DESIGN OF A FIXTURE TO BALANCE HELICOPTER ROTOR BLADES

MECH 4860 – Engineering Design
Final Design Report

Sponsor Company:
Advanced Composite Structures

Project Advisor:
Vijay Chatoorgoon

Submission Date: November30th, 2011

Team 1: HERB#3

Justin Albo

Abdullah Fattal

Manel Parellada Roura

Lance VanderVegte

Letter of Transmittal

December 5th, 2011

Dr. Paul Labossiere
Mechanical and Manufacturing Engineering
Engineering Design MECH4860
E1-546 Engineering Building
Winnipeg, Manitoba
R3T 5V6

Dear Dr.Labossiere,

As per the requirements of course MECH 4860 Engineering Design, on behalf of team H.E.R.B #3 we submit, *Design of a Fixture to Balance Helicopter Rotor Blades: Final Design Report* for your review. The purpose of this report is to present our final design of a system that will perform span-wise and chord-wise moment balances on helicopter blades for our client, Advanced Composite Structures.

This report outlines the background, problem definition, concept theory and finally, a design solution. Also included in the report is a detailed CAD drawing package and a total design cost analysis. All the pieces used are from 80/20 Inc. and Wagner, both companies with which our client has collaborated with confidence. The design team would like to thank Bruce Anning guidance and for being available to us and receptive to our ideas. The design team would like to thank Vijay Chatoorgoon, Curtis Carrick, and Aidan Topping for their advice and continued support of the project.

Sincerely,

Lance VanderVegte,
Team Leader

Table of Contents

List of Figures

List of Tables

1. Abstract

This report describes the design project presented by Advanced Composite Structures (ACS) regarding the balancing of helicopter rotor blades after repair and the design was recommended for performing the balancing procedure.

The final recommendation was comprised of three separate designs, each for a different blade length. The team recommends ACS continues using the current setup for the small and medium sized blades, but recommends a new design for weighing of larger and heavier blades.

The recommended final design makes use of the same parts as used for medium blades and therefore requires no retraining of personnel to assemble. The final design consists of a box-shaped frame which rests on three scales. Different scales are recommended for use with the final design in order to increase the maximum weight of blades able to be balanced. The tip rests on two scales to allow for chord-wise and span-wise balancing while a third scale at the root end of the blade allows for calculation of the total weight of the repaired blade. In the design, criss-crossing cables are used to eliminate error caused by lateral forces applied to the fixture when the helicopter blades are placed on it. Cables running below the fixture allow for deflection caused by the weight of the blade to be negated. The final design meets all the criteria were provided by ACS other than maintaining the same level of accuracy in the scale readings. The team feels this was the best option as it increases capacity but still takes into consideration the budget limitation.

2. Introduction

Advanced Composite Structures (ACS) repairs helicopter rotor blades and other composite aircraft parts. When a helicopter blade is repaired, the weight of repair affects the final mass of the blade. This change in mass causes a change in the balance of each blade which means each blade needs to be balanced after repair. The balancing technique performed must be done precisely and accurately; in order for the blade to operate correctly, the mass center and total mass must be restored to the correct value and location. The balancing procedure is completed by using a new ground breaking method.

To perform this balancing technique, ACS has an effective method to balance each blade to its original specifications. The entire setup the Company currently uses is illustrated in Figure 1. As seen in Figure 1 there are three scales resting on the strong aluminum support structure. On the three scales is the balancing fixture, used to hold the blades in place so the blades can be weighed correctly.

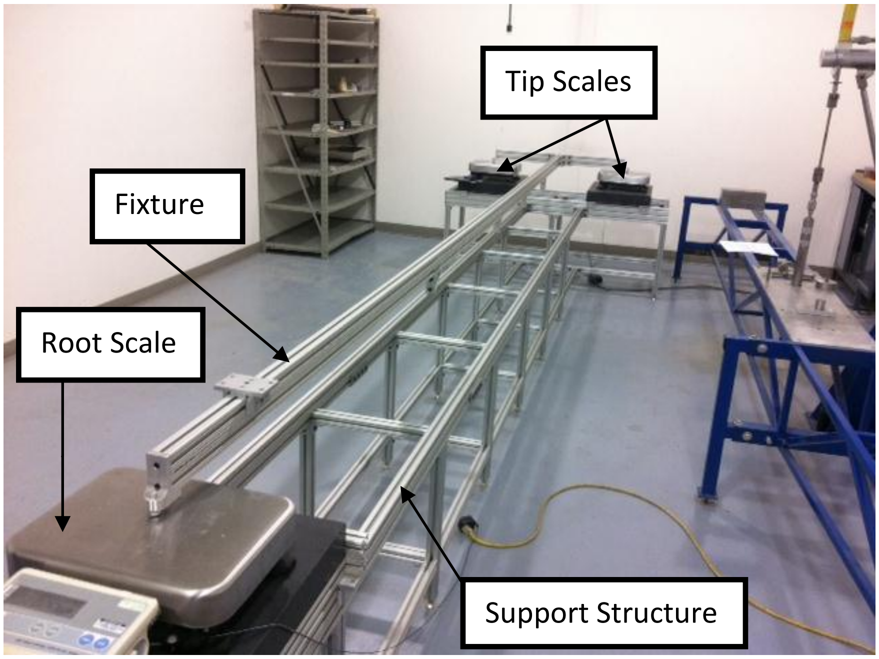


Figure 1: Current Balancing Fixture [1]

2.1. Customer Needs and Specifications

In order to serve a wider range of clients and increase profitably, ACS needs to be able to balance longer and heavier blades. The current fixture cannot support the weight of these larger blades; therefore, the client needs the following features from the design:

- minimal flex (ideally less than 0.1 inches) when heavy blades are placed on it;
- compatible with blades 24 feet long and weigh 120 kg;
- a high degree of accuracy (currently 0.002 kg for the two “tip end” scales and 0.005 kg for the “root end” scale);
- simple to set up and to use;
- some aesthetic appeal; and
- cost should be below $10,000 [2].

2.2. Problem Description and Design Objectives

The main objectives were to design a fixture reducing the maximum deflection while calculating the span-wise moment of large rotor blades and to increase the maximum size of blade able to be balanced. The deflection ACS was experiencing in the current fixture was approximately 1-2 inches when balancing medium sized blades. This deflection in the beam causes the three pins of the structure to rotate while resting on the scales, thus they were displaced. The displacement of the pins on the scales leads to an inaccurate reading, this affects the calculation of the moments. With heavier and longer blades, the deflection in the beam would be much more significant. ACS wants to optimize the rigidity of the structure in order to minimize sag in the beam, without making the fixture much heavier, which would result in higher capacity and less accurate scales being required. The main goal of this project is to allow ACS to increase the size ranges of the blades by increasing the maximum capacity of the scales and stiffening the support structure.

3. Research

The following section describes the internal and external searches that were used to develop concepts and select the recommended final design. Descriptions of concepts considered are included in Appendix C and Appendix D which outline the methods used to select the final design.

3.1. External Searches

External searches were conducted by speaking to the owner of ACS, Mr. Bruce Anning, about what he wanted to achieve with this project. During these discussions, Mr. Anning described the operation of the balancing system along with the limitations ACS has encountered with the current system. Mr. Anning also mentioned other possible concepts ACS had considered. Online searches for patents related to helicopter rotor blade balancing indicated the methods considered and the recommended design are all unique and do not infringe any current patents.

Locating scales and load cells the team began looking through several companies' online catalogues. It was later decided this method was slow and an inefficient use of the teams time. Emails were subsequently sent to several companies with an explanation of the capacity and accuracy needs. Pricing information for all items from WAGNER and H&C Weighing Systems was obtained online while pricing information for items from 80/20 Inc. were obtained by phone from their quoting services.

3.2. Internal Searches

The main method used for internal searching was brainstorming. Whenever the team had a meeting, an efficient brain storming technique was used to make the most out of the meeting time. Each member would take a turn to explain any ideas they may have come up with since the previous meeting. The team member would present drawing to help explain the idea. The team would then discuss each new idea. Once everyone finished sharing, the team's project advisor, Mr. Vijay Chatoorgoon would join the team. Mr. Chatoorgoon was useful for screening different ideas. He would provide informative criticism on the ideas presented and, based on his experience, explain possible reasons why or why not the idea would work or not. By using these brainstorming techniques together with information gained from external searching, the team was able to come up with preliminary concepts, modification those concepts, and finally a design recommendation.

