10/28/2019

EML4551-2

Team 519: Composite Airframe Life Extension

Cecil E. Evers; Christopher A. Ryan, Gabrielle E. Mohrfeld, Stefan Spiric

2525 Pottsdamer St. Tallahassee, FL. 32310

Table of Contents

List of Tables

List of Figures

Notation

NGC	Northrup Grumman Corporation
DOD	Department of Defense
FEA	Finite Element Analysis
ASTM	American Society for Testing of Materials
USAF	United States Air Force
USN	United States Navy
CALE	Composite Airframe Life Extension
HPMI	High Performance Materials Institute
EM	Electro-magnetic
FS	Fuselage Station
CF	Carbon Fiber
rCF	Recycled Carbon Fiber

Chapter One: EML 4551C

Project Scope

Project Description.

The objective of this project is to evaluate replacing aluminum with a composite material for use as a C channel in an E-2 Hawkeye, by designing and performing experiments, according to MIL-STD-810, comparing aluminum with various composite materials.

Motivation.

The E-2 Hawkeye is a carrier borne airborne early warning and control (AEW&C) aircraft. The E-2 family of aircraft have been in service since the 1960s; the modern variant is the E-2D Advanced Hawkeye produced by Northrup Grumman, shown below.

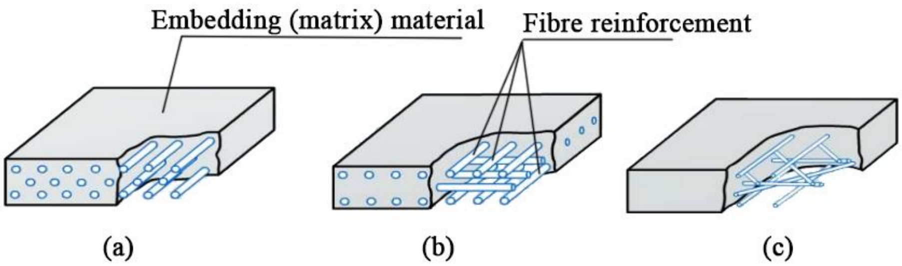
Figure 1: Northrup Grumman E-2D Advanced Hawkeye

Naval aviation has paradoxical size and weight requirements: the aircraft need to have large wings to decrease landing speed on short carrier flight decks and increase handling at low speed; however, the aircraft also need to be as lightweight as possible. (Wikipedia, 2019) Reducing airframe weight by using composites is a worthwhile goal because it reduces the lift required and therefore the size of the aircraft. In addition to improving flight characteristics, the weight saved by using lighter airframe materials can be allocated towards increasing the mission capability of the aircraft. In the case of the E-2, this could be more weight for sensory and communication equipment or fuel.

The second principle advantage composites offer is corrosion resistance; naval aircraft are continuously exposed to a corrosive environment while deployed. A composite material may need less maintenance than traditional materials, reducing operation costs and increasing readiness

Composites Background.

The Principle of Combined Action states that two materials with different properties can be combined to create a composite that incorporates the best parts of each material. Most composites are two phase materials with a distributed phase and a matrix phase. The distributed phase is generally a fibrous material with good tension strength which is enclosed in a matrix material with good shear strength. The result is an anisotropic material which is very strong in the direction of the fibers (the longitudinal direction) but significantly less strong in the direction perpendicular to the fiber direction (the transverse direction).



In figure 2a, the fibers are aligned in a single direction, resulting in an anisotropic material which is very strong only in a single direction (the direction of the fibers). Figure 2b, shows fibers going in two directions, resulting in a material which is strong in two directions. Figure 2c, shows fibers which are oriented randomly, resulting in a material that is approximately isotropic along the longitudinal and transverse planes. (Callister, 2014)

Composites are categorized by the matrix phase material. A ceramic matrix would be too brittle for a structural part of an airframe and would be far too heavy. A metal matrix would be extremely expensive and probably heavier than aluminum. This leaves polymer as the matrix material of choice. Polymer composites are extremely light, offer superior mechanical properties, and are used extensively in new airframe design. (Hale, 2006)

The distributed phase of polymer matrix composites are generally aramid fibers, glass fibers, or carbon fibers. Each type of fiber has a different use; carbon fibers see the most use in aerospace components; this family of composites are called Carbon Fiber Reinforced Polymers (CFRP). A more detailed discussion of distributed phase materials will occur later.

C Channel Background.

The C channel is a structural beam that is designed to hold a load. The C channel consists of two flanges attached to a web that allows for greater strength in bending. These structural channels have many applications, including in the airframes for many aircraft. These C channels can be manufactured from a variety of materials including steel and aluminum. These beams come in many standard sizes with varying cross-sectional dimensions and lengths. The back side of the web can often be mounted onto other structures. Two identical C channels may also be mounted back to back in order to form an I beam. Since developing a mold for composite I beams could be difficult, it common two see two composite C channels mounted back to back.

Insert a picture of it.

The governing equations are: bending y, bending x, moments of inertia, neutral axis. Its meant to be loaded in bending y because the most material is placed in the areas of highest stress. Explain St. Vennants principle and how tension will depend primarily on the attachment methods

Key Goals.

The key goals of this project are to find a lightweight composite material to replace an aluminum C channel with. From here, the phrase “the part” will be used in reference to the C channel. The team will validate the composite as structurally sound with at least five types of tests. The part holds a load and contributes to the structural rigidity of the airframe in general.

Determine Forces.

The stresses on the part must be determined so that the team can design the best material. The stresses will be determined by running a finite element analysis (FEA) on the part along with the governing equations. The FEA will show the areas of highest stress, which will be used to determine the most important tests to run and to design a composite system that will be appropriate to replace aluminum with.

Design Composite System.

Design a composite system that will withstand the stresses required, fulfills customer requirements, and is within the team's budget. The team will select the materials and design a custom composite system. This will include material selection and the design of the part. The composite system will be tested via FEA before manufacturing of test specimens.

Down-Select MIL-STD.

MIL-STD-810 details the environmental test methods for materials used by the Department of Defense (Department of Defense, 2019). There are far too many tests for the team to perform, so a small number of tests will be selected which will be tailored to the specific requirements of the part, as shown by the FEA. These tests will reflect the likely failure modes of composites and the operating conditions of the part. The tests the team runs will be heavily influenced by the team's budget and facility availability.

Perform Tests.

The team will design and perform a series of tests which will replicate maximum loading conditions of the part, as revealed by the FEA. All tests are to be done in accordance with MIL-STD-810 and any relevant ASTM standards.

Analyze Results.

Compare test results with values for aluminum alloys to determine if a composite will be a suitable replacement. Consider not just the mechanical properties, but also secondary advantages and disadvantages of composites. Also consider cost benefit of replacing aluminum with composite. Make a recommendation for further integration of composites into airframes.

Markets.

There are many applications of the techniques developed in this project.

Department of Defense.

Both the United States Navy and the United States Air Force are interested in replacing the aluminum and other airframe materials with composite components. (Milberg, 2015) Composites can offer superior strength, lifespan, electromagnetic properties, and weight savings.

Aerospace Companies.

Civilian aviation companies are also integrating composites in airframes, most notably the Boeing 787, which is 50% composite material. (Hale, 2006) The primary advantage composites offer in civilian aviation is fewer maintenance hours than aluminum, which means more profitable flight hours and less time grounded.

Secondary Markets.

Many allied militaries purchase systems from the US or develop their own systems. They may decide to use composite materials in the airframes of their aircraft as well.

Replacing metals with composites also has applications in the automobile industry where lighter cars will lead to fuel savings for the consumer. Not only are composites attractive because of their low weight, they can also offer more resilience than traditional metal parts.

Assumptions.

Several key assumptions are made to limit the possible scope of the project. It is assumed that part is to be mounted in an E-2D Advanced Hawkeye; the validation done on the composite material are assumed to reflect the specific operating conditions of this aircraft. The sponsor, Northrup Grumman, will be asked to provide information regarding the amount of force exerted on the part, the operating temperature of the part, vibration profiles, etc. If this information cannot be provided, the details in question will be studied further and assumed values will be assigned.

The two primary constraints on the project are budget and timeline. The project will be constrained by the delivery timeline. The available budget will be set at $2000. These assumptions are the primary limitations of the project scope and timeline. Under no circumstance will the project be allowed to surpass either of these constraints.

It is assumed that the facilities at the College of Engineering will be available to test specimens. In addition, these facilities need to perform the tests that are necessary to complete the selected tests. This assumption limits the possible scope of the project to only tests that can be done on campus, and within the team's budget. The team may be able to use facilities at the High-Performance Materials Institute (HPMI).

It is assumed that the test specimens obtained are reflective of the components used for the prototype. These specimens are assumed to behave in the same manner and have the same physical properties as the materials used in a full-scale prototype.

Stakeholders.

A stakeholder is anyone who has control, interest, or an investment in the project. This may be expressed as authority over the members of the project group, time allocated to the project in assisting the members of the project group, or financial investment in the project itself, among other things.

Northrop Grumman, Project Sponsor.

Northrop Grumman Corporation (NGC) sponsors the project; they invest time and money into the project and receive the product in the end. NGC has provided mentors to help guide the project.

Dr. Shayne McConomy, Senior Design Project Coordinator.

Dr. McConomy grades the deliverables for the project and will grade the student's performance in the Senior Design class. Along with the sponsor, Dr. McConomy invests time and can control the project in relation to what is required for the Senior Design course.

Dr. Lance Cooley, Faculty Technical Advisor.

Dr. Cooley is the faculty advisor for the project; he is interested in the success of the team. Dr. Cooley invests his time with the team by meeting with them on a biweekly basis and providing mentorship.

United States Navy.

The USN is the primary operator of the E-2, and it is also operated by other allied countries. The navy wants the lightest planes possible to catapult off of and land on carrier decks. Additionally, maintenance is more difficult on a ship, so a more durable part that requires less maintenance will lead to higher operational readiness rates and lower long-term cost.

United States Airforce.

The USAF is currently interested in switching out aluminum components for composite in many aircraft. Many airframes are undergoing life extension programs, and new designs make extensive use of composites. The Air Force Research Lab issued the Composite Airframe Life Extension (CALE) grant that this project is based off. (Air Force Research Lab, 2015)

High Performance Materials Institute.

HPMI is a multidisciplinary research institute at Florida State University with a primary technology research area in high-performance composite materials. Dr. Hao has graciously offered her expertise and facility access to the team.

Customer Needs

The customer needs were determined by asking NGC questions about the current part. In this case, the customer needs are more accurately called requirements; the composite part absolutely must withstand all the same conditions that the aluminum part already does. The customer requirements can be broken into two categories: functional and environmental.

The function of the part is the primary purpose of the part: what the part does in the airframe. It will determine how strong the part must be and the size of the part. This information is critical to completing the first key goal, determine stresses.

The environmental requirements describe the conditions the part must survive in. They do not represent the primary purpose of the part but describe the environmental conditions the part must withstand.

Functional Requirements.

NGC was asked about the specific dimensions and loading conditions of the part. Their response was that they did not have a specific C channel in mind. They were more interested in C channels as a class of components rather than one specific C channel in a particular location in the airframe. NGC uses standard dimension C channels of several sizes in many locations in the aircraft. The team selected the smallest standard size of c channel to design a replacement for. The smallest C channel that could be used in the E-2 has a web width of 2”. The smallest standard C channel with this web width is the Aluminum Association ABC, shown below.

As strong as aluminum.

It needs to have similar mechanical characteristics such that it can withstand the same loading conditions as aluminum. NGC wants to be able to remove aluminum channels and replace them with composite channels without having to redesign the airframe. Note that this means the team does not have to contend with safety factors because the loading of the channel and strength of the channel is not changing.

Easy to install.

Aluminum C channels come in standard sizes. NGC wants the part to be easy to incorporate into an airframe without having to redesign existing components. The part should have a similar size and geometry to a standard aluminum size. It should also have a simple attachment method, preferably holes for using traditional fasteners.

Competitive price.

The principle disadvantage of composites is the high price, relative to traditional components. NGC wants the part to be priced competitively, relative to aluminum. It is unlikely that composite parts will be as cheap as aluminum; therefore, any design more expensive than aluminum should have some redeeming qualities to justify the additional cost.

Environmental Requirements.

When asked about the operational conditions, NGC provided a list of the requirements for the aluminum part and the testing methods that were used to certify its use. It is unlikely that the team will be able to afford to do every test listed, so the team will have to down select to the most important and most feasible tests. Table 1 includes the list of each test done on components in the E-2. Not all the requirements are of equal weight; withstanding operational temperature is clearly more important than fungal resistance, for example.

