points and the attached AFC design has a score of 0. The "modular AFC" and the "layer cuts" criteria also contribute to the point discrepancy between the vertically inserted AFC design and the attached AFC design. The vertically inserted AFC ribbed design and the side inserted AFC ribbed design will continue to the next level of evaluation.

5.3 Third-Level Evaluation

The final step of evaluation is the head to head comparison of the two highest scoring designs from the foam core and ribbed core in a final weighted evaluation matrix. The four designs being analyzed are the vertically inserted AFC design foam core and ribbed and the side inserted AFC design foam core and ribbed. Table 5.6 shows the final weighted evaluation matrix. The numbers within the matrix have not changed since the second-level evaluation.

Table 5.6: Final weighted evaluation matrix

	Criteria / Concept	Importance	Foam Core				Ribbed				Max Score	
			Vertically inserted AFC Foam core		Side inserted AFC Foam core		Vertically inserted AFC Ribbed		Side inserted AFC Ribbed			
Aerodynamics	Similarity to original wing flap	9	3	**27**	3	**27**	3	**27**	3	**27**	4	**36**
	Functional flap with AFC inactive	10	3	**30**	3	**30**	3	**30**	3	**30**	4	**40**
	Obstructions in the airflow	9	4	**36**	4	**36**	4	**36**	4	**36**	4	**36**
Manufacturing	Mandrels	5	3	**15**	2	**10**	2	**10**	1	**5**	4	**20**
	Layer cuts	6	3	**18**	3	**18**	3	**18**	3	**18**	4	**24**
	Fiber Layup	7	2	**14**	2	**14**	2	**14**	2	**14**	4	**28**
	Assembly pieces	9	4	**36**	3	**27**	3	**27**	2	**18**	4	**36**
	Self aligning AFC	9	4	**36**	4	**36**	4	**36**	4	**36**	4	**36**
Maintenance	Accessible AFC	6	2	**12**	2	**12**	2	**12**	2	**12**	4	**24**
	Removable AFC	10	3	**30**	4	**40**	3	**30**	4	**40**	4	**40**
	Modular AFC	7	4	**28**	3	**21**	4	**28**	3	**21**	4	**28**
Structure	Continuous skin	8	2	**16**	2	**16**	2	**16**	2	**16**	4	**32**
	AFC detachment	10	4	**40**	4	**40**	4	**40**	4	**40**	4	**40**
	Stress concentrations	8	1	**8**	1	**8**	1	**8**	1	**8**	4	**32**
	Protected components	10	4	**40**	4	**40**	4	**40**	4	**40**	4	**40**
	Weighted Total			**386**		**375**		**372**		**361**		**492**
	Relative Total			**0.785**		**0.762**		**0.756**		**0.734**		**1**

The vertically inserted AFC foam core design has the highest weighted total with 386 points making it the best design option. Most of the rankings within the final evaluation matrix are identical between all of the designs. The vertically inserted AFC foam core design had three criteria where its rankings are higher than the other designs. The first criterion is "mandrels." The foam core variant of the vertically inserted AFC design only requires a single mandrel for each AFC device being inserted. The other designs require three or more mandrels per AFC device. The second criterion that the vertically inserted AFC foam core design ranked highest in is "assembly pieces." Only one assembly piece is required for the vertically inserted AFC foam core design while the other three designs require two pieces, and the ribbed variants also require the assembly of the ribs. The final differentiation between the vertically inserted AFC foam core design and the other designs is the “modular AFC” criterion. Both vertically inserted designs have completely modular AFC devices. With the side inserted AFC designs, the entire chain of AFC devices must be removed and then the damaged section can be detached and replaced. With the vertically inserted AFC designs, only the damaged AFC device needs to be removed. The vertically inserted AFC foam core design outscored the next highest scoring design, the side inserted AFC foam core design, by 11 points.