3.3. Features of the Design

The following section describes the features of the recommended design which are important for solving the ACS problem. The section also outlines how the features aid in meeting the design criteria, constraints and limitations. Appendix A outlines the procedure used in the selection of the beams and scales used.

The design is being recommended makes use of commercially available parts which means minimal machining is needed and the design will be easy to setup and use. The new design works in a similar manner to the ACS' current method which it will not require additional training of operators.

Since an increase in the size of blades to be measured was required, a new set of scales has been recommended. The increase in capacity provided by the new scale configuration now makes it possible to weigh and balance blades with a length of 24 feet and a weight of 250 pounds (120 kg). The accuracy of the scales is not as high as the current configuration however the team believes it should be adequate with an accuracy of +/- 5 grams for the tip end scales and +/- 10 grams for the root end scale.

Design weight was a factor in the initial design considerations because the team did not want to change to higher capacity scales which would result in lower accuracy. However, it was later concluded that a proper solution could not be obtained and the weight of the fixture would not be a major consideration.

In addition to increasing weighing capacity, it is important the new design not bend under the weight of the large blades. In order prevent bending, cables are attached along the bottom of the structure and tension is applied. This method has been utilized by ACS in the past and has been proven to be capable of eliminating bending from the structure.

The box style of the design along with the criss-crossing cables is important for two reasons. Firstly, parallel beams are used to allow for easy placement of the blades. The ease of placement should give the operator greater confidence then the current single beam design as they will not be placing a 24 foot, $500,000 blade on a 1.5 inch wide beam. The other advantage of the box and criss-crossing cables design is due to the tension present in the cables, any lateral disturbances of the frame will not result in a deformation of the beam. This is desirable as any lateral deflection will cause an error in the readings.

4. Drawings

The following section includes SolidWorks drawings of the final design as well as all the major components used in the design.

A corner bracket was used to connect the beams to each other. This is shown is Figure 2, the models of these pieces were downloaded from the 80/20 inc. website [3]. In order to attach the cross cable in the fixture, a new piece has been designed.

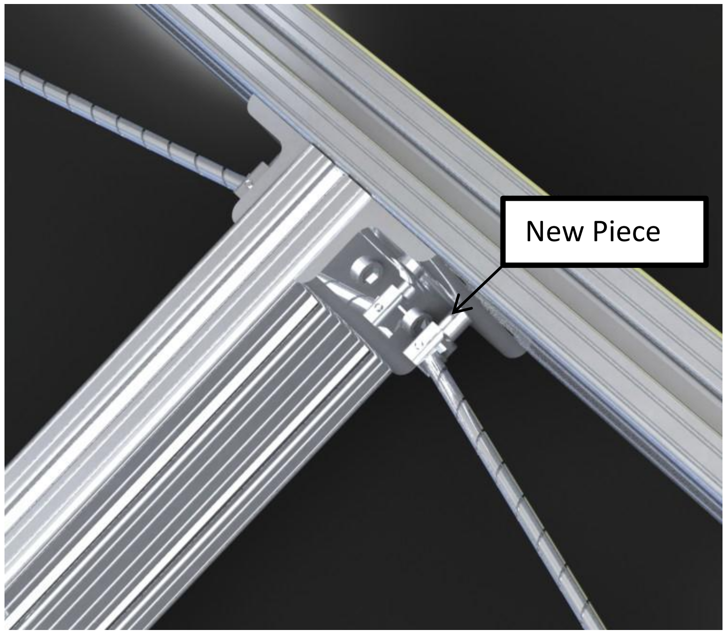


Figure 2: Small Piece to Attach the Cross Cable to the Fixture [4]

The cable is used to decrease deflection is attached underneath the fixture, as shown in Figure 3.

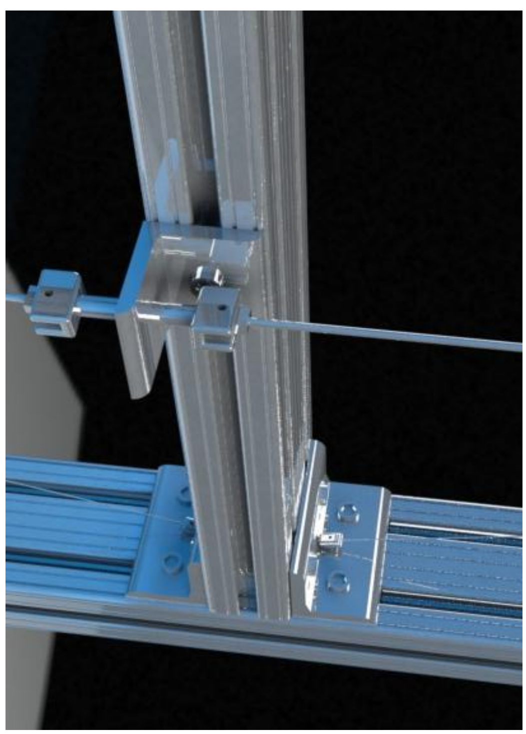


Figure 3: Attachment of Cable to Reduce Deflection [4]

Figure 4 shows the apparatus used for tensioning the cable. By turning the screw, the cable will gain additional tension. This procedure must be continued till the deflection of the beam is eliminated.

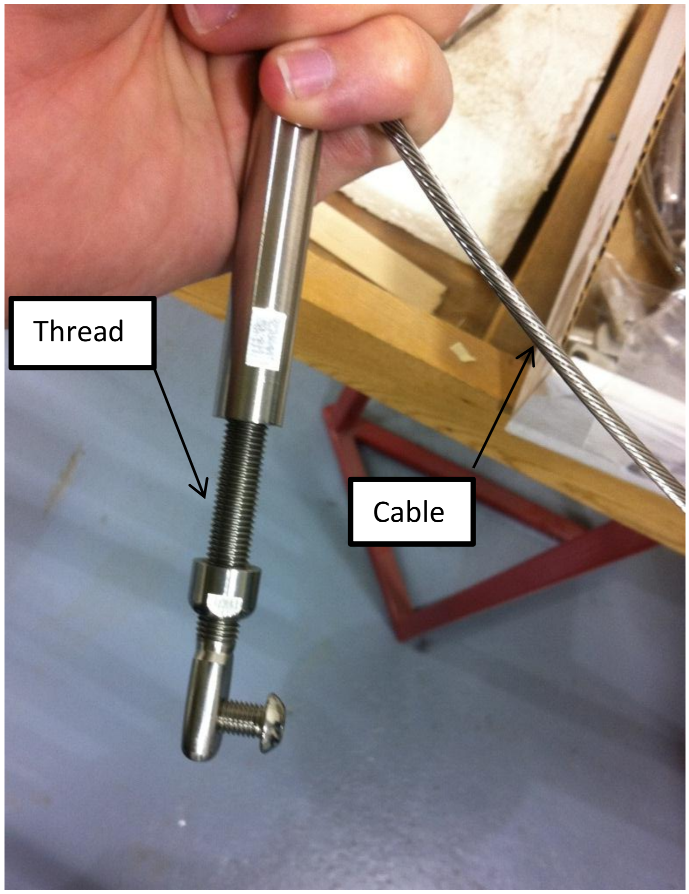


Figure 4: Cable Tensioner [1]

5. Operation

The follow section outlines the procedure used by ACS to balance the blades they receive from the customers.

Since every blade has different size and weight, ACS uses three different fixtures for different ranges of blades. Each of the fixtures rests on the scales which are located on top of the 24 foot structure shown in Figure 5. The tip scale can move along the structure, so every fixture can be adapted. The structure has a certain height, so the operator can work comfortably and easily.

Figure 5: ACS Support Structure [5]

For tail blades and short blades (1 to 3 feet) ACS uses a short fixture made of carbon fibre as shown in Figure 6. Since the fixture is short and the short blades are light, there will not be significant deflection.