Table 1
Environmental Requirements

Requirement	Limits	Recommended Test Procedure
Temperature: Operating	-20 to +55 C internal -60 to +55 C external	MIL-STD-810E Methods 501.3 and 502.3 Procedures II with modifications.
Temperature: Non-Operating	-40 to +85 C internal -60 to +85 external	MIL-STD-810 Methods 501.3 and 502.3 Procedures I with modifications.
Temperature Altitude: Operating	-20 to +55 C at and up to 35K ft internal -60 to +55 C at and up to 35K ft external	MIL-STD 810C Method 504.1-II, Cat 5, steps 5 and 10 with modifications
Thermal Shock: Non-Operating	-20 to +55 C for internal	MIL-STD-810E Method 503.3 with modifications.
Rapid Decompression	Continuous operation of equipment within pressurized volume while decompressing from 5K to 35K ft.	MIL-STD-810E Method 500.3 Procedure III with modifications
Humidity: Operating	Up to 100% RH including condensation.	MIL-STD-810E Method 507.3 Procedure III
Vibration: Operating	Functional and endurance levels are derived from flight test data and are location dependent within the aircraft.	MIL-STD-810E Method 514.4 Categories 4.
Shock	20 G, 11 ms operational 40 G, 11 ms crash safety	MIL-STD-810E Method 516.4, Procedure I and V
Sand and Dust: Non-operating	Withstand effects	MIL-STD-810E Method 510.3, Procedure I or III, and II

Fungus	No fungi nutrient materials to be used.	MIL-STD-810E Method 508 OR analysis
Salt Atmosphere: Non-operating	Withstand effects	MIL-STD-810E Method 509.3
Explosive Conditions	Equipment shall operate when exposed to a flammable atmosphere.	MIL-STD-810E Method 511.3, Procedure I

Temperature

There are three different temperature sets, which can be condensed into a single temperature range using the most extreme values. Polymers have lower temperature resistance than metals, so this is an area that will need to be validated.

Thermal Shock

Thermal shock causes failures in materials because the strain caused by thermal expansion or contraction becomes too much for the material and it fractures. Brittle materials tend to be more susceptible to thermal shock because they cannot absorb much strain, compared to ductile materials. Materials with extremely high stiffness can also absorb thermal shocks. CFRP behave as brittle materials with very high stiffness, so this may be a relevant test, depending on the thermal loading conditions.

Rapid Decompression

There are probably not facilities available to test this, and a structural component is probably not particularly vulnerable to rapid decompression.

Humidity

A naval aircraft will be continually exposed to a humid environment when on deployment, making this a relevant consideration. Condensation can cause swelling degradation in polymers, making this a relevant test. If the polymer is not susceptible to swelling, then this is an area where the composite might be more resistant to the corrosive side effects of hudity compared to metals.

Vibration

Due to the complex structure of composites, this will be an area that can probably only be validated experimentally, and it is possible that a composite could fail when exposed to the large variety of vibration frequencies.

Shock

This may be relevant, but there are not faculties available to test this, and it is not part of regular operational conditions.

Sand and Dust

This is not particularly important for an unexposed structural member with no moving parts or small pieces. It is probably reasonable to elect out of this test.

Fungus

This is not particularly important to test, and the criteria of simply not using a fungi nutrient material is probably simple to confirm.

Salt Atmosphere

This is very important for long life in a naval aircraft since it will be continually exposed to a salt atmosphere. This, along with humidity resistance are the secondary advantages composites offer compared to traditional metals. Polymers are generally not susceptible to the electrochemical corrosion caused by exposure to a salt atmosphere.

Explosive Conditions

This is another criterion which is probably less important, does not represent operational conditions, and a facility to test this are probably not available.

Customer Needs Statements.

The formal customer needs statements are a synthesis of the product requirements. They state "what" the shelf does, not "how" it does it. They are listed using positive phrasing, avoiding the terms "must" and "should". The statements are presented in a ranked order with the most important statements coming first.

1. Withstands loading

The part has the same strength as an aluminum part of the same size and can be loaded in the same manner as the aluminum part.

2. Withstand the environment

The part does not break under the operational conditions and will last a long time even when exposed to those conditions.

3. Interchangeable with aluminum part

The composite part can easily be placed into the same position in the airframe as the aluminum equivalent.

4. Low Weight

The composite part must not weight more than the aluminum equivalent.

5. Competitive price

The part is affordable and adds enough value compared to aluminum to be worthwhile.

Functional Decomposition

The functional decomposition (FD) breaks down the actions that the part performs into the smallest possible components (McConomy, 2018). These functions describe either the actions the part takes, or the outcomes of the part. The functions were generated by analyzing the customer needs to break down the actions the part must do into the simplest possible components.

This section introduces the functions in graphical form through Figures 1 and 2, afterwards, the functions are explained in detail. This section concludes by discussing how the functions relate to each other and to the project at large.

Hierarchy Chart.

The hierarchy chart focuses on the distribution of functions and how the relate to the main systems. There are two main systems which reflect the two categories of customer needs: withstanding loading and enduring environment. Withstanding loading refers to the mechanical stresses that are induced in the part. Enduring environment refers to the conditions that the part will be exposed to. The part must withstand each loading condition in each environmental condition. This first hierarchy chart shows all the functions and how they relate to the two systems.

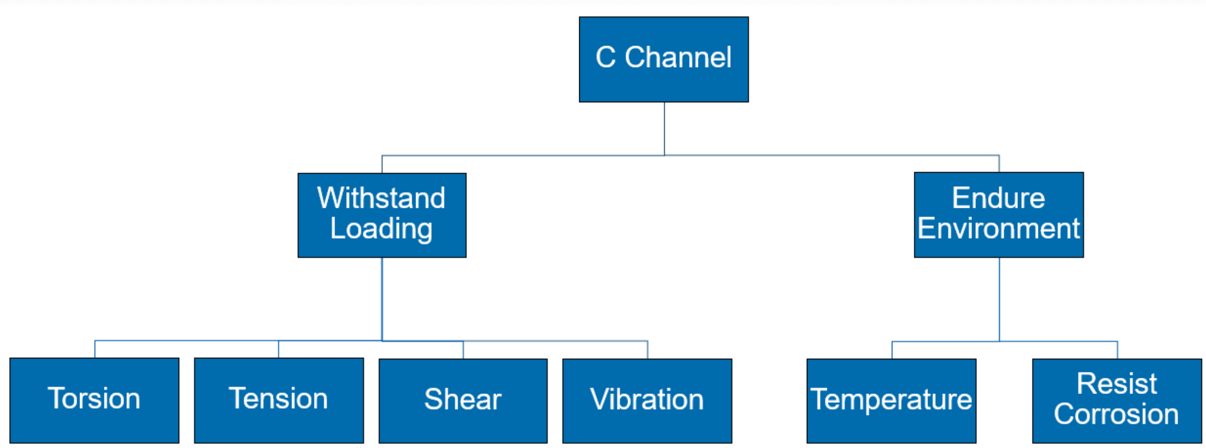


Figure 1. Functional hierarchy graphic depicting functions and branches.

Cross Reference Figure.

As discussed in the customer needs section, some of the customer requirements are not as important as the others. A cross reference figure will compare each function with each other function to down select out of functions that are not very important. This chart is part of the key goal “down select MIL-STD".

The importance of a function is decided by how much it impacts the operation of the aircraft. For example, while a fungal buildup could become problematic, but a layer of fungus on the part will probably not cause the aircraft to crash immediately. On the other hand, if the part cannot withstand the operational temperature and it fractures in flight, this could have severe consequences, thus temperature resistance is more important than fungal resistance. Additionally, some environments are more likely to be encountered than others. For example, the part will probably never be involved in a crash, and even if the aircraft does crash it will only happen once, thus shock is not as important as something like vibration, which the part will be exposed to during every flight.

The functions in the columns are compared against the functions in the rows. If a function in a column is deemed more important than the function in a row, then that cell is filled with a 1, if not it is filled with a 0. The bottom row lists the sum of all cells in that column. The higher the number, the more important that function is to fulfill the customer’s needs.

	Provides Support to Airframe	Shear	Tension	Torsion	Resist Acoustic Vibration	Resist Electrical Current	Absorb EM Radiation	Control Heat Transfer	Resist Corrosion
Provides Support to Airframe		1	1	1	1	0	0	1	1

Shear	0		1	0	0	0	0	0	0
Tension	0	0		0	0	0	0	0	0
Torsion	0	1	1		1	0	0	1	1
Resist Acoustic Vibration	0	1	1	0		0	0	1	1
Resist Electrical Current	1	1	1	1	1		1	1	1
Absorb EM Radiation	1	1	1	1	1	0		1	1
Control Heat Transfer	0	1	1	0	0	0	0		0
Resist Corrosion	0	1	1	0	0	0	0	1	
Total	**2**	**7**	**8**	**3**	**4**	**0**	**1**	**6**	**5**

Figure 2. Function cross reference table depicting the relationship between customer needs and shelf functions.

The customer needs and functions can be divided into three categories: Critical functions, secondary functions, and tertiary functions. Critical functions scored the highest, indicating they are the most important functions and should be the highest priority to test and validate. Tertiary functions scored the lowest, indicating they are the least important functions and will not be tested. Further testing of these functions is recommended but is outside the scope of this project.

Secondary functions are those that could impact the performance of the part over the long term, or the tension and torsion loading cases which the part may experience occasionally, but withstanding those loads is not the primary purpose of this part. Secondary functions will be validated as budget and time allows.

The critical functions are the most important to validate because the failure of a critical function would mean the immediate failure of the part, which would endanger the aircraft. The critical loading conditions are the way the part is designed to be loaded.

Revised Hierarchy Chart.

Now that the relative importance of the functions has been established, a revised hierarchy chart drops the tertiary functions. This chart contains the functions that will be evaluated in detail.

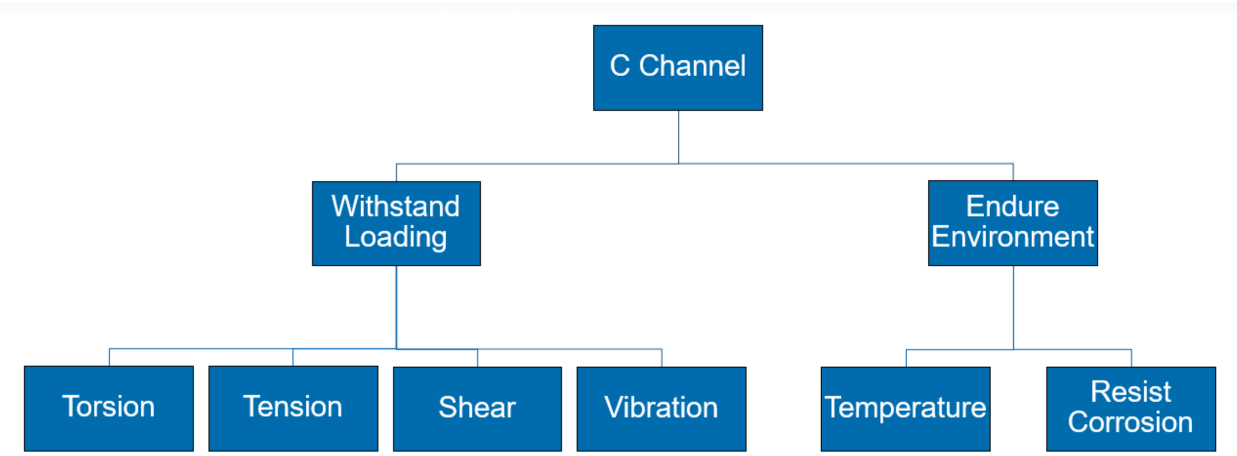


Figure 1. Functional hierarchy graphic depicting functions and branches.

Function List

This is a list of all the important functions in order of importance as determined by the cross-reference table.

Bending y.

The primary purpose of a C channel is to hold a load along the y direction; therefore, this is the most important function. The part holds a load along the y direction.

Bending x.

The part holds a load along the x direction.

Temperature.

The part will be exposed to both high and low temperature extremes and it must provide full strength thorough that range and it must not degrade from extended exposure to those extremes. This is a primary concern because polymers can lose strength before they melt; the part provides adequate strength at the temperature extremes. Also, the part does not degrade after prolonged exposure to the temperature extremes.

Tension.

The part holds a load when loaded in tension.

Vibration.

The part will be exposed to a range of vibration whenever the engines are activated. The part maintains the required strength throughout the vibration profile.

Humidity.

The part will certainly be exposed to a humid environment, which is of concern because some polymers are susceptible to degradation when exposed to water. The part does not degrade at the maximum temperatures and 100% humidity.

Torsion.

There will be some nominal torsion load on the part. It is not the primary loading condition, but the part does need to be somewhat stiff. The part withstands a torsion load.

Thermal Shock.

Some composites can be susceptible to thermal shock, depending on the loading conditions. The part withstands the greatest anticipated thermal shock.

Salt Atmosphere.

The aircraft will continually be exposed to a corrosive environment onboard a carrier. The part resists corrosion caused by salt air.

Sand and Dust.

The part might be exposed to a desert environment with airborne particles. The part is not damaged by exposure to sand.

Function Relationships.

The two systems on the revised hierarchy chart can be understood as loading conditions within the environments. The part must withstand each loading condition while it is exposed to each environmental condition. It is not enough that the part withstands tension in general, it must withstand tension while at high temperature and at low temperature and when wet, etc.

Innovation Opportunity.

The aluminum C channel performs all the functions in each condition; a composite material innovates by performing the same functions at a lower weight and competitive price. The team innovates by leveraging the superior mechanical and secondary properties of composites, like humidity and corrosion resistance. Composites offer more flexibility in the design stage, allowing the engineer to create a part with the exact strength required.

The weight saved by incorporating composites can be allocated to installing more powerful sensing and communication equipment, increasing fuel capacity, or adding additional functionality to the C channel part. A new function could be cable management or airflow channeling to cool the computer systems.

Function Outcome.