The side inserted AFC foam core design is followed closely by the vertically inserted AFC ribbed design in points. There is only a three point difference between the two designs which means that if the side inserted AFC foam core design remains a valid design option, the vertically inserted AFC ribbed design must also. The difference between the first and last place designs is twenty-five points. This point difference is quite significant. The side inserted AFC ribbed design is no longer considered a viable design option for the integration of an AFC into a composite wing flap.

5.4 Chapter Summary

This chapter used the evaluation matrix design tool to determine the most appropriate design concept from Chapter 3. The highest scoring design was the vertically inserted AFC foam core design followed by the side inserted AFC foam core design. The vertically inserted AFC ribbed design had a score similar to that of the side inserted AFC foam core design which allowed it to remain a viable design option. The side inserted AFC ribbed design had the lowest score eliminating it from the evaluation.

The first-level of evaluation used a base evaluation matrix which ranked each design concept against the design criteria on a scale of 0 to 4. The vertically inserted AFC foam core design achieved the highest ranking in the foam core base evaluation matrix with 47 points. In the ribbed base evaluation matrix, the vertically inserted AFC design again received the highest score with 44 points. The second highest scoring design for the foam core variant was the side inserted AFC design. For the ribbed designs, both the side inserted AFC design and the vertically inserted AFC design tied in points for second place.

The second-level evaluation applied an importance weight to the evaluation matrix which increased the evaluation resolution. The importance weights were determined by the how critical the design criteria was to the functionality of the assembled design. The importance weights were based on an absolute scale between 0 and 10. The foam core weighted evaluation matrix produced a high score of 386 points for the vertically inserted AFC design. The highest scoring ribbed design was also the vertically inserted AFC design with 372 points. In both cases, the second highest scoring design was the side inserted AFC design. The top two designs from the second-level evaluation for both the foam core and ribbed designs were compared to determine the most fitting design concept for the design criteria. The conclusions from the final evaluation are presented in Chapter 5 along with suggestions for the continuation of this research.

Chapter 6:

CONCLUSIONS

Fluidic oscillators can be used to delay the stall a wing flap experiences by blowing energized air into the boundary layer on the upper surface of the wing flap. The fluidic oscillator used in this thesis is an active flow control (AFC) device. One method commonly used to integrate an AFC device involves cutting holes into a wing flap and mechanically fastening the device. Cutting holes into composite components causes adverse environmental effects and delamination between the layers of composite fibers on top of structural issues caused by the creation of the hole. This thesis proposed a set of alternative designs that integrates the AFC devices before the fabrication of the wing flaps is completed and the flaps are placed on the aircraft wing, eliminating many of the issues caused by current integration methods. The designs to integrate the AFC device into a composite wing flap were developed using four main design requirements: aerodynamics, manufacturing, maintenance, and structure. Two major design categories were created to satisfy the design requirements: external designs and internal designs. Each of the design concepts within these categories possesses foam core and ribbed design variants.

The external designs place the AFC device on the exterior surface of the wing flap. The benefits of the external designs are simplicity in concept and in manufacturing. The concepts are simple because the AFC device is seated in a grooved channel on the exterior surface of the wing flap and glued into place. The simplicity in manufacturing comes from the continuity of the carbon-fiber layers around the entire wing skin. The wing skin is able to be laid up as a single piece that both begins and ends at the trailing edge of the flap. The external placement the AFC device on the wing flap poses some large problems for the designs. The first problem corresponds to the aerodynamics. The AFC protrudes from the surface of the wing flap which will disrupt the airflow over the wing flap changing the flight characteristics of the system. The second problem is that the device can become a projectile if it is unseated during flight. There is nothing to safeguard the device from detaching from the wing flap and causing damage to the aircraft or bystanders. The last major issue with the external designs is the maintenance of the AFC devices. The AFC devices are glued into the grooved channels on the surface of the wing skin which makes removal without damaging the AFC device or the wing flap almost impossible. In the case of the external AFC designs, the negative aspects of the designs outweigh the benefits. All four of the external designs were eliminated as viable design options for the integration of an AFC into a composite wing flap.