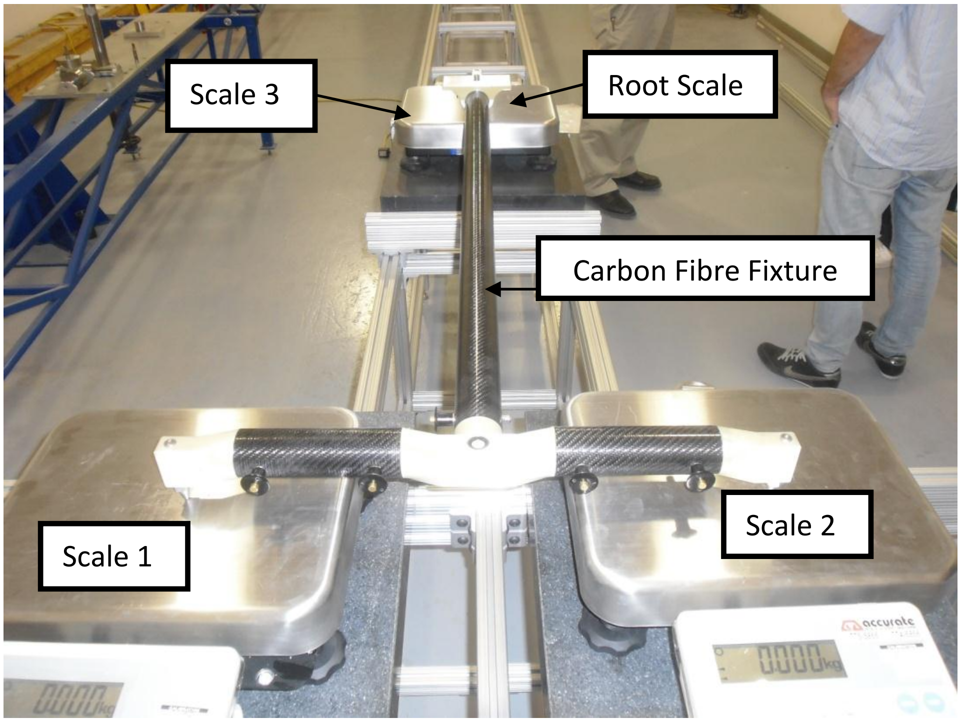


Figure 6: Carbon Fibre Fixture for Short Beams [6]

To balance medium blades (8 to 15 feet) ACS uses a fixture with a 'T' shape as shown in Figure 7.

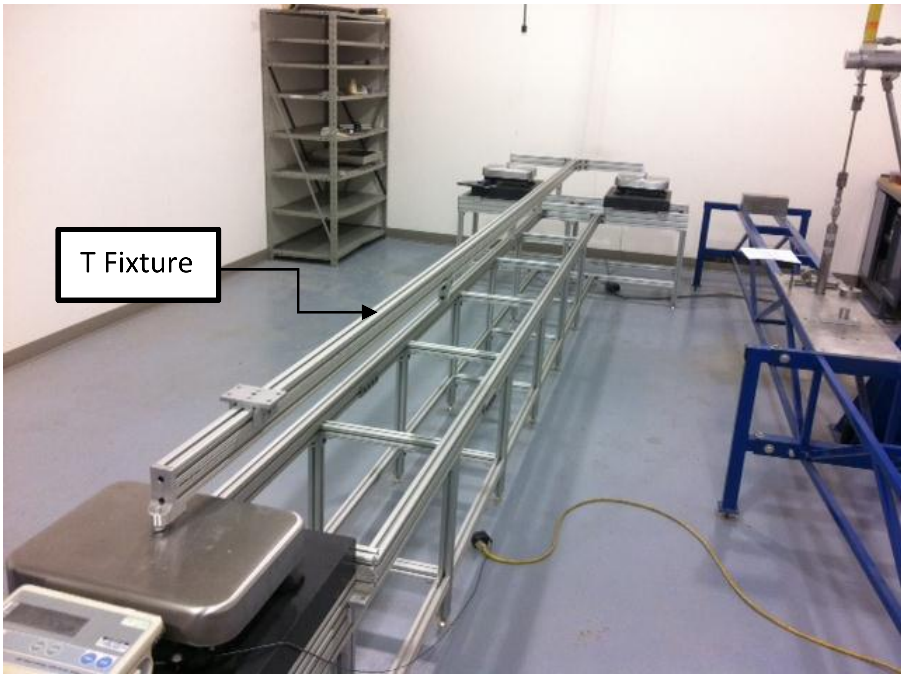


Figure 7: 'T'-Shape for Middle Blades [5]

To balance the longest blades (15 to 24 feet) ACS will use the final design. As the blades are longer and heavier, a stiffer structure is required to minimize the deflection. This structure is shown in Figure 8.

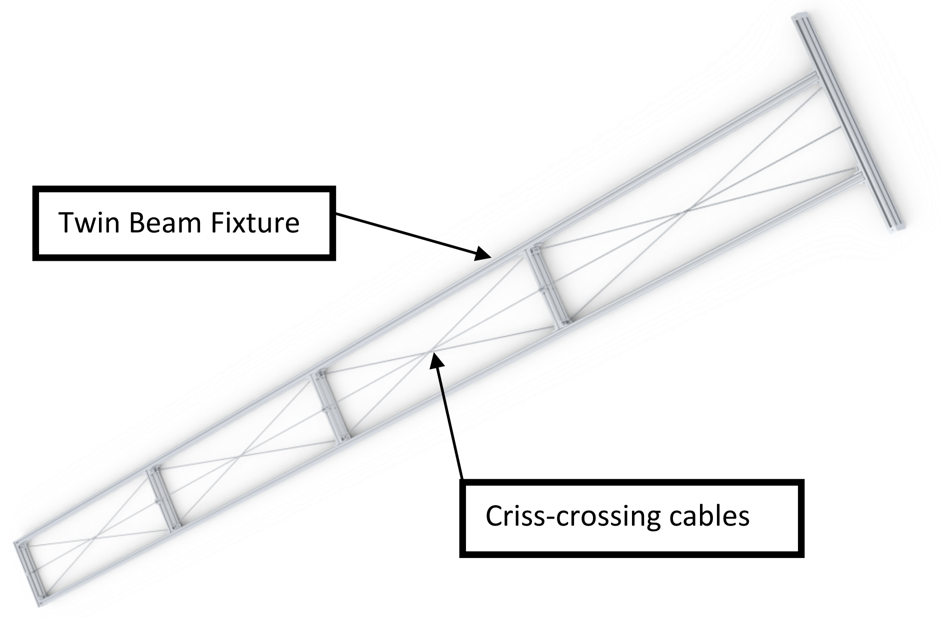


Figure 8: Twin Beam Fixture with Criss-Crossing Cables [4]

The procedure used to balance the blades is as follows:

1. First, the operator needs to choose the fixture that will be used depending on the blade length.
2. Next, the operator will move the scales to the correct positions. The scales must have the same spacing as the pins of the fixture.
3. Once the scales are in the correct position the fixture is placed on the scales.
4. The tare button on each scale is now pressed. This will cause all display a value of zero. Therefore neglecting the weight of the fixture.
5. Next the blade is placed on the fixture. ACS knows where the required location of the mass centre line and therefore can ensure this line is in the center of the fixture. This is done by attaching a cap to the fixture to block the blade in the desired position.

6. The cables run along the bottom of the fixture and can be adjusted to minimize the deflection caused by the weight of the blade. Different amounts of tension are required for each different blade size.
7. Due to the repairs of the blade, the mass centre will have shifted from its original location. In order to change the weight read on the scales, ACS moves small weights located inside the blade. By moving these weights they are able to change the values of the scales until they reach the desired balance point.

The blade will be balanced when:

- For chord-wise balancing: the value displayed on the two root scales is equal,
- For span-wise balancing: the blade manufacturer provides ACS with the value of the span-wise moment. ACS calculates this span-wise moment for the repaired blade and matches it with the required value. In order to calculate the span-wise moment the readings of the tip scales are added and multiplied by the length of the fixture.

The third scale (tip scale) is only used to determine, the final weight of the blade after repair. Due to the aerodynamic nature of helicopter blades, the moment calculations need to be very precise. This is due to the fact the moment of the blade affects the angle of the blade when it is being used. If the angle is different than the other blades, the imbalance will cause the blade to operate differently than the other blades of the helicopter which may affect the operability.