The primary function of the part is to provide the same support to the airframe that an aluminum c channel would provide. This means it must have equivalent mechanical strength when loaded in the same manner. The secondary function of the part is to survive the environment. This means it must endure the conditions the aircraft will be in and it must continue to provide support to the airframe throughout those conditions.inue to provide

Targets and Metrics

Targets and metrics are used to validate functions and designate specific values to the design's criteria (McConomy, 2018). These targets and metrics address the part's functions and elaborate on more aspects of the design, relative to the customer's needs. Each critical and secondary function corresponds to a metric and target. There are also some other metrics that do not directly correspond with a function. The purpose of this section is to explain what the targets are and how those specific values were determined. For a detailed description of the validation methods, see the testing section.

Critical targets and metrics were selected based on the function priorities. Critical functions correspond to critical metrics. See the previous section for the rationale on the differentiation of critical and secondary functions. The critical targets and metrics are listed below, and a comprehensive catalogue can be found in appendix B.

Critical Targets and Metrics.

Table 3

Critical Targets and Metrics

Functions	Metrics	Targets
	Tensile Strength	x MPa
Withstand Loading	Shear Strength	x MPa
	Vibration Frequency/Intensity	Varies
Control Heat Transfer	Maximum Temperature	85˚C
	Minimum Temperature	−60˚C

Describe this table

Target 1: Bending Strength.

The target is to have the same yield strength in bending as aluminum. According to the bending equations, the aluminum beam has a bending strength of 2274 Nm along the y direction and 358 Nm along the x direction. Detailed calculations are found in the appendix.

Bending in both x and y directions is done with the same test. ASTM D790 covers Flexural properties of reinforced plastics and ASTM D2344 covers short-beam strength of polymer matrix composite materials. Both tests are 3-point-bend style tests with rectangular specimens. The machine used will be the MTS 858 Mechanical Test System located at HPMI.

Target 2a: Maximum Temperature.

From the customer requirements, the maximum temperature the part must withstand is 85˚C, which is in non-operating conditions. The part must maintain the required strength at this temperature. Elevated temperatures can cause a reduction in mechanical properties due to two distinct phenomena: glass transition and thermal degradation.

ASTM D5418 dynamic mechanical properties in flexure is used to determine thermal degradation of the composite, including glass transition and the modulus with respect to temperature.

TA Instruments q800 Dynamic Mechanic Analyzer which tests the mechanical properties with respect to time, temperature, and frequency. This test will determine the thermal degradation of the composite system under high temperature.

The MIL-STD requires the sample to be held at the maximum temperature for a period time, and for the mechanical properties to be evaluate at the end of that period while the specimen is still hot.

Specimens will be placed in an oven and cycled between room temperature and 85˚C over a period of 72 hours. Afterwards ASTM D790 will be done while the specimens are still at 85C.

Target 2b: Minimum Temperature

The minimum temperature the part must withstand is -60˚C, which is the absolute minimum temperature any external part will be exposed to under any conditions or altitude. The part must maintain appropriate strength at this temperature.

ASTM D5418 will be used to determine the material's performance at below freezing temperatures.

TA Instruments q800 Dynamic Mechanic Analyzer which tests the mechanical properties with respect to time, temperature, and frequency. This test will determine the mechanical properties of the composite system under low temperature.

Target 3: Tensile Strength.

While not the primary loading, the part will be loaded in tension to some degree. The actual stress in the part will depend mostly on the attachment methods employed. These can vary greatly, so the test done will be a standard tensile test.

ASTM D3039 tensile properties of polymer matrix composite materials will be done to determine the tensile modulus of the composite. The target is the tensile strength of the beam is equivalent to the aluminum beam, which is 152120 N.

The Shimadu tensile tester will be used, located at HPMI.

Target 5: Vibration.

The part will be subjected to continuous vibration during flight operations, with the intensity and frequency dependent upon the location in the aircraft. This test will need to be outsourced because the team does not have access to facilities that operate at the required frequencies.

There are three location groups with vibration profiles respective to each. These vibration profiles are shown below in the following order: Forward FS 100, Between FS 100 – 240, Aft of FS 240. (Fuselage Station (FS) indicates where along the aircraft the part is, along an axis running from nose to tail.)

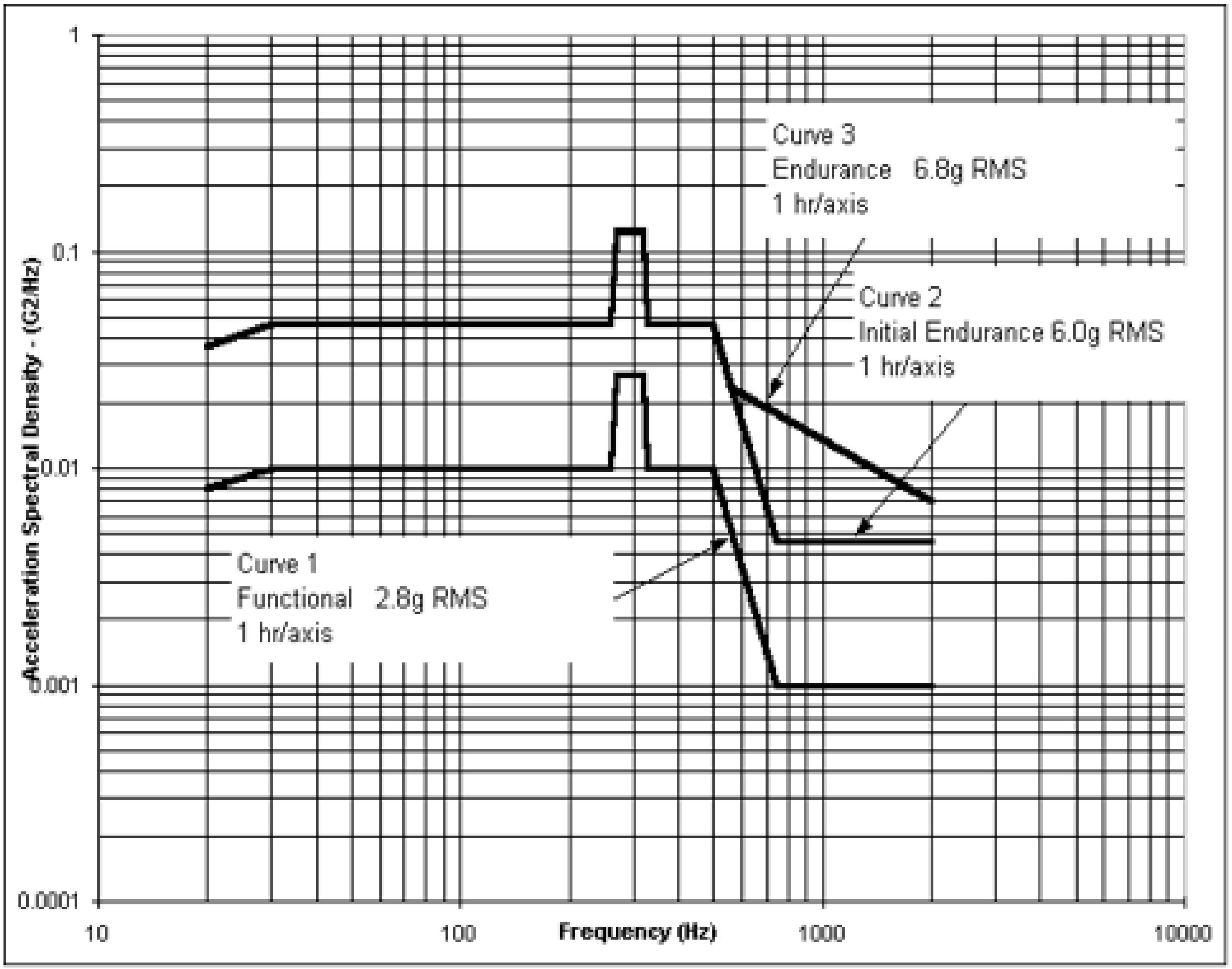


Figure 3: Vibration profile Forward of FS 100.