The internal designs place the AFC device within the wing flap skin, which eliminates the major problems that were seen with the external designs. The internal designs are not exposed to the free stream air and therefore do not have the same aerodynamic problems as the external designs. The location of the device within the flap skin also eliminates the possibility of the AFC device becoming a projectile for two of the internal designs, although one design still runs this risk. Finally, all of the internal designs' AFC devices are secured in place without the use of glues, which allows for easy, non-destructive removal of the device for maintenance purposes. Although they eliminate the problems encountered by the external designs, the internal designs have problems of their own. To allow the air exiting the AFC device to blow tangential to the upper surface of the wing flap, sections must be removed from the wing flap skin. By removing sections of the wing flap, stress concentrations and other structural strength issues arise. The removal of these sections also complicates the manufacturing process because cuts and holes must be created before the composite wing flap is laid up and infused with resin. The positive aspects of the internal designs outweigh the negatives. Two of the internal design concepts are viable design options for the integration of an AFC into a composite wing flap.

As previously stated, the evaluation of the seven design concepts eliminated all four of the external designs and one of the internal designs. The evaluation was completed by using two levels of evaluation matrices, one of which had an importance rating. The two remaining designs each with a ribbed and foam core variant were compared to determine the final design. The vertically inserted AFC foam core design emerged as the most fitting design for the integration of an AFC device into a composite wing skin because of its simplicity in the "mandrels" and "assembly pieces" criteria from the design evaluation chapter. The secondary design is the side inserted AFC foam core design with the vertically inserted AFC ribbed design a close third. The score difference between the two designs is small enough that the vertically inserted AFC ribbed design cannot be ignored. All three of these designs are viable and testing is needed to select the best one(s).

6.1 Future Work

Further research is required to determine if the selected designs will function as theorized. Wind tunnel testing should be completed to investigate if the aerodynamic characteristics of the wing flaps have been compromised by the addition of the AFC devices. Data should be gathered with the AFC both active and inactive. The comparison of these data will show the performance attributes of both the wing flap and the AFC. Although eliminated by the design evaluation, it is important to wind tunnel test at least one of the external designs for comparison purposes. Structural testing also must be conducted on the wing flaps. The testing will mimic the loading that the wing flap will see during a typical flight. The effects of adding an AFC slot to the wing flap skin must be determined and additional support added if necessary. Analysis needs to be performed on the core selection for the final design selected after the wind tunnel and structural tests. No analysis was performed in this thesis for the structural, weight, or cost benefits of a foam core versus a ribbed design. Once a design has completed the aerodynamics, structural, and core analysis testing, it needs to be put into large scale flight testing as the final determining factor before production.

Appendix A:

Weighted Evaluation Matrices

Table A-1: Complete foam core weighted evaluation matrix

	Concept		**External Designs**								**Internal Designs**							
	Criteria	**Importance**	Rounded groove straight AFC		Rounded groove tilted AFC		Semi-circular groove straight AFC		Semi-circular groove tilted AFC		Side inserted AFC		Vertically inserted AFC		Attached AFC		Max Score	
Aerodynamics	Similarity to original wing flap	9	2	**18**	2	**18**	2	**18**	2	**18**	3	**27**	3	**27**	3	**27**	4	**36**
Aerodynamics	Functional flap with AFC inactive	10	1	**10**	1	**10**	1	**10**	1	**10**	3	**30**	3	**30**	3	**30**	4	**40**
Aerodynamics	Obstructions in the airflow	9	2	**18**	2	**18**	2	**18**	2	**18**	4	**36**	4	**36**	4	**36**	4	**36**
Manufacturing	Mandrels	5	4	**20**	4	**20**	4	**20**	4	**20**	2	**10**	3	**15**	2	**10**	4	**20**
Manufacturing	Layer cuts	6	4	**24**	4	**24**	4	**24**	4	**24**	3	**18**	3	**18**	2	**12**	4	**24**
Manufacturing	Fiber Layup	7	2	**14**	2	**14**	2	**14**	2	**14**	2	**14**	2	**14**	3	**21**	4	**28**
Manufacturing	Assembly pieces	9	4	**36**	4	**36**	4	**36**	4	**36**	3	**27**	4	**36**	3	**27**	4	**36**
Manufacturing	Self aligning AFC	9	4	**36**	4	**36**	2	**18**	2	**18**	4	**36**	4	**36**	4	**36**	4	**36**
Maintenance	Accessible AFC	6	4	**24**	4	**24**	4	**24**	4	**24**	2	**12**	2	**12**	2	**12**	4	**24**
Maintenance	Removable AFC	10	1	**10**	1	**10**	1	**10**	1	**10**	4	**40**	3	**30**	4	**40**	4	**40**
Maintenance	Modular AFC	7	3	**21**	3	**21**	3	**21**	3	**21**	3	**21**	4	**28**	3	**21**	4	**28**
Structure	Continuous skin	8	4	**32**	4	**32**	4	**32**	4	**32**	2	**16**	2	**16**	3	**24**	4	**32**
Structure	AFC detachment	10	0	**0**	0	**0**	0	**0**	0	**0**	4	**40**	4	**40**	0	**0**	4	**40**
Structure	Stress concentrations	8	2	**16**	2	**16**	3	**24**	3	**24**	1	**8**	1	**8**	3	**24**	4	**32**
Structure	Protected components	10	0	**0**	0	**0**	0	**0**	0	**0**	4	**40**	4	**40**	4	**40**	4	**40**
	Weighted Total			**279**		**279**		**269**		**269**		**375**		**386**		**360**		**492**
	Relative Total			**0.567**		**0.567**		**0.547**		**0.547**		**0.762**		**0.785**		**0.732**		**1**

Table A-2: Complete ribbed weighted evaluation matrix

	Concept		**External Designs**								**Internal Designs**							
	Criteria	**Importance**	Rounded groove straight AFC		Rounded groove tilted AFC		Semi-circular groove straight AFC		Semi-circular groove tilted AFC		Side inserted AFC		Vertically inserted AFC		Attached AFC		Max Score	
Aerodynamics	Similarity to original wing flap	9	2	**18**	2	**18**	2	**18**	2	**18**	3	**27**	3	**27**	3	**27**	4	**36**
	Functional flap with AFC inactive	10	1	**10**	1	**10**	1	**10**	1	**10**	3	**30**	3	**30**	3	**30**	4	**40**
	Obstructions in the airflow	9	2	**18**	2	**18**	2	**18**	2	**18**	4	**36**	4	**36**	4	**36**	4	**36**
Manufacturing	Mandrels	5	3	**15**	3	**15**	3	**15**	3	**15**	1	**5**	2	**10**	2	**10**	4	**20**
	Layer cuts	6	4	**24**	4	**24**	4	**24**	4	**24**	3	**18**	3	**18**	2	**12**	4	**24**
	Fiber Layup	7	2	**14**	2	**14**	2	**14**	2	**14**	2	**14**	2	**14**	3	**21**	4	**28**
	Assembly pieces	9	3	**27**	3	**27**	3	**27**	3	**27**	2	**18**	3	**27**	2	**18**	4	**36**
	Self aligning AFC	9	4	**36**	4	**36**	2	**18**	2	**18**	4	**36**	4	**36**	4	**36**	4	**36**
Maintenance	Accessible AFC	6	4	**24**	4	**24**	4	**24**	4	**24**	2	**12**	2	**12**	2	**12**	4	**24**
	Removable AFC	10	1	**10**	1	**10**	1	**10**	1	**10**	4	**40**	3	**30**	4	**40**	4	**40**
	Modular AFC	7	3	**21**	3	**21**	3	**21**	3	**21**	3	**21**	4	**28**	3	**21**	4	**28**
Structure	Continuous skin	8	4	**32**	4	**32**	4	**32**	4	**32**	2	**16**	2	**16**	3	**24**	4	**32**
	AFC detachment	10	0	**0**	0	**0**	0	**0**	0	**0**	4	**40**	4	**40**	0	**0**	4	**40**
	Stress concentrations	8	2	**16**	2	**16**	3	**24**	3	**24**	1	**8**	1	**8**	3	**24**	4	**32**
	Protected components	10	0	**0**	0	**0**	0	**0**	0	**0**	4	**40**	4	**40**	4	**40**	4	**40**
	Weighted Total			**265**		**265**		**255**		**255**		**361**		**372**		**351**		**492**
	Relative Total			**0.539**		**0.539**		**0.518**		**0.518**		**0.734**		**0.756**		**0.713**		**1**