6. Overall Cost and Bill of Materials

The following section outlines a list of all the materials needed to implement the recommended design. The list also includes where each part can be purchased and the total cost of each part. This information can all be found in TABLE I.

TABLE I: BILL OF MATERIALS AND OVERALL COST

Part #	Part Description	Supplier	Quantity needed	Price per unit	Additional Charge	Total Cost
CR8AS2	CABLE SS .250 TYPE 316 1 X 19 LEFT HAND LAY	WAGNER [7]	72 feet	$1.5875 per foot	$25 (re-spool)	$139.30
CRSC8	SCREW SS 3/8-24 X 3/4	WAGNER [7]	24	$1.1875 per part	N/A	$28.50
CRF8	FERRULE SS .250 CABLE 316 CABLE RAILING	WAGNER [7]	24	$1.75 per part	N/A	$42.00
CRAJTE8	ADJUSTABODY SS .250 CABLE W/THRDED EYE TENSIONER W/CRSC8	WAGNER [7]	24	$33.0375 per part	N/A	$792.90
T(15/30)	1530 T-slotted profile aluminum beam	8020 [3]	58	$11.16 per foot	$500* (minor machining)	$1147.28
4304 15S	4 hole inside corner bracket	8020 [3]	16	$4.40 per part	$200* (minor machining)	$270.40
4302 15	2 holes inside corner	8020 [3]	3	$2.95	N/A	$8.85

S	bracket with					
T-nut	Slide-in T-nut	8020 [3]	70	$0.79	N/A	$55.30
FG-60KBM	60kg capacity A&D® - FG-K High Resolution (non-NTEP) Series Bench Scales	H&C Weighing Systems [8]	1**	$488.95 per scale	N/A	$488.95
FG-150KBM	150kg capacity A&D® - FG-K High Resolution (non-NTEP) Series Bench Scales	H&C Weighing Systems [8]	1	$488.95 per scale	N/A	$488.95
					Total Cost	**$3462.43**

*These machining costs are estimates and are expected to be higher than actual costs
**Although the design requires two scales with a 60 kg capacity ACS already has one of the scales being quoted

7. Conclusion

The following design meets all the requirements as outlined by ACS. The final design has the desired minimal flex of less than 0.1 inches as it uses tension cables to remove deflection from the fixture. ACS can now weigh the largest blades due to the increased size of the fixture and higher capacity scales. Unfortunately, due to the need for increased scale capacity some accuracy is lost. The accuracy of the tip end scales drops from 0.002 kg to 0.005 kg and the accuracy of the root end scale drops from 0.005 kg to 0.010 kg. One of the advantages of the new design is it uses parts ACS is already familiar with, no additional operator training will be required. Another advantage is the use of commercially available and easily machined parts, the final design is simple to setup and use.

The final design meets the required of being aesthetically appealing, thanks to the clean and smooth nature of all the parts used in the construction. Finally, the total cost of the design is estimated to be $3500 which is much less than the $10,000 budget imposed on the design.

8. References

[1] L. VanderVegte, (2011, October 20). Current balancing fixture (photograph).

[2] B. Anning (private communication). [2011, September 20].

[3] 80/20 Inc. the Industrial Erector Set. (2003). *80/20 Design Tools*.[Online]. Available:

http://8020.net/Design-Tools-31.asp [2011, October 07].

The reference is the Company's commercial website. This Company designs and manufactures aluminum frames and accessories. The manager of ACS referred the team to the 80/20 inc. website. The website contains SolidWorks drawings of the current beams cross-sectional area. Finding and downloading the required design will give the team the opportunity of saving time while designing the cross section and conducting the FEA simulations on it.

[4] A.Fattal, (2011, November 28). (SolidWorks Drawings).

[5] M.P.Roura, (2011, November 10). ACS Support Structure (photograph).

[6] J.Albo, (2011, September 24). Carbon Fibre Fixture for Short Beams (photograph).

[7] The Wagner Companies. *Hardware and Cable.* [Online]. Available:

http://www.wagnercompanies.com/Hardware_and_Cable.aspx

The Wagner Companies is a manufacturer of standard products for metal fabrications primarily for handrails. This reference was used for quoting the price of cables and cable related attachments.

[8] H&C Weighing Systems (2005). *Affordable Scales and Balances*. [Online]. Available:

http://www.affordablescales.com

The H&C Weighing Systems company is a provider of scale of high capacity and accuracy. The scales ACS is currently using are from this company. This reference was used for quoting the price of the scales.

Appendix A – Design Analysis

This Appendix outlines the process used in the selection of the beams and scales used in the final design.

During the process of designing the structure to support the blades, the best company to purchase the beams from is 80/20 inc. The reason for this is ACS has dealt with 80-20 in the past and trusted the company for their accuracy, price and quick turn-over rate on orders. The team selected a cross-section from 80/20 inc. catalogue [1].

Assumptions

The following assumptions were made for performing analysis on the various design options:

- Each beam cross-section will have different weights and lengths. For analysis the heaviest and longest blade was used (the case which will have the most deflection). If the design can handle this blade, then it will be able to handle the full range of blades.
- The weight of the blade is not going to be perfectly distributed over the whole length of the beam. Usually, the blade is heavier near the rotor than in the tip. For performing the analysis it is assumed the blade weight is a distributed load.
- Due to the force of the helicopter rotor blade being assumed to be a distributed load. The two vertical forces of the tensioned cables will be exactly the same.
- The material is linear elastic so the principle of superposition can be used.
- The material used is isotropic.
- The forces applied to the fixture by the cables which run along the bottom of the fixture can be approximated as point forces. In addition, the center two cables will not exert a vertical force on the design. The center two cables will only ensure the members the cables are attached to will not rotate under the force of the cable.
- The horizontal, criss-crossing cables do not need to be included in the FEA as they will not have a significant effect on the deflection.

Analysis

After designing the fixture in SolidWorks, it was noted the program could not handle the calculations while performing the FEA. The main reason for this problem was because the 80/20 inc. cross-section used in this design was too complex for SolidWorks. In order to solve this issue, an alternative beam with a simpler cross section and the same inertia was designed. The deflection obtained would be the same as the actual deflection. This method was used for all FEA models.

Two designs were reviewed to aid in the selection of the final cross-section:

- The current 'T'-shaped structure used by ACS; and
- A box structure using a 1530 T-Slotted profile.

These profiles are further explained below.

Current 'T'-shaped structure

The first design reviewed was the 'T'-shape. ACS currently uses this structure moment calculations (see Figure 7). This structure uses an 80/20 inc. beam and 1530 T-Slotted Profile. The beam has a width of 1.5 inches and a height of 3.0 inches. The actual cross-section is shown in Figure 9.

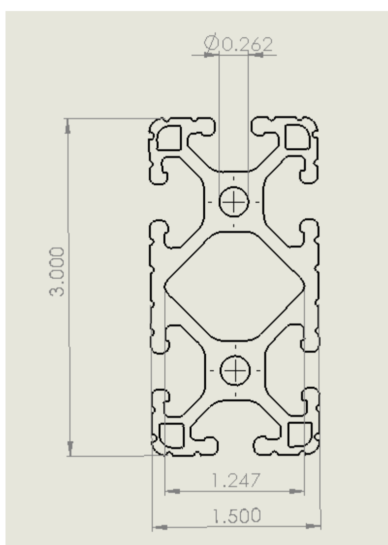


Figure 9: Cross Section of Beam 1530 T-Slotted Profile [2]

In order to design the alternative beam design as described in the beginning of the analysis section, we looked up the moments of inertia of the cross section on 80/20 inc. website [1] was reached. The values are as follows:

$$I_x = 1.8042\text{in}$$
$$I_y = 0.4824\,in$$

In order to simplify the FEA, the team designed an alternative beam with a simpler cross section. With this strategy the beam will have a rectangle cross section and no holes. By assuming the cross section of the beam is rectangular, using the equations of the rectangular inertia moment, the dimensions of the cross section here determined as follows:

$$I_x = \frac{1}{12} \cdot a \cdot b^3 = 1.8042\text{in}$$
$$I_y = \frac{1}{12} \cdot a^3 \cdot b = 0.4824\,in$$

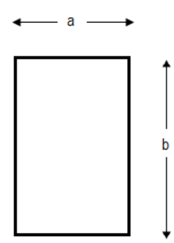


Figure 10: Cross Section of Alternative Beam [3]

After solving this system, the values obtained are: a =1.31534 inches and b = 2.54376 inches. The forces applied on the beam are the following:

- Three fixed parts: one in the root and two in the tip.
- Distributed load of the blade weight: 120 kg x 10 m/s^2= 1,200N
- Distributed load of the fixture: 25 kg x 10m/s^2 = 250 N

When the analysis was performed the solution was converging after four loops. The deflection obtained with this design is shown in Figure 11. The deflection scale in Figure 11 is 3:1.