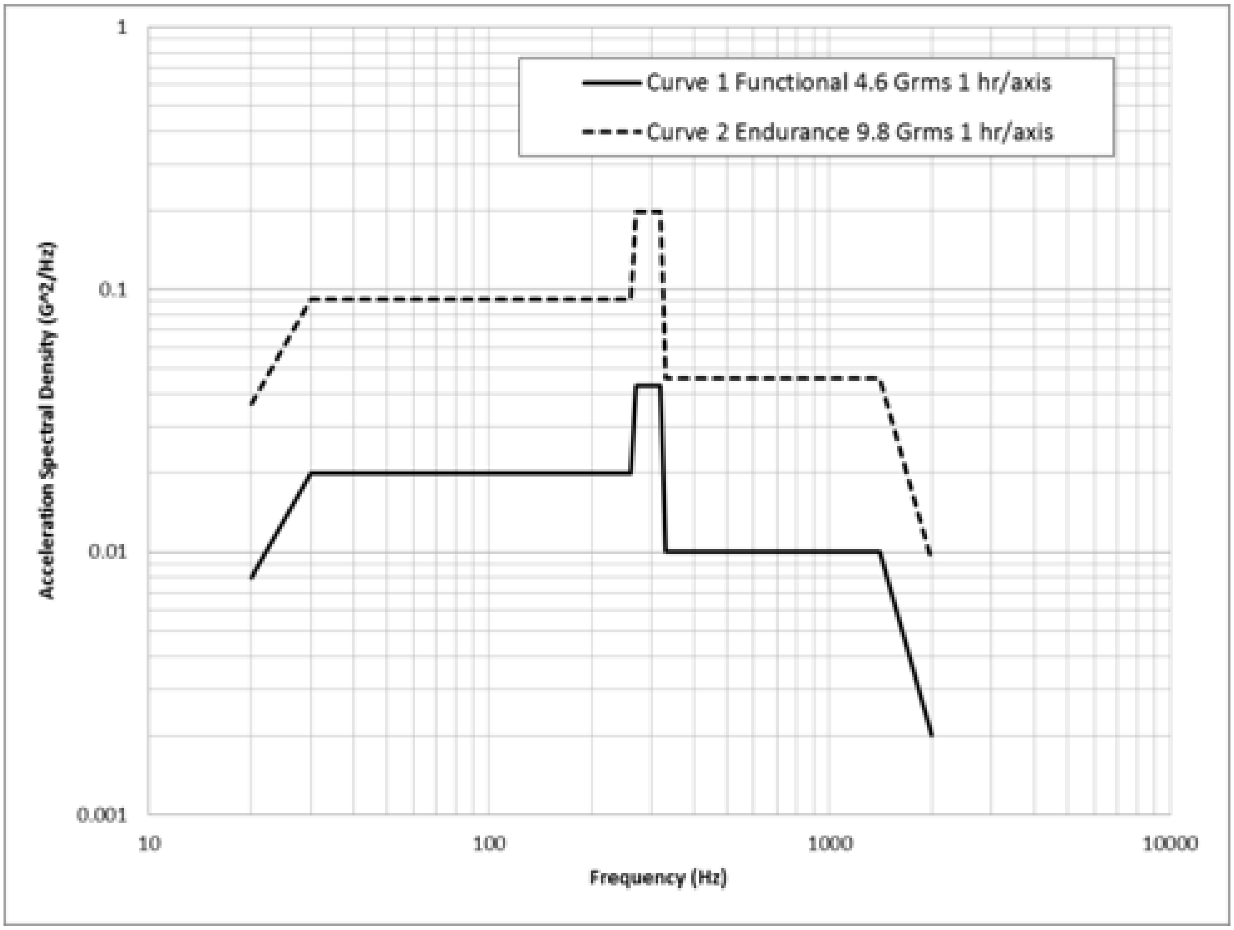


Figure 4: Vibration profile between FS 100 and FS 240

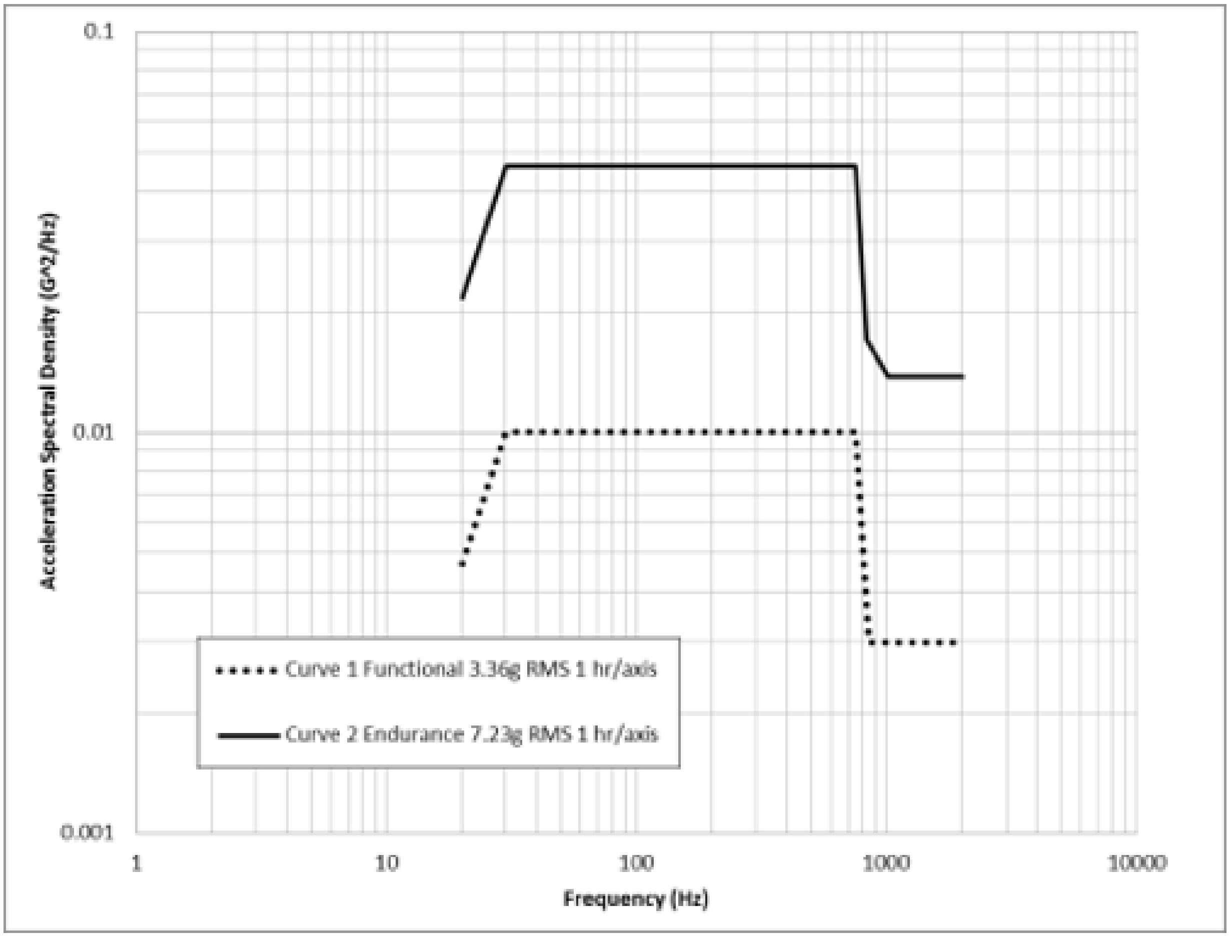


Figure 5: Vibration profile aft of FS 240.

Target 6 Humidity

There are several methods to test swelling degradation in a polymer. Since the MIL-STD test is to immerse the specimen in water, we will put it in a chamber at 85C and test how much water has accumulated within the material or do ASTM D709.

A Hot-Wet machine will be used, located at HPMI.

Target 7: Torsion

The minimum temperature the part must withstand is -60˚C, which is the absolute minimum temperature any external part will be exposed to under any conditions or altitude. The part must maintain appropriate strength at this temperature. The test to validate this target is the Cold/Wet test, during which a specimen is immersed in cold water, then taken out and analyzed by the TA Instruments q800 Dynamic Mechanic Analyzer which tests the mechanical properties with respect to time, temperature, and frequency. This test will determine the thermal degradation of the composite system under low temperature. While this test cannot accommodate a temperature below 0˚C, it is likely the best method available to the team. Accurate predictions can be made by extrapolating the change in mechanical properties at various known temperatures within the limited temperature range the team can test at (0˚C to 100˚C).

This concludes the critical target discussion. A complete targets catalogue can be found in Appendix B.

Concept Generation

Figure 6: Longitudinal and Transverse directions

Additionally, a weaker core material may be placed between two layers of composite which will have a similar effect, creating a composite of composites. The orientation of the distributed phase can be arranged to provide strength in more than one direction; fibers can be woven into fabrics that provide strength in every direction along a plane; further, the amount of fibers can be varied, and is usually reported as volume fraction. The arrangement of the fibers is generally determined after the fiber material is selected. Lastly, the geometry of the component can be shaped in a way that distributes stress and takes advantage of the composite properties. (Callister, 2014)

Concept generation is an ideation process to open the possibilities for consideration. Concepts were created based on the class of materials to be used for each of the three phases, the orientation of the distributed phase, and the cross-section geometry of the part. Several concept generation techniques were used to facilitate the creation of new and innovative ideas. The methods used were morphological chart, anti-problem, biomimicry, and basic brainstorming. A catalog of 100 ideas can be found in Appendix C.

A total of nine concepts are presented the Concept Generation section: five medium resolution concepts and three high resolution concepts. These concepts are a result of using the various concept generation tools in Appendix C and will be evaluated in more detail in the Concept Selection section. The focus of medium resolution concepts is to determine a single design variable. These concepts tend to offer a significant single advantage, but consequently include several disadvantages. The high resolution concepts are more balanced, generally without significant disadvantages.

Morphological Chart.

The morphological chart focuses on the material selection component, varying the three materials which make up the composite: the distributed material, the matrix material, and the core material. A chart can be created with many different design possibilities that can be mixed and matched together to create hundreds of possibilities, shown in table 4. Following the table, a brief discussion of the merits of each entry in each column relative to the other entries in the column can help narrow down the possible designs to a more manageable number.

Table 4

Morphological Chart

Distributed Phase	Matrix Phase	Core Material
CF low modulus	Thermoplastic polymer	None
CF high modulus	Thermoset polymer	DaVinci Foam
CF Recycled	Metal	Balsa Wood
Aramid Fiber	Ceramic	Polymer
Glass Fiber	Carbon	CF Recycled

Distributed Phase.

Glass fibers are not as light or strong as CF and would probably not give enough increase to be worth extra cost over aluminum. Aramid fibers, of which Kevlar is the most prominent example, are more flexible and should dampen vibration better than carbon (which is why Kevlar is used in body armor) but will result in a larger and heavier part at a comparably high price point. CF is becoming cheaper and more well-known all the time, hence this project. Low modulus CF can offer vastly superior properties to aramid or glass at relatively affordable price point. High modulus could be considered, but if the low modulus can deliver good enough properties, there is no need to overengineer and use more expensive high modulus. NGC probably has access to a large amount of carbon fibers which can be cheaply recycled, making this the cheapest option from their point of view. The recycled material will be substantially weaker than the full-length carbon fibers and may need to be larger or of a different geometry.

The table below includes several grades of carbon fibers available Toray, a leading carbon fiber manufacturer. Exact pricing is not available online, but the low modulus material is significantly cheaper than the high modulus material.

Table 5

Carbon Fiber Grades

	Type	Elastic Modulus (msi)	Tensile Strength (ksi)	Cost
LOW MODULUS	T300	33.4	512	LOW
	T400H	36.3	640	
	T700S	33.4	711	
	T700G	34.8	711	
HIGH MODULUS	M35J	49.8	654	HIGH
	M40J	54.7	640	
	M46J	63.3	609	
	M50J	69	597	
	M55J	78.2	583	
	M60J	85.3	584	

Matrix Phase.

Some of these options can be ruled out easily: the carbon matrix and metal matrix will be far too expensive for this application, even if the team had the budget to afford them. A ceramic matrix would be too brittle for a structural part of an airframe and would be far too heavy. This leaves either a thermoplastic or thermosetting polymer. Most epoxy materials are thermosetting since thermoplastic tends to be more expensive. Thermosetting offers better performance at extreme temperatures, but it is brittle. Thermoplastic behaves more like a traditional ductile metal and may be better for this application but is generally less strong and may or may not be harder to manufacture at a large scale. Thermosetting is easier to manufacture at a small scale since it is liquid at room temperature, which probably makes it the best choice for the team, given the facilities and expertise available. Since the distributed phase is responsible for most of the strength in the composite, a matrix material can be selected based on other parameters, specifically cost. While a stronger, more expensive matrix will offer better performance, if it is not paired up with a comparable improvement in fiber quality, the improvement will not be noticeable.

Core Phase.

Core material is predominantly used in flat laminate panels, not structural components. It should be possible to use the core in the web section, but that will involve additional manufacturing challenges. The additional challenges will probably outweigh any advantages gained, which is why cores are generally not used in structural beams. If a core material was to be used, the best option is likely to be the recycled CF since it will be significantly stronger than any other core material.

Geometry.

The cross section of the beam does not necessarily have to be in the shape of a traditional C-channel. The greater strength of composites opens the possibility for different geometries to be considered. The figure below shows 30 possible cross sections.

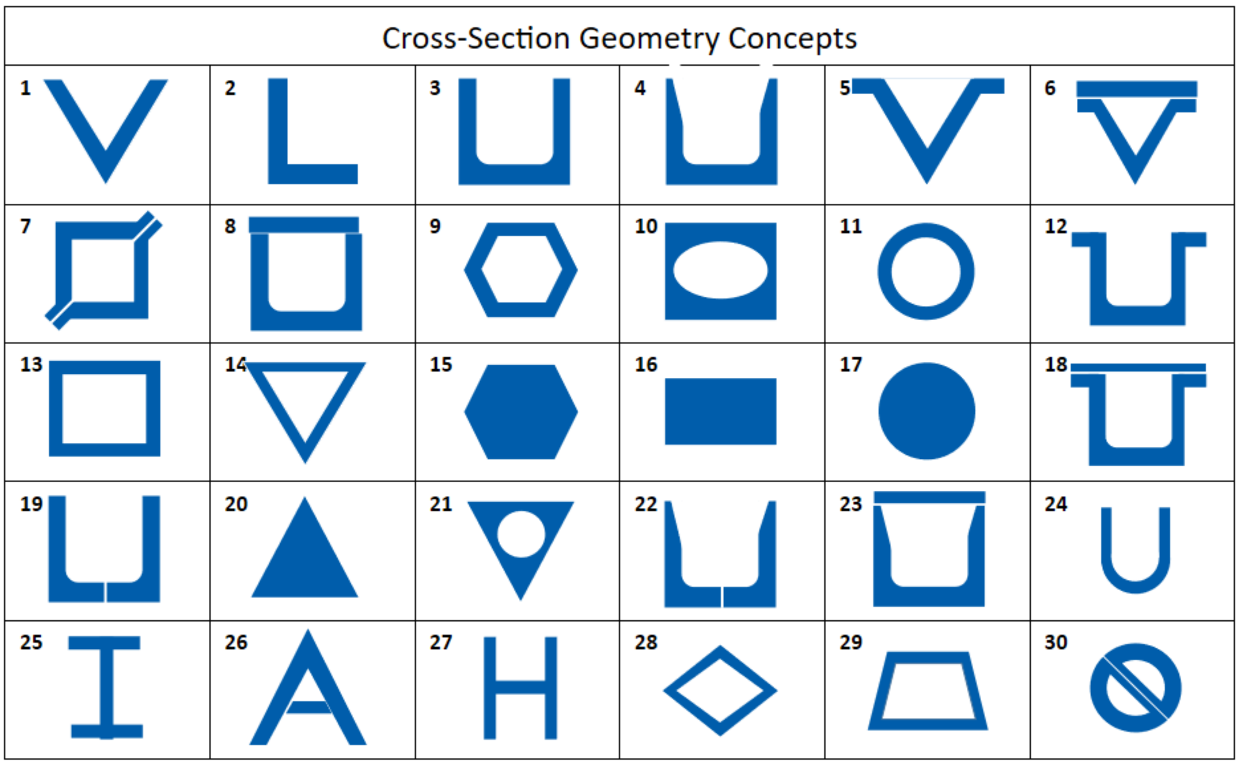


Figure 7: Cross-Section Geometry Concepts

Clearly not all the concepts are equally viable, but the idea of having a two-piece component offers additional functionality to the part (concepts 6, 7, 8, 18, 23). A second piece could be incorporated using the weight saved by the composites to add an additional function to the part. This second piece could be a mounting plate. The plate would not have to be load bearing, it could instead have a slit in it so that other hardware can be attached to the airframe using traditional fastening methods. Depending on the location in the aircraft, the part might need to support computer systems or other equipment; having the option to use traditional bolts to secure these items to the airframe will be an advantage the composite part offers over aluminum.

Since composites are stronger than aluminum, the size of the part may be able to be reduced while providing the same strength. Should the composite prove strong enough, one of the flanges from the C channel could be removed, resulting in an L shape (concept 2). If the composite was not as strong, like in the case of the recycled CF, additional flanges could be added, resulting in an I shape (concept 25).

Medium Resolution Concepts.

Medium resolution concepts are defined in a manner similar to experimental design. Generally, the concepts have a single design parameter which is varied (analogous to the independent variable) and upon which the other design variables depend (analogous to the dependent variables).

Concept 1.

High modulus carbon fiber distributed phase. A composite system using high modulus carbon fiber would add much more stiffness to the airframe than aluminum does. It would be able to withstand even greater loads; however, it is not necessarily needed in this scenario. High modulus carbon fiber would provide more strength than is needed for component. The result would be an overengineered part which would be much stronger and much more expensive than it needed to be.

Concept 2.

A thermoplastic polymer matrix phase could be used in a composite system for the component. Thermoplastic polymers are pliable at high temperatures and can be reshaped easily; they can be recycled or rearranged after the first process of heating and cooling. Thermoplastic polymers are a great matrix phase with high strength and high resistance to shrinkage. They also add ductility to the system, which can be an advantage since the fibers are relatively brittle and the airframe does require a certain degree of ductility. The downside of them would be that it would be difficult to manufacture given need for high temperature. Additionally, many thermoplastics would lose too much strength at the upper operating temperature (85 C).

Concept 3.