REFERENCES

Cislunar Aerospace, I. (1999, Feburary 11). *Laminar, Turbulence, Transition and Flow Separation*. Retrieved July 22, 2011, from http://wings.avkids.com/Tennis/Book/laminar-01.html

Cowley, W. L., & Levy, H. (1920). *Aeronautics in Theory and Experiment* (Second ed.). London: Edward Arnold.

Denker, J. S. (n.d.). *Av8n*. Retrieved February 24, 2012, from http://www.av8n.com/how/htm/airfoils.html

Dole, C. E., & Lewis, J. E. (2000). *Flight Theory and Aerodynamics. 2nd ed.* New York: John Wiley & Sons.

Fineline Prototyping Inc. (2012). *Fineline Prototyping*. Retrieved March 26, 2012, from http://www.finelineprototyping.com/

Gere, J. M., & Timoshenko, S. P. (1997). *Mechanics of Materials* (Fourth ed.). Boston: PWS Publishing Company.

Glenn, J. C., Hale, J. S., Lippincott, D. H., Longson, N. A., & Simmons, N. L. (1965). *Fluidics*. Boston: Fluid Amplifier Associates, Incoporated.

Gregory, J. W., Sakaue, H., & Sullivan, J. P. (2002). Fluidic Oscillator as a Dynamic Calibration Tool. *22nd Aerodynamic Measurement Technology & Ground Testing Conference* (p. 2). Saint Louis: American Institute of Aeronautics and Astronautics.

Hall, J. (n.d.). *Processing and Performance of Continuous Fiber Ceramic Composites Using Vacuum Assisted Resin Transfer Molding and Blacglas Preceramic Polymer Pyrolysis.* Honolulu: University of Hawaii.

Interiot. (n.d.). *Stall Information*. Retrieved March 8, 2012, from http://wwwsam.brooks.af.mil/af/files/fsguide/HTML/Graphics/fig_28-11.gif Image

Joyce, J. W. (1983). *Fluidics: Basic Components and Applications.* Alexandria: U.S. Army Material Development and Readiness Command.

Lan, E. C., & Roskam, J. (1981). *Airplane Aerodynamics and Performance.* Ottawa,: Roskam Aviation and Engineering.

Mallick, P. K. (2008). *Fiber- Reinforced Composites: Materials, Manufacturing, and Design* (3rd ed.). Boca Raton: CRC Press.

Meridian International Research. (2005, September 22). *The Coanda Effect*. Retrieved August 1, 2011, from http://www.meridian-int-res.com/Aeronautics/Coanda.htm

Oertel, H. (2010, July 23). RANS Simulation of a Fluidic Oscillator. Wikimedia Commons.

Singhose, W., & Donnell, J. (2011). *Introductory Menchanical Design Tools.* www.lulu.com.

Society of Manufacturing Engineers. (n.d.). *Fundamental Manufacturing Process Video Series Study Guide.* Retrieved February 27, 2012, from Fastening and Assembly: http://manufacturing.stanford.edu/processes/Fastening&Assembly.pdf

Street, R. L., Watters, G. Z., & Vennard, J. K. (1996). *Elementary Fluid Mechanics. 7th ed.* New York: John Wiley & Sons.

Strong, A. B. (1989). *Fundamentals of Composite Manufacturing: Materials, Methods, and Applications.* Dearborn: Society of Manufacturing Engineers.

Wright, N., & Makowski, L. (2006, June). *New Airliners Influence Lightning Tests.* Retrieved March 7, 2012, from Evaluation Enginnering.