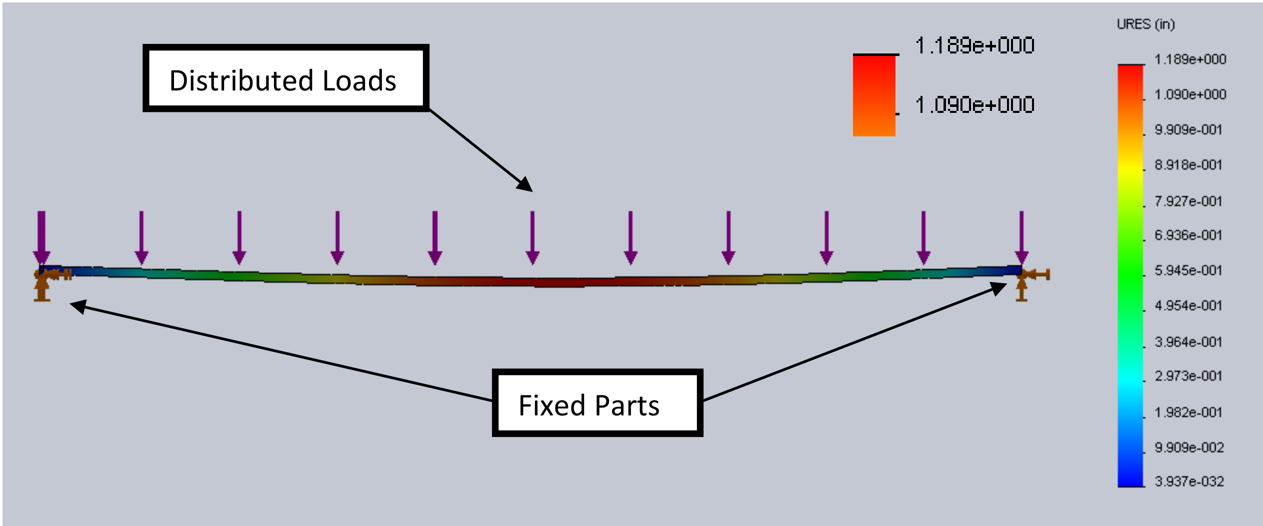


Figure 11: Deflection Plot of the First Design

The maximum deflection obtained is in the middle point of the beam. The value obtained with this design is 1.189 inches, however the maximum value of deflection ACS accepts is 0.1 inches. Since the deflection obtained in the first design is larger than what ACS considers the maximum allowable deflection, the team must improve the design to make the deflection lower.

Weight was an important factor to consider when calculating the deflection, therefore it was important highlighting the weight of the alternative beam and the original beam are going to be different. Furthermore, 80/20 inc. cross section is optimized to be as light as possible, so the alternative beam will be slightly heavier. This means the value determined for the deflection will be an approximate value and the actual deflection will be less than the determined value.

1530 Box Structure

The second design was a structure with two long parallel beams connected by short beams. The design included the same cable which was used in the 'T'-shape model, the current design, to reduce the deflection. Parallel beams were used to increase the area on which the blades can be placed.

The forces applied in this design are:

- Three fixed parts: one in the root and two in the tip.
- Distributed load of the beam: 120 kg x 10 m/s^2 =1200N.
- Distributed load of the fixture: 55kg x10 m/s^2 = 550N.
- Vertical forces of the cables: 220N.

When the analysis was performed the solution was converging after four loops. The deflection obtained with this design is shown in Figure 12. In this case as there has minimal no deflection, the deflection scale used is 1:1.

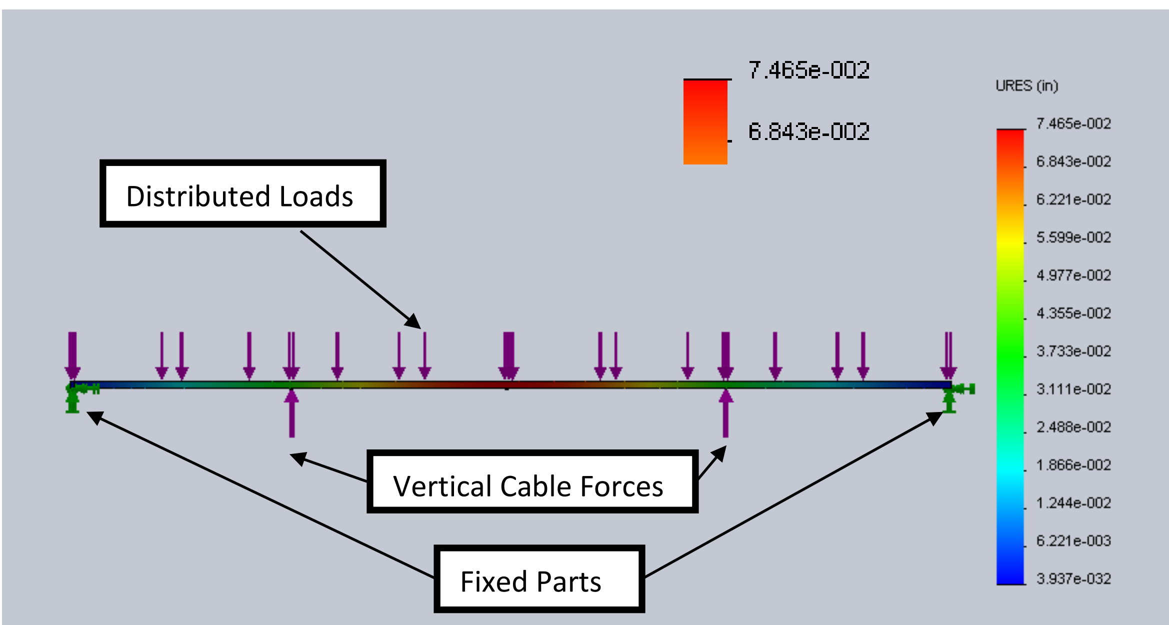


Figure 12: Deflection Plot of the Second Design 1530 Box Structure

The maximum deflection obtained in this design was less than 0.1 inches. The vertical forces of the cables were determined experimentally by trial and error until the deflection reached the desired value. Once the vertical forces of the cable were found, the tension of the cable is shown in Figure 13.

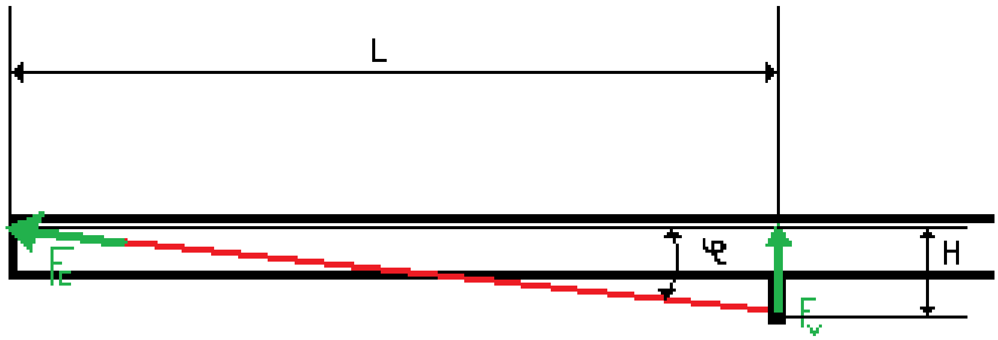


Figure 13: Cable Angle of the Second Design [4]

The angle of the cable is the following:

$$\varphi = arctg\left(\frac{H}{L}\right) = arctg\left(\frac{3}{72}\right) = 2.3859^{\circ}$$

The cable tension is then calculated as:

$$F_{TENSION\ CABLE} \equiv F_C = \frac{F_V}{\sin(\varphi)} = \frac{200N}{\sin(2.3859)} = 4{,}804.25N$$

The cable used has a diameter of 0.5 inches and a maximum tensile strength of 36,000 N [5]. The cable can handle the tension required to remove the deflection. By using cables ACS would be able to reduce all the deflection by increasing the tension of the cable.