Aramid fibers with a thermoset polymer is a medium resolution concept because of its reasonable mechanical properties and ability to absorb energy. This characteristic of the aramid fiber would be beneficial in an airframe because it would dampen the vibration produced by the aircraft better than carbon fibers. This composite system is considered a medium resolution because it would probably not offer enough substantial improvements relative to aluminum. Aramid fibers are heavier and weaker than carbon fibers, so the part would be larger and heavier, mitigating the advantages offered by composites. Kevlar is also more expensive than aluminum, given the expense of replacing aluminum, it makes sense to choose the carbon fibers which are superior in every sense except ductility.

Concept 4.

Another possible composite with aramid fibers is to use a thermoplastic polymer matrix. The advantage to this design is it would dampen vibration the most out of any other material combination. It would probably not be extremely expensive, since the higher cost of the matrix could be offset by the lower cost of the fibers. Additionally, the lower strength of the fibers could be somewhat offset by the higher strength of the matrix.

Concept 5.

Given the additional strength offered by composites, the same strength of the two C channel flanges may be able to be achieved with a single flange, resulting in an L shape. This L shaped cross-section could possibly withstand the required loads and also save costs relative to a C channel due to using less materials to get the same results. This shape is possible if used with a strong enough composite system but may not fit the dimensions to fit the section where the C channel is used currently.

Concept 6.

Recycled carbon fiber is much weaker than other options for a distributed phase, but it is significantly cheaper than other materials because it is made from old carbon fiber weaves. Similar to concept 4, the shape of the cross-section can be modified to withstand the load necessary. If the recycled fiber was not strong enough for a traditional C shaped cross section, additional flanges could be added to the beam, resulting in an I shape. The additional material could be enough for the recycled material to provide the required strength.

High Resolution Concepts.

Without a detailed analysis, which will come later, the three designs most likely to succeed are represented here. Note that as of the time of writing, the team still does not know the loads the part will need to withstand, or if there are any specific size requirements for the part. Therefore, there will be not be an FEA included for the high resolution concepts at this time.

This also means that the volume fraction of fibers to matrix cannot be determined at this time, so the high resolution concepts will be limited to selecting the exact materials to be considered.

Concept 7.

The first concept is a low modulus carbon fiber and a thermoset matrix phase with no core and in a C shaped geometry. This would serve as the control design; it is simple with the only substantial change being the change in materials from aluminum to composite. This will be relatively cheap and easy to manufacture and could be integrated very easily into existing airframes.

This composite system would contain a T300 Carbon Fiber distributed phase and an Epon 862 polymer matrix. The T300 Carbon Fiber is used because its elastic modulus and tensile strength are sufficiently higher than that of Al6061. While carbon fibers with higher moduli and tensile strengths exist, T300 offers a significant performance improvement at the lowest price point.

Epon 862 is a very common matrix used in composite manufacturing because of its ease of handling during manufacturing. Epon 862 has a low density that allows for easier hand layup of the composite; being a liquid at room temperature allows Epon 862 to be brushed onto the specimen easily. A higher density matrix would need to be heated constantly, requiring equipment such as a heating table, which would add difficulty and potential create unsafe working conditions during hand layups of the composite.

Concept 8.

The second high resolution concept is to only use pure recycled carbon fiber as the distributed phase. Recycled carbon fiber is much weaker than other options for a distributed phase, but it is significantly cheaper than other materials because it is made from old carbon fiber weaves. As an unaligned and discontinuous fiber, it will be isotropic, which means there is more freedom in design since it resembles traditional aluminum. Like aluminum, it can be machined after manufacture. The recycled carbon fiber can have holes for fasteners and rounds to reduce stress concentrations and various other things that would be expensive to include into anisotropic composites.

Epon 862 would be a suitable matrix for this composite for the same reasons it was the best matrix for the previous concept. It is easy to work with, lightweight, and inexpensive. The low cost of this matrix material complements the low cost of the recycled fibers. Using a single matrix phase material will also simplify the purchasing and manufacturing stages of the project.

Concept 9.

The final concept is a combination of the previous two: A hybrid composite using both T300 fibers and recycled fibers. Again, both options were chosen primarily to save on costs. The orientation of the fibers would depend on the loading of the part, which as of time of writing is not available. Given that the T300 is roughly three times as strong as aluminum, there will probably be room to add some cheaper material and still meet the strength target. This hybrid composite also offers a tailored combination of the T300 Carbon Fiber composite and the fully recycled composite to generate an optimized strength-cost ratio. Utilizing the highest volume fraction of recycled carbon fiber as possible in the structure would be ideal for the purpose of meeting the cost reduction requirement.

The best matrix material to use to minimize costs is, as above, Epon 862. This is the cheapest and easiest material to work with and using the same matrix material will streamline the manufacturing process.

Concept Selection

The goal of concept selection is to devise a method to analyze the concepts from concept generation and determine which of those concepts best satisfies the design criteria. This is done by comparing the engineering characteristics to determine which are the most important. The design criteria are based on the functions and targets that were determined earlier in the design process. The concepts will be compared against each other and based on the results of this analysis, the final concept will be chosen. The methods that were used to evaluate the best concepts are a house of quality, Pugh charts, and the analytical hierarchy process.

The top three concepts will be selected to build and test. Only testing one design will not provide enough data to make a conclusive recommendation to NGC. The ideal concepts will address the primary customer needs of lowest possible cost and most reliable design, additionally NGC was particularly interested in the use of recycled material.

House of Quality.

The house of quality is a tool that compares the engineering characteristics with the customer requirements to determine which engineering characteristics are the most central to fulfilling the customer needs. For a trivial example, the tensile strength of the part is more important than the color the part is painted. The customer requirements are on the left side and the engineering characteristics run along the top. The customer requirements are weighted to reflect their relative importance in a pairwise comparison contained in appendix D. Unsurprisingly, the most important customer requirement is that the part withstand the same loading as aluminum.

In the middle of the house of quality, there are four possible scores in each cell: a score of 9 indicates that the engineering characteristic is absolutely critical to fulfilling the customer requirement, a score of 3 indicates that the engineering characteristic is directly involved in fulfilling the customer requirement, and a score of 1 indicates that the engineering characteristic is indirectly involved in fulfilling the customer requirement. If there is no relation, the score assigned is 0 and the cell is left empty to improve readability.

		Engineering Characteristics										
Improvement Direction		=↑	=↑	↓	↑	↑	↑		↓			
Units		GPa	GPa	GPa	deg C	N/A	N/A	N/A	kg/m^3	sec	$	$
Customer Requirements	**Importance Weight Factor**	**Tensile Strength of Component**	**Shear Strength of Component**	**Vibration Frequency/ Intensity**	**Endure Temperture Extremes**	**Resist Corrosion**	**Attaching to Airframe**	**Access to Material**	**Density of Component**	**Takt Time**	**Cost of Manufacturing**	**Material Cost**
Manufacturing Ability	1							1		3	9	3
Weight	2	1	1	1			1		9			1
Cost	4						3	3	1	3	9	9
Available Material	5	1	1					9				3
Withstand Loading	6	9	9	9	3		1					
Weatherproof	4	3	3		9	9	1					
Long Life Cycle	1			3	3	9	1		9			
Attachment Method	5	1	1	3		1	9					
Raw Score (612)		78	78	74	57	50	70	58	31	15	45	56
Relative Weight %		12.75	12.75	12.09	9.314	8.17	11.44	9.477	5.065	2.451	7.353	9.15
Rank Order		1	1	3	6	7	4	5	10	11	8	7

The bottom row shows the results from the house of quality. The engineering characteristics are rank ordered by their importance to the project. Note that the tensile and shear strength are in terms of specific strength: strength vs density. Every concept is designed to be exactly as strong as aluminum, no more and no less, but this will come at the cost of weight and volume, depending on materials and geometry.

As expected, the most important characteristics, according to the house of quality, are the tensile and shear strength. These impact every customer need. Other noteworthy characteristics are the vibration and temperature resistance.

Pugh Chart.

The series of Pugh charts are in appendix D. They compare the nine medium and high-resolution concepts from the previous section against each other. The purpose of this tool is to select the best concept according to the most important engineering criteria as determined by the house of quality. The concepts from the previous section are called systems 1 through 9 in this section and are shown below.

Systems Key	
Datum:	Aluminum
System 1:	High Modulus CF + Thermoset Polymer + C-Channel
System 2:	High Modulus CF + Thermoplastic Polymer + C-Channel
System 3:	Aramid + Thermoset Polymer + C-Channel
System 4:	Aramid + Thermoplastic Polymer + C-Channel
System 5:	High Modulus CF + Thermoset Polymer + L-Beam
System 6:	Recycled CF + Thermoset Polymer + I-Beam
System 7:	Low Modulus CF + Thermoset Polymer + C-Channel
System 8:	Recycled CF + Thermoset Polymer + C-Channel
System 9:	Hybrid CF and Recycled CF + Thermoset Polymer + C-Channel

The first chart compares all nine concepts against aluminum, and records whether they are better or worse in each category.

Pugh Chart 1										
Selection Criteria		Concepts								
	Aluminum	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8	System 9
Tensile Strength of Component	Datum	+	+	-	-	+	S	+	-	S
Shear Strength of Component		+	+	S	S	+	S	+	-	S
Vibration Frequency/ Intensity		S	S	+	+	S	S	+	+	+
Attaching to Airframe		S	S	S	S	S	+	S	+	+
Access to Materials		-	-	S	S	-	+	-	+	S
Endure Extreme Temperatures		+	-	+	-	+	+	+	+	+
Material Cost		-	-	-	-	S	S	-	+	S
# of Pluses		3	2	2	1	3	3	4	5	3
# of Minuses		2	3	2	3	1	0	2	2	0

In the first Pugh chart, there are three concepts with more negatives than positives: systems 2, 3, 4. These can be eliminated from consideration, since they scored worse than aluminum. System 1 was also eliminated because it has the lowest ratio of positives to negatives. The remining five concepts are then compared in Pugh chart 2. System 7 was selected as the new datum because it was considered the best overall concept. Note that while system 8 has more positives than system 7, system 8 scored worse in the tensile and shear strength, which are the most important criteria. For this reason, system 7 was considered the best concept.

The second Pugh chart compares systems 5, 6, 8, 9 against system 7.

Pugh Chart 2						
Selection Criteria		Concepts				
	System 7	System 5	System 6	System 8	System 9
Tensile Strength of Component	Datum	+	S	-	S
Shear Strength of Component		+	S	-	S
Vibration Frequency/ Intensity		S	+	+	S
Attaching to Airframe		S	+	+	+
Access to Materials		S	+	+	+
Endure Extreme Temperatures		S	S	S	S
Material Cost		-	+	+	+
# of Pluses		2	4	4	3
# of Minuses		1	0	2	0

System 6 scored the highest and will be the datum for the next chart. System 5 scored the lowest and was removed from further consideration. The purpose of the final chart, Pugh chart 3, is to remove a single concept so that only three remain.

Pugh Chart 3				
Selection Criteria		Concepts		
	System 6	System 7	System 8	System 9
Tensile Strength of Component	Datum	+	-	+
Shear Strength of Component		+	-	+
Vibration Frequency/ Intensity		S	+	S
Attaching to Airframe		S	S	S
Access to Materials		S	S	-
Endure Extreme Temperatures		S	S	S
Material Cost		-	S	-
# of Pluses		2	1	2
# of Minuses		1	2	2

Concept 8 is eliminated because it's worse than six, while the other two are either superior or equivalent. These three concepts are the chosen systems. These results make sense because they align closely with the customer needs. System 6 will likely be the cheapest possible design because it uses the cheapest possible fiber and the strongest possible geometry. It may be more difficult to incorporate into the airframe, but that is secondary to strength and price. System 7 represents a good baseline design; it uses reliable materials, but also should be relatively cheap. System 9 aims to be a compromise between the other two systems in terms of strength and cost.

Analytical Hierarchy Process.

The analytical hierarchy process (AHP) is a technique to derive weighted values to use when comparing design characteristics. It is easy for the designer's biases to color their concept selections; the AHP can help identify these discrepancies. The AHP is discussed in Appendix D.

Final Selection.

The top three concepts selected are systems 6,7,9. Three concepts were selected so that the team can make a good recommendation to NGC. There are two primary areas of concern for NGC: reliability and cost. The concepts selected focus on these two primary customer needs.

System 6.

System 6, or concept 6 from page 34, is a composite system made from recycled carbon fiber, thermoset polymer, with a cross-section of an I. This system was selected because it is the best concept to fulfill the customer need of being affordable. Using all recycled fiber and a thermoset resin should make for the cheapest possible material. NGC was also very interested in using recycled carbon fiber because their company probably has a substantial quantity of this material at their advanced composites center in California, left over from the B-2 and B-21 programs. The recycled carbon fiber beam has a cross-section of an I to add extra material at the points of highest internal stress in the beam structure. The I beam design scored higher than the C channel design because the recycled material is weaker than the other fibers, and so more of it will be required, but the lower cost of the recycled fibers should still result in a cheaper product.

System 7.

System 7, or concept 6 from page 35, is a composite system made from low modulus carbon fiber, thermoset polymer, with a cross-section of a C. This system was selected because it is the best concept to fulfil the customer need of being reliable. Part of NGC's motivation for sponsoring this project was the relative lack of industry experience with replacing aluminum airframe structures with composite. From their perspective, it is easier to use the more proven aluminum components rather than design new composite components and go through the time and expense of validating the new material. For this reason, the team selected a concept that will work well as a baseline. Low modulus CF is understood the best out of all of the materials under consideration and will provide excellent strength at a good price point. High modulus CF would probably be stronger than it needed to be and would probably be more expensive than it needed to be, additionally there is a larger supply of low modulus fibers available.

System 9.

The final design selected is a hybrid of the previous two designs and can be found on page 36 as concept 9. While the first two focused on affordability and reliability, respectively, the final design tries to establish a balance between the two by using both low modulus CF for strength at a competitive price and incorporating recycled CF to achieve the same strength and similar reliability at the lowest possible price. The detailed design for this concept can be made from comparing the design characteristics of the previous two designs, since a combination of the two distributed phases using the same matrix material should yield a result that is somewhere in the middle of the two. A graph can be made comparing the modulus of the recycled material and the modulus of the pure material on the y axis and the volume fraction on the x axis. This will allow the team to see the approximate characteristics of any possible volume fraction and make an educated choice when selecting a particular volume fraction for this hybrid concept.

Appendices

Appendix A: Code of Conduct

The code of conduct represents the procedures that the team will follow throughout the senior design curriculum. It reflects the culture of the College of Engineering, Northrop Grumman Corporation, and the team members.

Mission Statement.

Our vision is to bring quality service to our stakeholders and achieve a standard that surpasses the status quo. We strive to be a leader in composite airframe development by working with the utmost integrity and determination for our stakeholder's satisfaction.

Team Roles.

Each member of the team is assigned a title; however, they are not confined to the responsibilities implied by their title since there will be tasks that do not fall under the explicit responsibility of any specific team member. Members are encouraged to take on these tasks as sub-roles. In the case that a duty needs to be assigned, it will be discussed during the weekly meeting and it will be assigned to a member.

Cecil Evers: Advanced Materials Engineer.

Responsible for leading the investigation into which composite materials will be selected to test. Upon testing, the Advanced Materials Engineer will analyze the experimental results to select the best composite for the prototype. Additionally, he will perform the final grammar and style edits to all assignment submissions.

Christopher Ryan: Design Engineer.

Responsible for leading the CAD and simulation of the physical prototype. The Design Engineer will design based on generated concepts, customer needs, and test results. Additionally, he will maintain the OneDrive where all team documents and digital resources are located.

Gabrielle Mohrfeld: Composite Manufacturing Engineer.

Responsible for leading the manufacturing of physical test specimens of composite materials and final prototype. The composite manufacturing engineer is responsible for supplying test specimens and securing a location for component manufacturing. Additionally, she will maintain the budget and record meeting minutes for each sponsor, advisor, and team meeting.

Stefan Spiric: Project Lead/ Test Engineer.

Responsible for organizing the team dynamics and primary point of contact for advisors and sponsors. The Test Engineer is responsible for leading the design of experiments, followed by acquisition and analysis of test data to be used for determination of experiment's success.

Communication.

Team members are expected to stay in close contact throughout the project: responses must be within 24 hours. In the event a group member has a time conflict and cannot attend a meeting, they must let the group know 24 hours beforehand to reschedule. The primary internal communication medium is Group-Me, and all meetings will be scheduled there. Important files including deliverables and references are uploaded to the shared FSU OneDrive so that all group members can access, edit, and review these files. The primary communication medium for faculty advisors, Dr. McConomy and Dr. Cooley, is the university email system. The primary communication mediums with the sponsor are conference calls and email.

Dress Code.

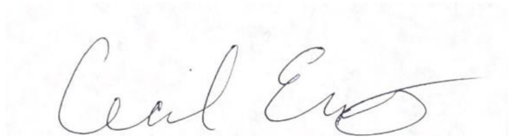
For group and advisor meetings, casual dress code is allowed. Any sponsor or other professional meetings in person or over video will require a business casual dress code. All group presentations will include a business professional dress code, with a specified matching color.

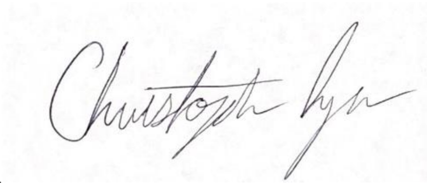
Attendance Policy.

Our team will have a weekly meeting on Sundays at 10:00am to discuss productivity and work for the week. There will be reoccurring meetings with our advisor and sponsors that will be scheduled with each member's personal schedule in mind. Members of the team are required to come to each advising, sponsor, lecture, and team meeting unless it is agreed on by everyone else in the team. Attendance will be noted by whoever is recording the meeting minutes, usually Gabrielle. If a team member cannot attend a meeting because it was scheduled at a time when they are unavailable, then they may be excused if the rest of the team is made aware of their absence. In the case of three missed meetings, Dr. McConomy will be notified and action will be taken.

Statement of Understanding.

By signing this document, each member agrees with rules, roles, and the National Society of Professional Engineers (NSPE) Engineering Code of Ethics.

Cecil Evers 

Christopher Ryan 

Gabrielle Mohrfeld 

Stefan Spiric 

Appendix B: Targets Catalog

Appendix B includes every target, including secondary targets and three that are not functions. All targets can be found in table B1, with a description following.

Table B1

Comprehensive Targets and Metrics

Functions	Metrics	Targets
Withstand Loading	Tensile Strength	x MPa
	Shear Strength	x MPa
	Vibration Frequency/Intensity	Varies
Withstand Temperature	Maximum Temperature	85˚C
	Minimum Temperature	–60˚C
Resist Corrosion	Qualitative Visual Inspection	< Al
Other	Density	< 2.698 g/cm^3
	Cost per Pound	< 0.15$/lb
	Size	< x < y < z

Target 1: Tensile Strength.

The behavior under tension for the part will be evaluated by conducting a three-point bend test using an MTS 858 Mechanical Test System. Three-point bend tests are preferred for carbon fiber due to the difficulty of manufacturing traditional tensile specimens, and its nature as a brittle material. Understanding the part's tensile characteristics are crucial for validating that it has sufficient strength the withstand the forces on the airframe. The MTS 858 performs a multi-stress test; acquiring data for tension, compression, and shear all at once. The system has a 25 kN applied loading capability, allowing for destructive testing as well as non-destructive testing.

Target 2: Shear Strength.

The behavior under shear for the part will be evaluated by conducting a three-point bend test using an MTS 858 Mechanical Test System. Understanding the part's shear characteristics are crucial for validating that it has sufficient strength the withstand the forces on the airframe. The MTS 858 performs a multi-stress test; acquiring data for tension, compression, and shear all at once. The system has a 25 kN applied loading capability, allowing for destructive testing as well as non-destructive testing.

Target 5: Vibration.

The fatigue limit will be tested using a Landmark Hydraulic Mechanical Test System, which allows cyclic loading with a 150 kN capacity. The part will be subjected to continuous vibration during flight operations, with the intensity and frequency dependent upon the location in the aircraft. There are three location groups with vibration profiles respective to each. These vibration profiles are shown below in the following order: Forward FS 100, Between FS 100 –

240, Aft of FS 240. (Fuselage Station (FS) indicates where along the aircraft the part is, along an axis running from nose to tail.)

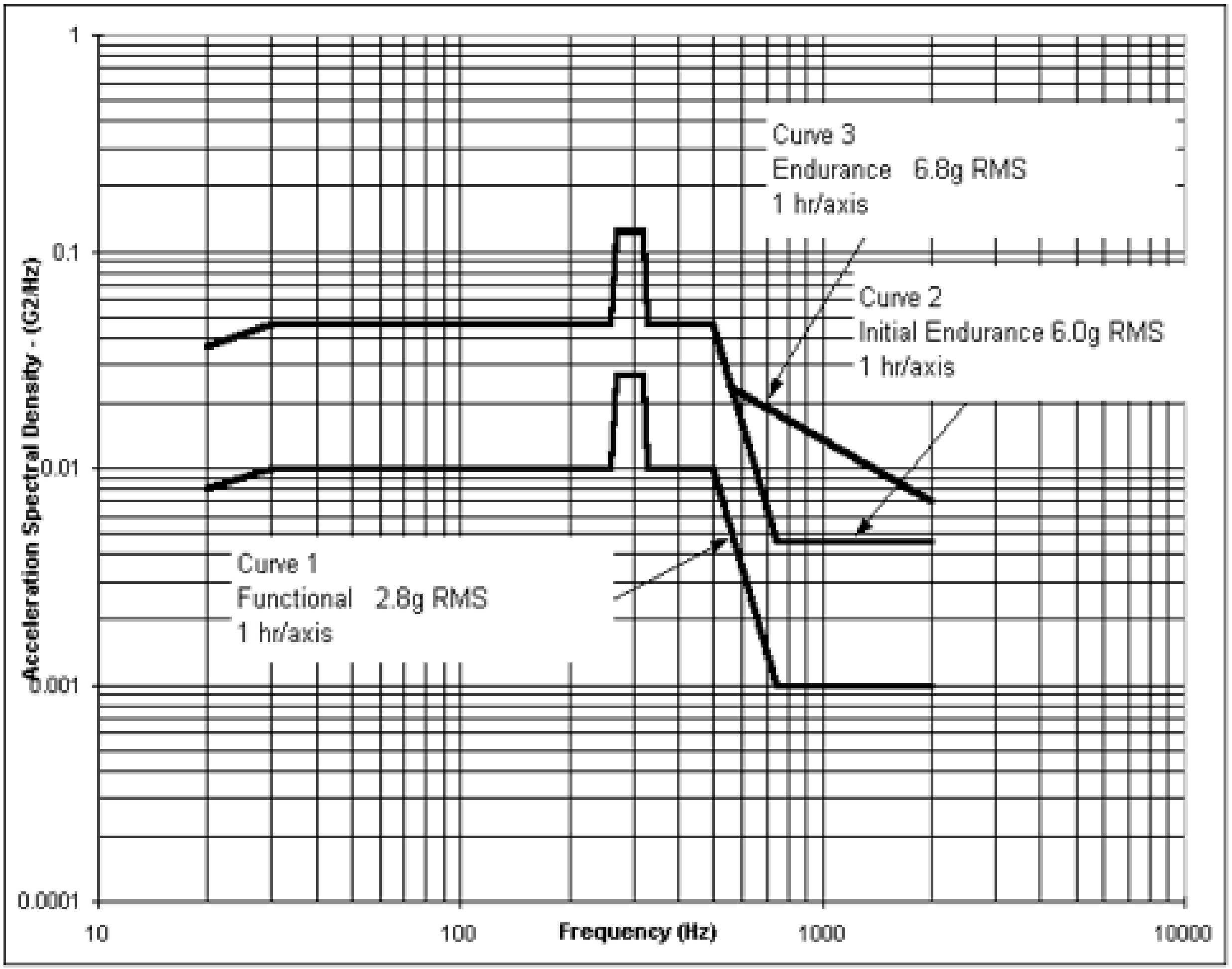


Figure B2: Vibration profile Forward of FS 100.