References

[1] 80/20 Inc. the Industrial Erector Set. (2003). *80/20 Design Tools*.[Online]. Available:

http://8020.net/Design-Tools-31.asp [2011, October 07].

The reference is the Company's commercial website. This Company designs and manufactures aluminum frames and accessories. The manager of ACS referred the team to the 80/20 inc. website. The website contains SolidWorks drawings of the current beams cross-sectional area. Finding and downloading the required design will give the team the opportunity of saving time while designing the cross section and conducting the FEA simulations on it.

[2] A.Fattal, (2011, November 14). (SolidWorks Drawings).

[3] M.P.Roura (2011, October 30). Cross Section of Alternative Beam (photograph).

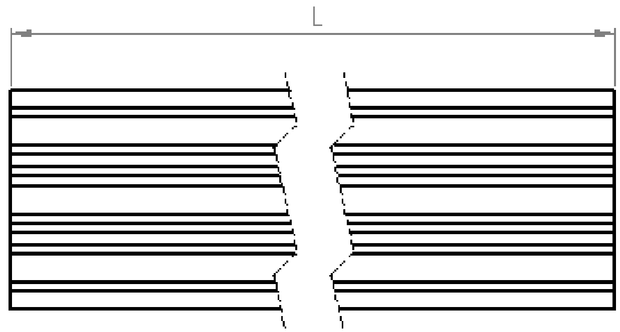
[4] M.P.Roura (2011, November 28) Cable Angle of the Second Design (drawing).

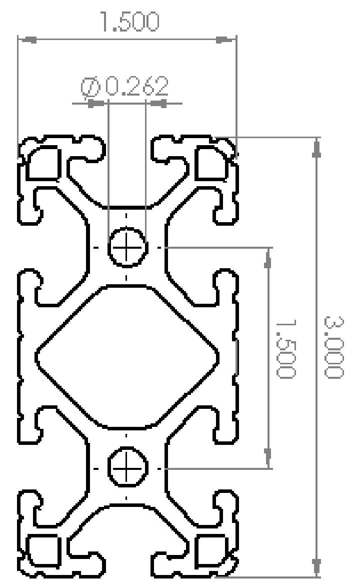
[5] The Wagner Companies. *Hardware and Cable.*[Online]. Available:

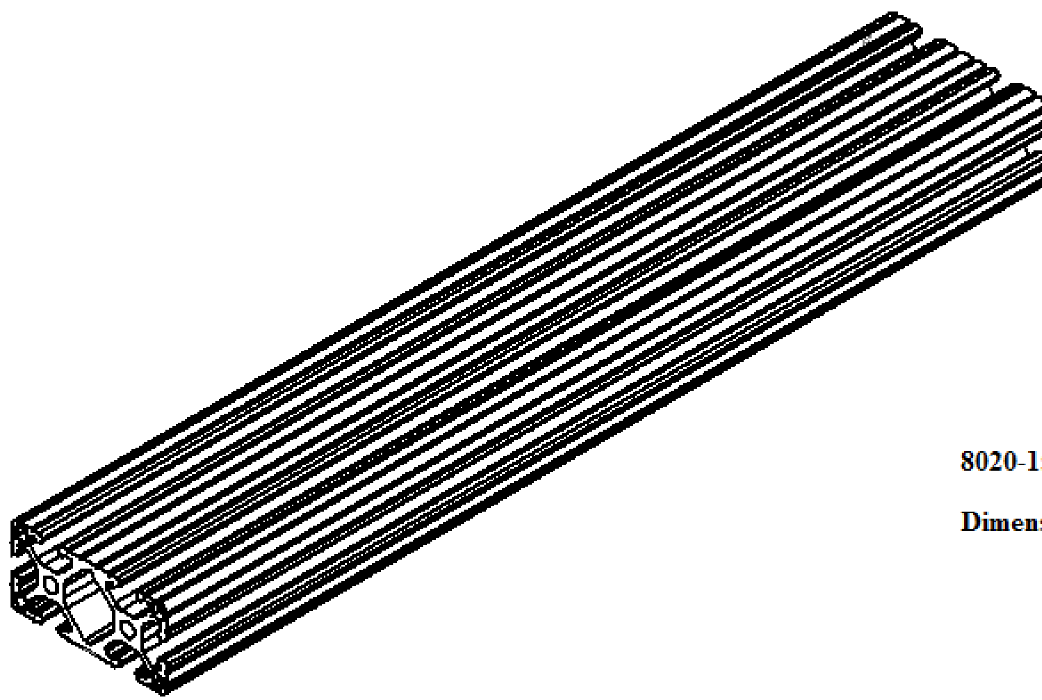
http://www.wagnercompanies.com/Hardware_and_Cable.aspx.

The Wagner Companies is a manufacturer of standard products for metal fabrications primarily for handrails. This reference was used for quoting the price of cables and cable related attachments.