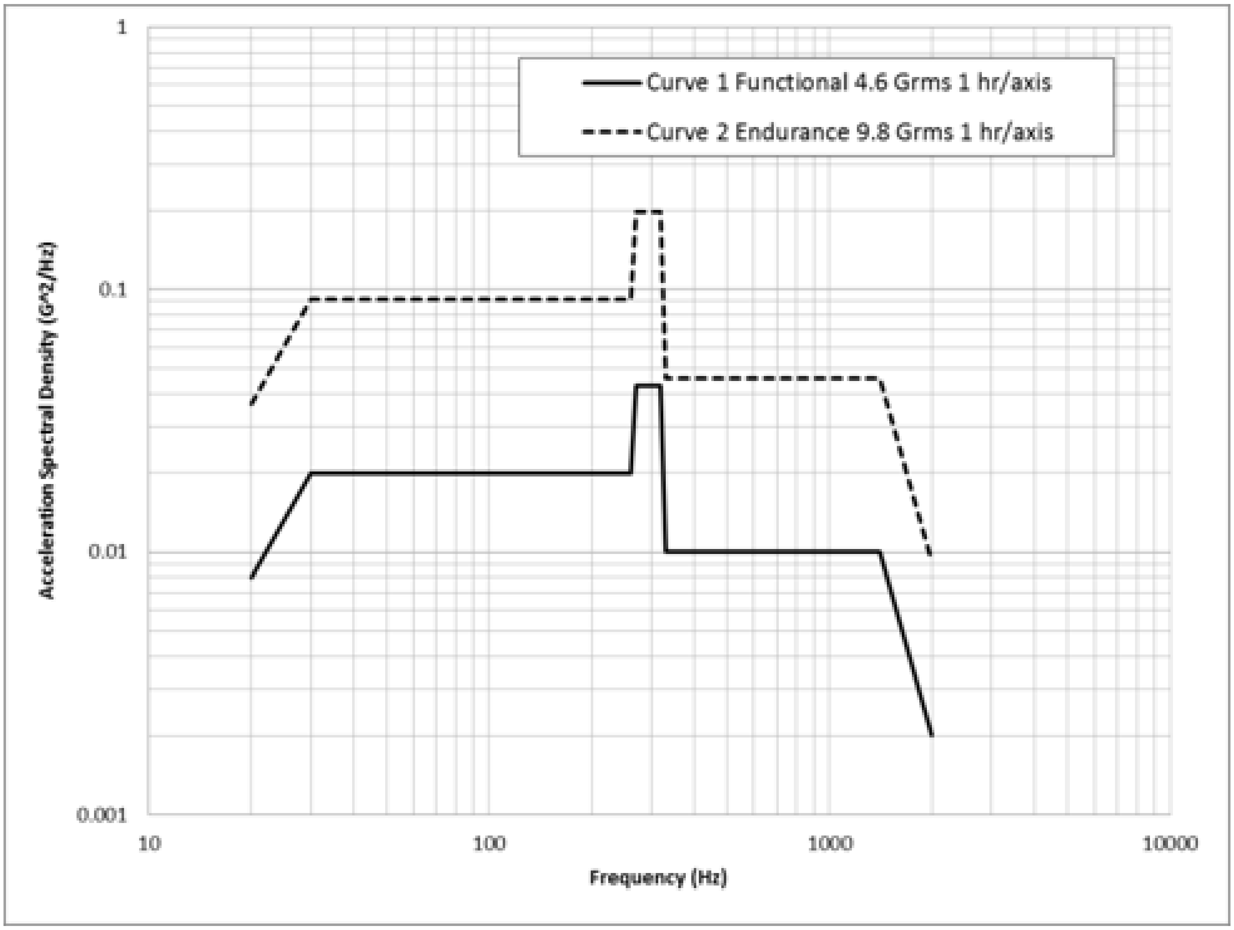


Figure B3: Vibration profile between FS 100 and FS 240

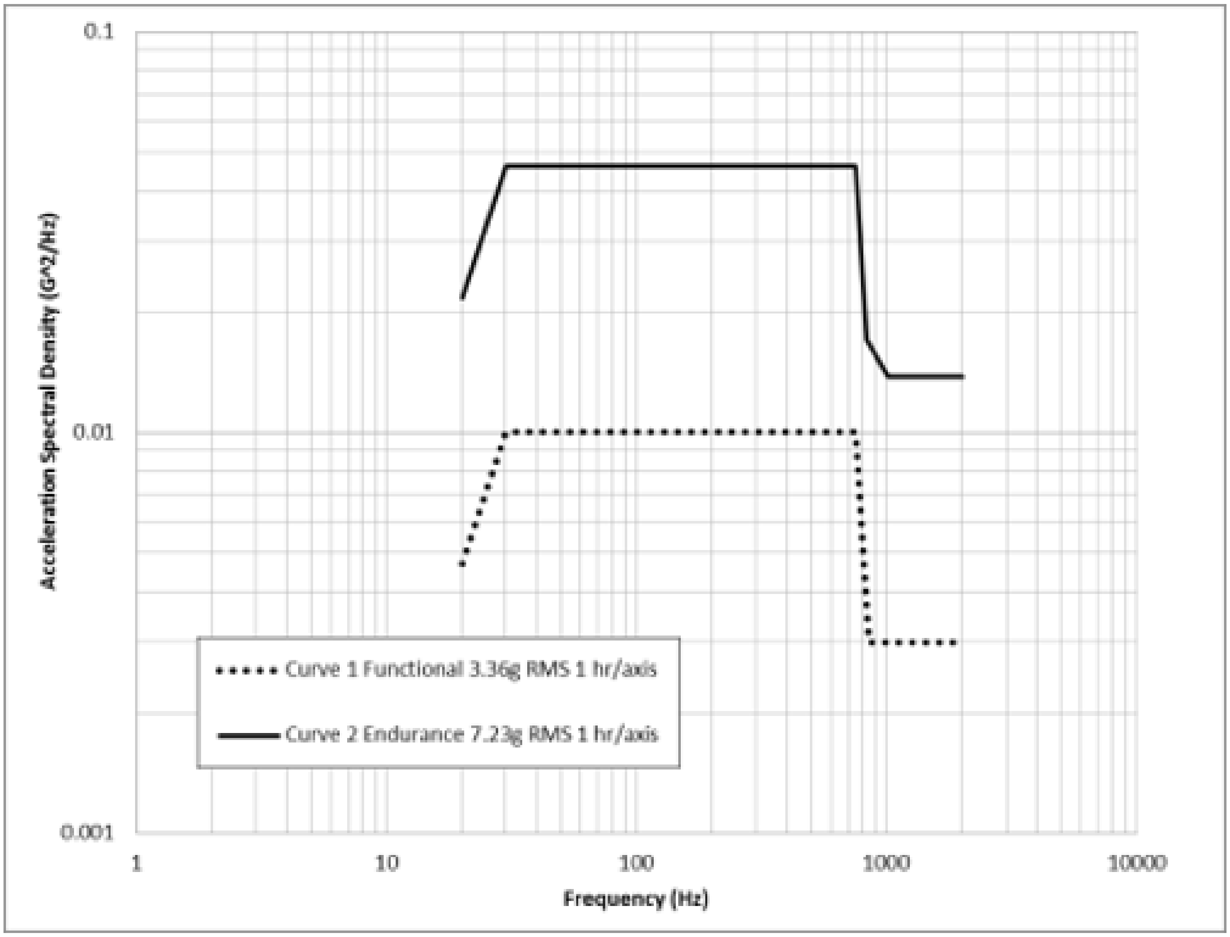


Figure B4: Vibration profile aft of FS 240.

Target 6: Maximum Temperature.

The maximum temperature the part must withstand is 85˚C, which is in non-operating conditions. The part must maintain appropriate strength at this temperature. The test to validate this target is the Hot/Wet test, during which a specimen is immersed in hot water, then taken out and analyzed by the TA Instruments q800 Dynamic Mechanic Analyzer which tests the mechanical properties with respect to time, temperature, and frequency. This test will determine the thermal degradation of the composite system under high temperature.

Target 7: Minimum Temperature.

The minimum temperature the part must withstand is -60˚C, which is the absolute minimum temperature any external part will be exposed to under any conditions or altitude. The part must maintain appropriate strength at this temperature. The test to validate this target is the Cold/Wet test, during which a specimen is immersed in cold water, then taken out and analyzed by the TA Instruments q800 Dynamic Mechanic Analyzer which tests the mechanical properties with respect to time, temperature, and frequency. This test will determine the thermal degradation of the composite system under low temperature. While this test cannot accommodate a temperature below 0˚C, it is likely the best method available to the team. Accurate predictions can be made by extrapolating the change in mechanical properties at various known temperatures within the limited temperature range the team can test at (0˚C to 100˚C).

Target 8: Corrosion Qualitative Visual Inspection.

Naval aircraft are continually exposed to corrosive environments. The corrosion target is simply to have less corrosion than Al, which is extremely likely. The way to test this is to expose an Al and composite specimen to salt water for a period of time, then to examine both under an optical microscope for visible corrosion. If the composite has less visual evidence of corrosion, then it can be considered better than Al.

Target 9: Electrical Resistance.

The team does not have the ability to test the radar cross section (RCS) of the part, and the team may not be able to afford an electromagnetic interference (EMI) test either. The third best option to get an estimate of how much the part will reflect radar waves is an electrical resistance test. A Four-Point probe is used to measure the resistivity of the specimen over an area. This can serve as a very rough estimate for how well the part will reflect radar waves. If the part is more resistive than Al, then it will probably contribute to a smaller RCS.

Target 10: Density.

The density of the material can be found by measuring the dimensions of the part using calipers and determining mass using a scale. Once the dimensions are known, volume can be determined. The average density can then be found by dividing the mass by the volume. The target density is to be less than aluminum, which has a density of 2.698 g/cm^3.

Target 11: Cost.

Cost is a primary disadvantage of composites; however, the team is hoping to mitigate this by using recycled materials. The team is very interested in the cost of the part; the target is to be cheaper than Al6061, which costs 0.15$/lb. (The exact price of the aluminum part is not known at the time of writing because the size of the aluminum part has not been disclosed to the team yet).

Target 12: Size.

The specimens and any prototypes will need to be manufactured in specific sizes. These sizes will be measured using electronic calipers. The specimen sizes depend on the tests being run, and the strength NGC wants the part to have, which has not yet been disclosed to the team as of the time of writing.

Appendix C: Concept Generation

Many potential concepts were created for this project. A catalog of 50 concepts is presented here, along with the morphological chart.

The morphological chart is a way to compare many different subcomponents of a larger project. In this case, there are three materials which make up the composite: the distributed material, the matrix material, and the core material. A chart can be created with many different design possibilities that can be mixed and matched together to create hundreds of possibilities. A chart with five options in three categories gives a total of 243 possible composite combinations, shown below. Following the table, a brief discussion of the merits of each entry in each column relative to the other entries in the column can help narrow down the possible designs to a more manageable number.

Table C-1

Morphological chart

Distributed Phase	**Matrix Phase**	**Core Material**
CF low modulus	Thermoplastic polymer	None
CF high modulus	Thermoset polymer	DaVinci Foam
CF Recycled	Metal	Balsa Wood
Aramid	Ceramic	Polymer
Glass	Carbon	CF Recycled

The next section contains geometry concepts (the part does not have to necessarily follow the shape of a standard C channel.) 30 potential shapes are presented below.

Figure C-2

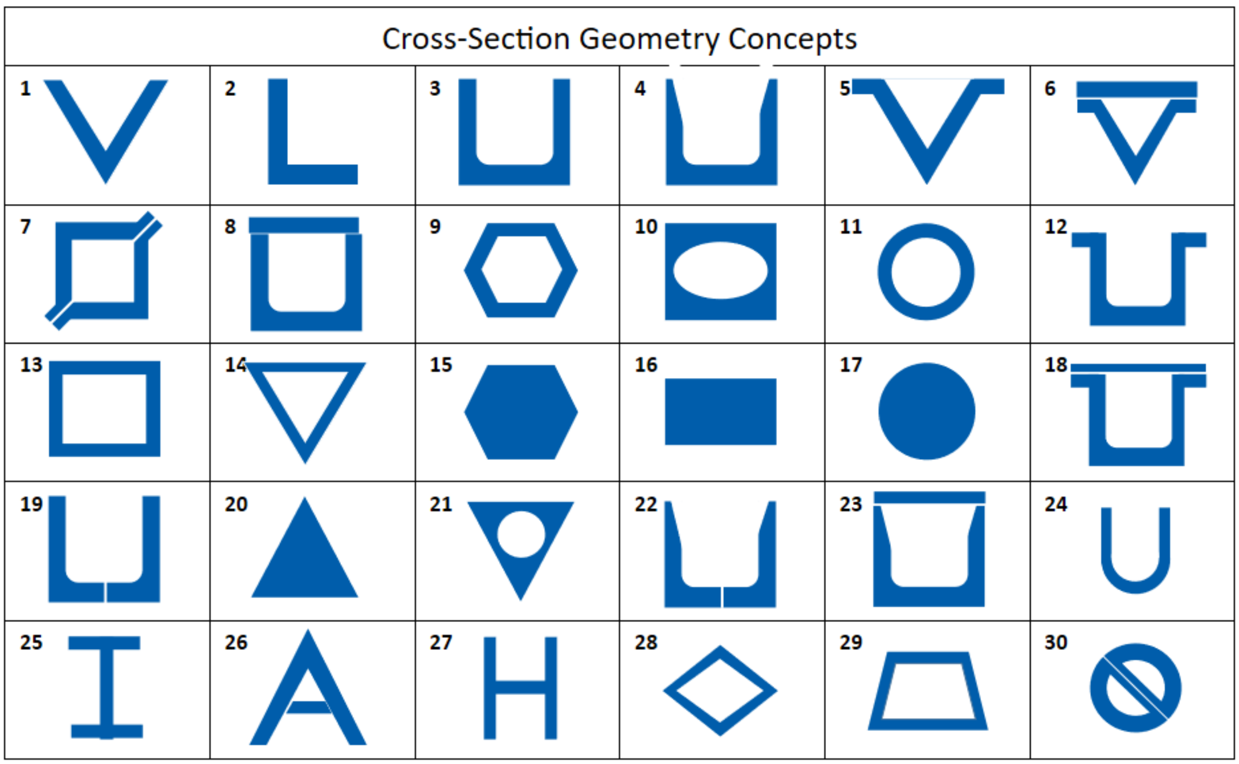


Figure C-2: Cross Section Geometry Concepts

Biomimicry.

One tool for generating concepts is biomimicry; which involves looking to see how similar problems are solved in nature. Sometimes obvious solutions are overlooked by engineers, Biomimicry helps with structural ideas relating to how animals build their homes or how trees stand independently. This technique is especially relevant in the field of composites since two of the most commonly used items throughout human history are composites: bone and wood. Both are a combination of a strong, anisotropic fibrous material embedded in a more isotropic matrix phase. Balsa wood is lightweight and still used in laminate composites to this day, and a material to consider in the design. Natural fibers, such as sisal can also be used as the distributed phase.

Fibers and core material are found in bone. Bone is considered a composite of Dahllite crystals, type 1 collagen fibers, and water. Bone tends to have very good compressive and tensile strength; however it tends to have a much lower shear strength.

Trees need to support the weight of their branches, as well as avoid breaking from the force of the wind. The cells in wood are long, thin fibers that point in the direction to which the wood is stressed. In addition, the cells are hollow, this greatly reduces the weight that needs to be supported while also maintaining enough strength. Hollow structures are used often in large structures and will be considered in the team's designs.

Below are 10 concepts inspired by biomimicry.

1) Bone is considered a composite of Dahllite crystals, type 1 collagen fibers, and water. Bone tends to have very good compressive and tensile strength; however, it tends to have a much lower shear strength lower shear strength.

2) Balsa wood is lightweight and still used in laminate composites to this day, and a material to consider in the design.

3) Sisal is a natural fiber that can be used as the distributed phase.

4) Weaves of tolls for fibers, like carbon fiber can be inspired by spider webs.

5) Muscles of a mammal's body can be used as inspiration for fiber weaves.

6) Trees need to support the weight of their branches, as well as avoid braking from the force of the wind. The cells in wood are long, thin fibers that point in the direction to which the wood is stressed.

7) Honeycombs are shaped in a way that can withstand the weight of a school of bees as well as other weight added to the nest. The shape and its pattern can be used in the design.

8) Beaver dams are designed to be structurally sound and provide strength from lightweight wooden sticks.

9) Spider silk is considered the strongest biological substance.

10) Mammal teeth are strong, made out of dentin, cementum and pulp, and is considered the most durable part of the body.

Anti-Problem.

The anti-problem method for concept generation uses the negatives and problems that could be encountered when the part is in use. The concepts from anti-problem are considered “bad ideas” which will be avoided or taken into consideration to resolve in the design process. In the process of generating bad ideas, some good, unexpected ideas may be generated. 10 of the 100 concepts generated come from this method. These materials are considered bad for the airframe structure based on the criteria of NGC’s needs and will allow for the ideas to be narrowed down to specific composites.

1) Steel is a very dense material.

2) Aluminum is already used and would not satisfy the customer needs.

3) Cast iron is a dense and brittle material.

4) Brick’s mechanical properties do not meet the standards for the airframe’s needs.

5) Concrete is a heavy composite.

6) Clay material reacts to contact with water and would fail quickly.

7) ABS plastic would soften and not be able to withstand the loadings for the airframe.

8) Water is a liquid and could affect other components of the aircraft.

9) Sodium chloride is soluble in water; the part cannot dissolve

10) Iron reacts with oxygen, causing corrosion.

Appendix D: Analytical Hierarchy Process

This appendix contains the complete analytical hierarchy process (AHP). The AHP is a technique to derive weighted values to use when comparing design characteristics. It is easy for the designer's biases to color their concept selections; the AHP can help identify these discrepancies.

The first step is to compare the engineering characteristics relative to each other and make a reciprocal matrix where all those relative weights add up to a value of 1. The concepts are then compared relative to each other with respect to each criterion on an individual basis, resulting in seven more charts. A consistency check is done for each criterion to determine if there is any bias in that chart.

The first AHP chart is shown below. Scores are assigned in the upper right half as 1,3,5,7 and then in the lower left diagonal is assigned the reciprocal value of the corresponding upper right cell. The columns are added up instead of the rows, making the chart easier to fit on this page. The lower score in the sum column means the more important the engineering characteristic is. The second chart is a normalized version of the first, such that all categories sum to 1 (the values are different, but the ratios are the same).

Criteria Comparison Matrix							
	Tensile Strength of Component	Shear Strength of Component	Vibration Frequency/ Intensity	Attaching to Airframe	Access to Materials	Endure Extreme Temperatures	Material Cost
Tensile Strength of Component	1.000	1.000	3.000	5.000	5.000	3.000	5.000
Shear Strength of Component	1.000	1.000	3.000	5.000	3.000	3.000	7.000
Vibration Frequency/ Intensity	0.333	0.333	1.000	3.000	1.000	5.000	3.000
Attaching to Airframe	0.200	0.200	0.333	1.000	3.000	5.000	7.000
Access to Materials	0.200	0.333	1.000	0.333	1.000	0.200	3.000
Endure Extreme Temperatures	0.333	0.333	0.200	0.200	5.000	1.000	1.000
Material Cost	0.200	0.143	0.333	0.143	0.333	1.000	1.000
Sum	**3.267**	**3.343**	**8.867**	**14.676**	**18.333**	**18.200**	**27.000**

Criteria Comparison Matrix								
	Tensile Strength of Component	Shear Strength of Component	Vibration Frequency/ Intensity	Attaching to Airframe	Access to Materials	Endure Extreme Temperatures	Material Cost	Criteria Weight {W}
Tensile Strength of Component	0.306	0.299	0.338	0.341	0.273	0.165	0.185	**0.272**
Shear Strength of Component	0.306	0.299	0.338	0.341	0.164	0.165	0.259	**0.267**
Vibration Frequency/ Intensity	0.102	0.100	0.113	0.204	0.055	0.275	0.111	**0.137**
Attaching to Airframe	0.061	0.060	0.038	0.068	0.164	0.275	0.259	**0.132**
Access to Materials	0.061	0.100	0.113	0.023	0.055	0.011	0.111	**0.068**
Endure Extreme Temperatures	0.102	0.100	0.023	0.014	0.273	0.055	0.037	**0.086**
Material Cost	0.061	0.043	0.038	0.010	0.018	0.055	0.037	**0.037**
Sum	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

Now that the engineering characteristics are properly weighted, each of the three systems will be compared against each other with respect to each engineering characteristic. The manner of comparison is the same as the previous two charts with a raw score of 1,3,5,7 in the upper right diagonal, followed by the inverse score in the lower left diagonal. The results are normalized in the second chart, then a consistency check is performed. The final result of the consistency check is a simple “yes” or “no” answer to the question “is the comparison consistent?”

The seven engineering characteristics charts are presented on the following pages. Each engineering criteria proved to be consistent except for the vibration resistance. This is probably because the only way to make predictions of composite behavior over a wide range of vibrations is through experiment. In other words, the composite system is too complex to allow for the team to model or even predict the behavior of the system over a wide range of frequencies. Specialized composite FEA software takes several minutes even to simulate the most basic static loading conditions; the only way to know how well a design will perform is to test a physical prototype. Therefore, it is not surprising that the team’s best estimates were biased and possibly unreliable.

Criteria 1: Tensile Strength of Component

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	0.143	0.333
System 7	7.000	1.000	5.000
System 9	3.000	0.200	1.000
Sum	**11.000**	**1.343**	**6.333**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.091	0.106	0.053	**0.083**
System 7	0.636	0.745	0.789	**0.724**
System 9	0.273	0.149	0.158	**0.193**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	0.251	0.083	3.014
System 7	2.273	0.724	3.141
System 9	0.588	0.193	3.043

Avg Consistancy:	3.066
Consistency Index:	0.033
Consistency Ratio:	0.063
Is Comparison Consistent?	Yes

Criteria 2: Shear Strength of Component

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	0.143	0.333
System 7	7.000	1.000	5.000
System 9	3.000	0.200	1.000
Sum	**11.000**	**1.343**	**6.333**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.091	0.106	0.053	**0.083**
System 7	0.636	0.745	0.789	**0.724**
System 9	0.273	0.149	0.158	**0.193**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	0.251	0.083	3.014
System 7	2.273	0.724	3.141
System 9	0.588	0.193	3.043

Avg Consistancy:	3.066
Consistency Index:	0.033
Consistency Ratio:	0.063
Is Comparison Consistent?	Yes

Criteria 3: Vibration Frequency/Intensity

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	5.000	3.000
System 7	0.200	1.000	3.000
System 9	0.333	0.333	1.000
Sum	**1.533**	**6.333**	**7.000**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.652	0.789	0.429	**0.623**
System 7	0.130	0.158	0.429	**0.239**
System 9	0.217	0.053	0.143	**0.138**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	2.231	0.623	3.579
System 7	0.777	0.239	3.250
System 9	0.425	0.138	3.089

Avg Consistancy:	3.306
Consistency Index:	0.153
Consistency Ratio:	0.294
Is Comparison Consistent?	No

Criteria 4: Attaching to Airframe

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	5.000	1.000
System 7	0.200	1.000	0.333
System 9	1.000	3.000	1.000
Sum	**2.200**	**9.000**	**2.333**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.455	0.556	0.429	**0.480**
System 7	0.091	0.111	0.143	**0.115**
System 9	0.455	0.333	0.429	**0.405**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	1.460	0.480	3.044
System 7	0.346	0.115	3.010
System 9	1.230	0.405	3.033

Avg Consistancy:	3.029
Consistency Index:	0.015
Consistency Ratio:	0.028
Is Comparison Consistent?	Yes

Criteria 5: Access to Materials

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	5.000	3.000
System 7	0.200	1.000	0.333
System 9	0.333	3.000	1.000
Sum	**1.533**	**9.000**	**4.333**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.652	0.556	0.692	**0.633**
System 7	0.130	0.111	0.077	**0.106**
System 9	0.217	0.333	0.231	**0.260**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	1.946	0.633	3.072
System 7	0.320	0.106	3.011
System 9	0.790	0.260	3.033

Avg Consistancy:	3.039
Consistency Index:	0.019
Consistency Ratio:	0.037
Is Comparison Consistent?	Yes

Criteria 6: Endure Extreme Temperatures

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	1.000	1.000
System 7	1.000	1.000	1.000
System 9	1.000	1.000	1.000
Sum	**3.000**	**3.000**	**3.000**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.333	0.333	0.333	**0.333**
System 7	0.333	0.333	0.333	**0.333**
System 9	0.333	0.333	0.333	**0.333**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	1.000	0.333	3.000
System 7	1.000	0.333	3.000
System 9	1.000	0.333	3.000

Avg Consistancy:	3.000
Consistency Index:	0.000
Consistency Ratio:	0.000
Is Comparison Consistent?	Yes

Criteria 7: Material Cost

Criteria Comparison Matrix			
	System 6	System 7	System 9
System 6	1.000	7.000	3.000
System 7	0.143	1.000	0.200
System 9	0.333	5.000	1.000
Sum	**1.476**	**13.000**	**4.200**

Normalized Criteria Comparison Matrix				
	System 6	System 7	System 9	**Criteria Weight**
System 6	0.677	0.538	0.714	**0.643**
System 7	0.097	0.077	0.048	**0.074**
System 9	0.226	0.385	0.238	**0.283**
Sum	1.000	1.000	1.000	**1.000**

Consistency Check			
	Weighted Sum Vector	**Criteria Weight**	**Consistency**
System 6	2.008	0.643	3.121
System 7	0.222	0.074	3.013
System 9	0.866	0.283	3.062

Avg Consistancy:	3.066
Consistency Index:	0.033
Consistency Ratio:	0.063
Is Comparison Consistent?	Yes

The consistency scores of the previous charts are compiled in the consistency check chart and analyzed to give a final result as to whether the entire process was without bias. The final result is that the comparison is not consistent.

Consistency Check			
	Weighted Sum Vector	Criteria Weight	Consistency
Criteria 1	2.394	0.272	8.788
Criteria 2	2.334	0.267	8.727
Criteria 3	1.323	0.137	9.656
Criteria 4	1.180	0.132	8.938
Criteria 5	0.522	0.068	7.717
Criteria 6	0.695	0.086	8.074
Criteria 7	0.303	0.037	8.118

Avg Consistancy:	**8.574**
Consistency Index:	**0.262**
Consistency Ratio:	**0.194**
Is Comparison Consistent?	**No**

RI Values	
# of Criteria	RI Value
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35

One reason for the inconsistency is the difficulty with predicting the behavior of the composite systems over a wide range of vibrations. Another possible bias could be bias towards the tensile and shear strength of the part. These are clearly the most important engineering characteristics because if the part is not as strong as aluminum the design is a failure. If the part fails some other test, perhaps an argument could still be made for its adoption and it would not be a complete failure, but if the part is weaker than the current aluminum component, there is no point to investigate it further. Holding the same load as an aluminum c channel is the primary customer need and the primary function of the composite c channel in the airframe. This bias probably influences the results of the AHP and the concept selection process in general, resulting in favoring more robust systems that are the most likely to withstand the required loading forces.

References

Air Force Research Lab. (2015, June 1). Composite Airframe Life Extension.

Callister, W. (2014). *Materials Science and Engineering an Introduction.* Hoboken, NJ: John Wiley & Sons Inc.

Department of Defense. (2019). *MIL-STD-810H Environmental Engineering Considerations and Laboratory Tests.* Aberdeen: U.S. Army Test and Evaluation Command.

Hale, J. (2006). Boeing 787 from the Ground Up. *Aero Magazine*, 17.

L3 Harris. (2019, July). *AN/ALQ-214 IDECM*. Retrieved from harris.com: https://www.harris.com/solution/analq-214-idecm-fa-18-countermeasure-system

McConomy, S. (2018). *Characteristics, Functions, Targets, and Metrics.* Tallahassee: FSU COE.

McConomy, S. (2018). *EML 4550 Engineering Characteristics* . Tallahassee: FAMU-FSU COE.

Milberg, E. (2015, September 8). *Air Force Wants Composites to Replace Titanium in Military Aircraft.* Retrieved from CompositesManufacturing.com: http://compositesmanufacturingmagazine.com/2015/09/air-force-wants-composites-to-replace-titanium-in-military-aircraft/

Wikipedia. (2019, September). *Boeing F/A-18E/F Super Hornet*. Retrieved from Wikipedia.com: https://en.wikipedia.org/wiki/Boeing_F/A-18E/F_Super_Hornet

Wikipedia. (2019, September 20). *Lockheed Marting F-35 Lightning II*. Retrieved from wikipedia.org: https://en.wikipedia.org/wiki/Lockheed_Martin_F-35_Lightning_II