Appendix B – Part Drawings

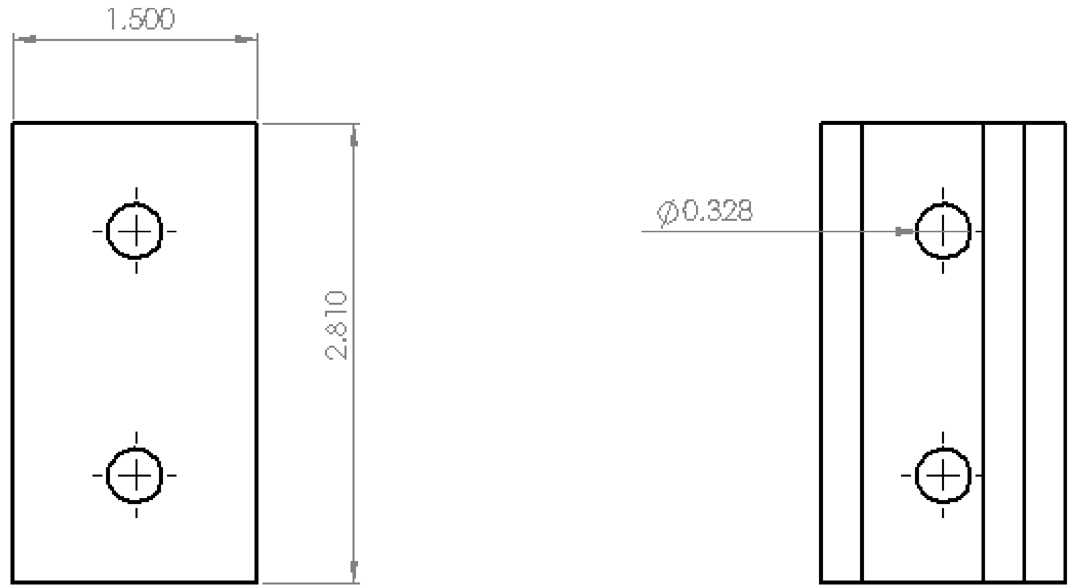


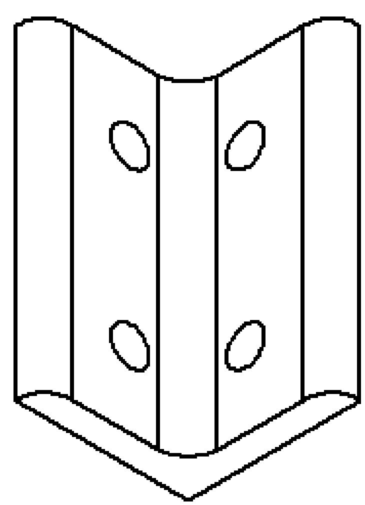




8020-1530-lite

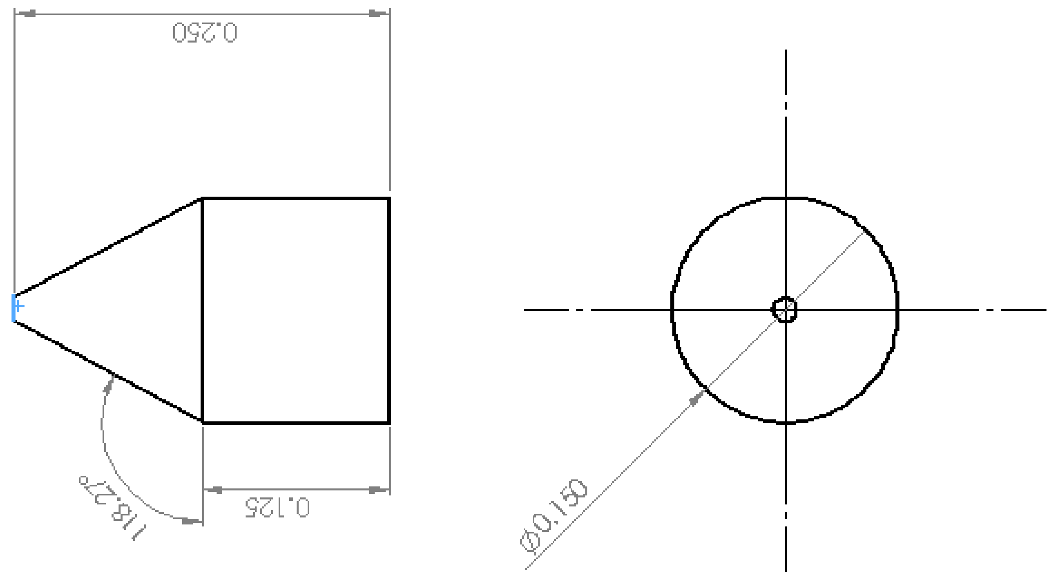
Dimensions in Inches

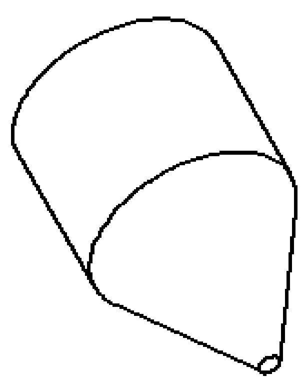




Bracket

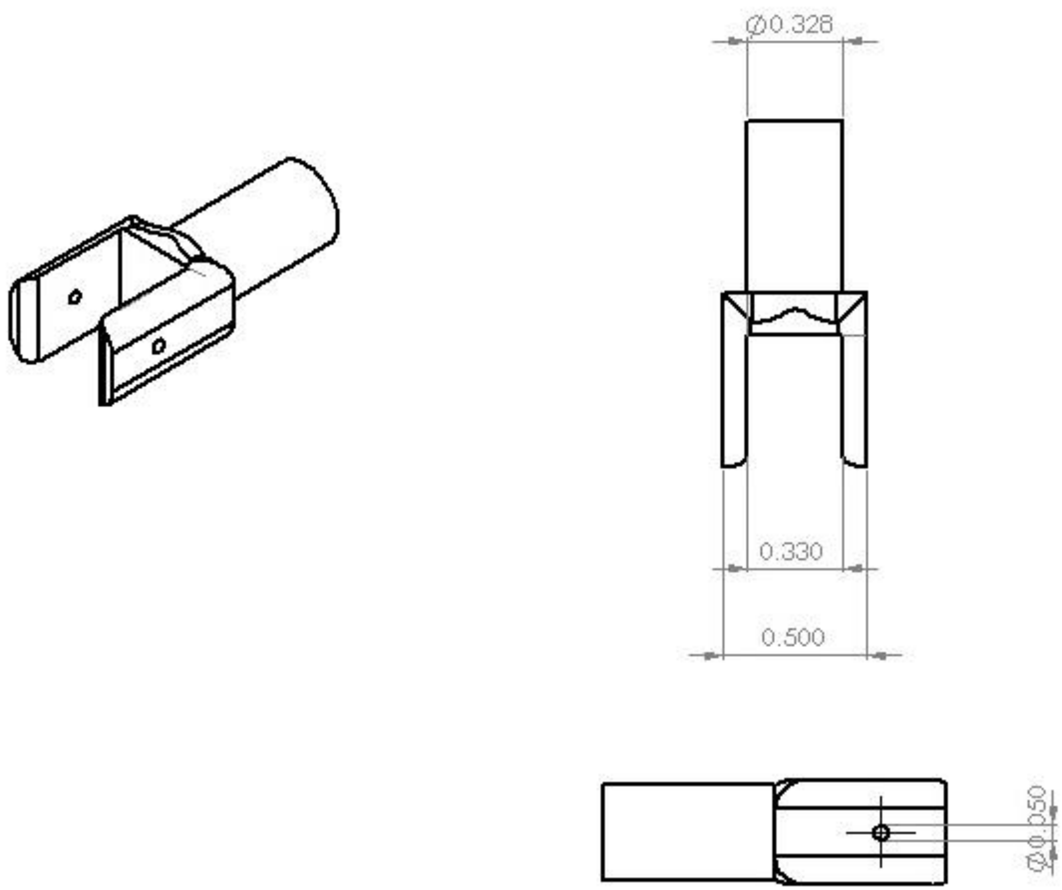
Dimesions in Inches



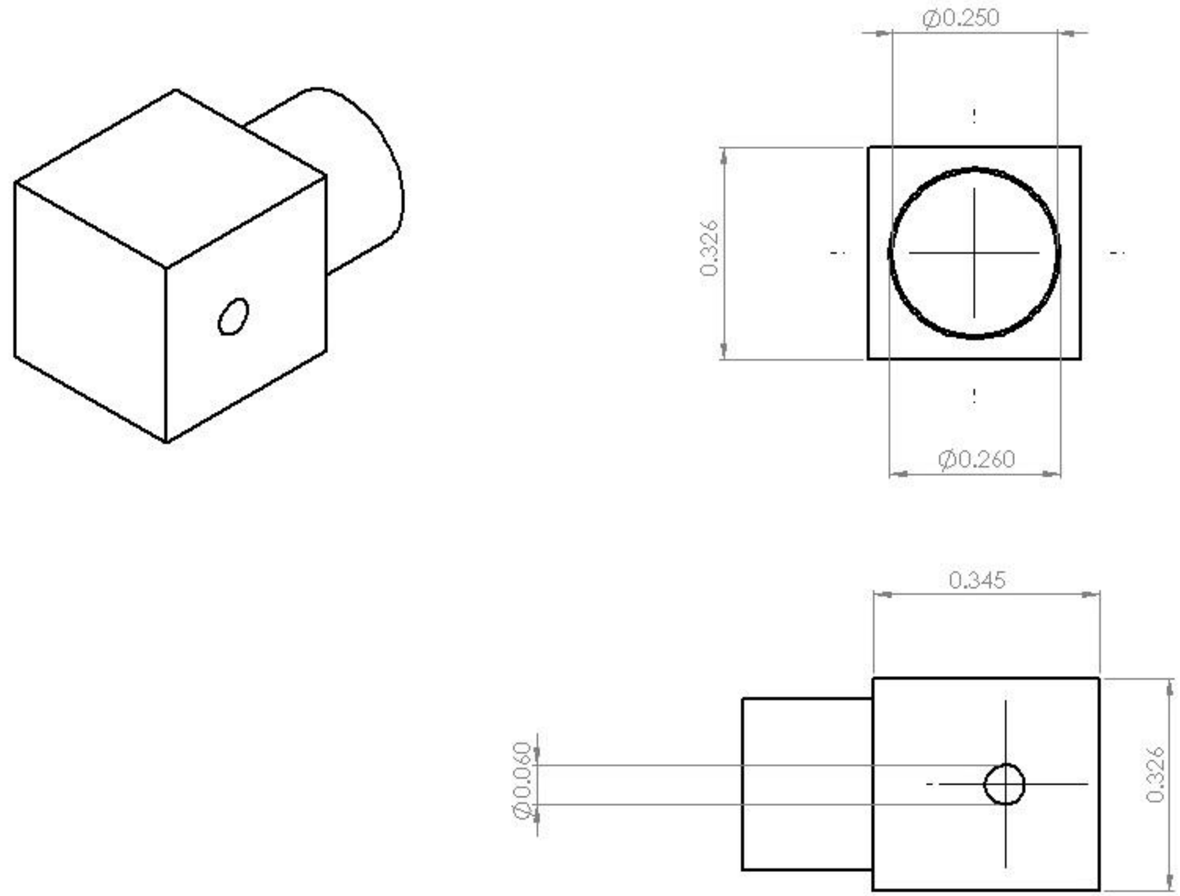


Pin

Dimensions in Inches



Cable Connector
Dimension in inches



Cable connector(Second Part)
Dimensions in inches

Appendix C – Concepts considered

This Appendix outlines some of the concepts which were considered at the beginning of the project.

When trying to solve the problems the company is currently dealing with, the team came up with three possible solutions.

- The fixture is currently being used has a hollow center, so the first idea the team had was to fill the center using a titanium rod. This design, although it meant increasing the weight, it will also decrease the deflection, because titanium is much stiffer than aluminum.
- The second idea the team came up with was to replace the entire fixture with carbon fibre. The following section on this concept shows it to be expensive and difficult to machine.
- The final idea was to redesign the current structure and add more aluminum beams to decrease the bending.

Fill the Hollow

The first idea came to mind during one of the brainstorming sessions was to reinforce the current structure with a stiffer material that could help decrease the deflection of the current structure. The reinforcement was going to be applied is to fill the hollow space in the middle beam of the structure with a stiffer material than aluminum, the material that is currently used in the structure. The current design used by ACS was built from a customized beam cross-section which was made by 80/20 inc. [1], as shown in Figure 9.

The SolidWorks drawing file of the beam was downloaded from the manufacturer website. The main concern by looking at hollow filling is the weight. The maximum weight that is allowed to be added to structure was approximately 7 Kg. The first step in investigating was to research up a low density material that has a higher rigidity than that of the Aluminum. The material that was found to be suitable for the case was 6-4 Titanium. The 6-4 Titanium material has a low density of 4428.78 kg/m^3 and a higher modulus of elasticity than that of aluminum, therefore resulted in minimal added total weight to the beam of 5.509 kg over an 18 foot length. In the early stages investigating had to be designed filling beam and conducting some Finite Element Analysis using SolidWorks software. This was understood of how ridged the 6-4 Titanium filling beam was by subjecting it to 355.9 N load or 80 lb as 70% of the total weight of a blade weight. The deflection test consisted of fixing one end of the rod and the bottom of the other end of the rod. The 355.9 N was assumed to be uniform along the beam for the sake of examining the filling beam as it is subjected to this specific load. Figure 14and Figure 15 show the two fixed ends of the beam.

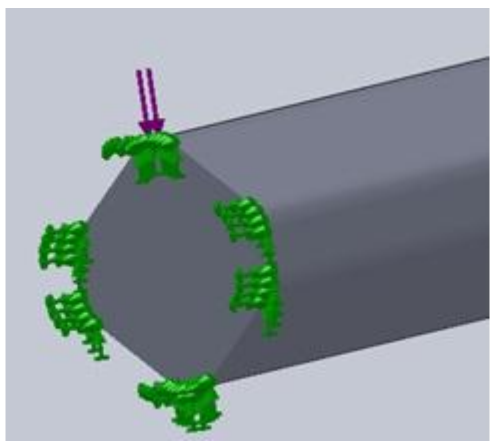


Figure 14: Fixed end of the rod [2]

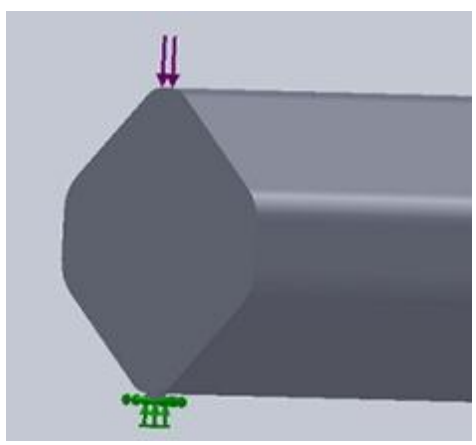


Figure 15: End that rests on the scale [2]

The resulting deflection, as seen in Figure 16 shows that the maximum deflection in the middle of the beam, the red coloured portion was 2.263 inches. The deflection in the designed beam is relatively high at 2.263 inches and considering that the load is applied only on the designed beam, a more need detailed analysis had to be completed to examine the deflection of beam reinforcement structure.

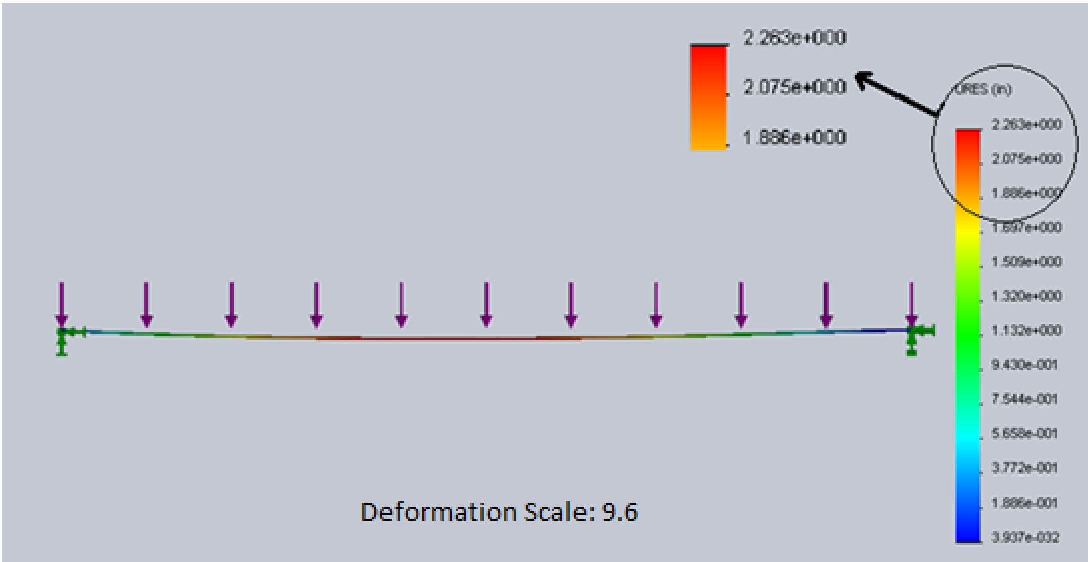


Figure 16: Deflection of titanium rod in inches [2]

After research and consultation with Mr. Anning at ACS about 6-4 Titanium manufacturing and extrusion, it was determined to be very costly and beyond the budget of the Company for this specific project. As a result this concept was not accepted and had to be eliminated.

Carbon Fiber Beam

When considering a lightweight alternative to the currently used aluminum beam, carbon fiber was considered as the best material option. The scoring matrix seemed to confirm carbon fiber as the best option. Therefore, additional research and calculations were performed to determine if carbon fiber was actually the best solution.

After completing some research on a carbon fiber specialist company, Dragon Plate [3], the team decided on three basic points to be examined. These points were maximum deflection, cost, and weight of the structure.

In order to perform the calculations the following assumptions were made:

- The weight of the blade was equally distributed over the beam;
- The mass center was in the middle of the beam;
- There are no junctions; and
- The beam was made of one piece.

Calculations were performed using the largest beam available on the website. The website provided the team with the Young modulus (E=234.42 GPa) and the density (ρ= 711.75 kg/m^3) of the beam [4]. The cross-section dimensions of the beam are indicated in Figure 17.

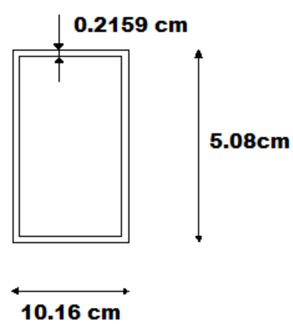


Figure 17: Cross-section of a carbon fibre beam [2]

The inertia of this beam is calculated as follows:

$$I = \frac{1}{12} b \cdot h^3 = \frac{1}{12}(5.08 \cdot 10.16^3 - (5.08 - 2 \cdot 0.2159) \cdot (10.16 - 2 \cdot 0.2159)^3 = 8.736 \cdot 10^{-7}\, m^4$$

Using this inertia the deflection can be calculated as follows:

$$\delta_{\max} = \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I} \quad [4] \tag{1}$$

The maximum deflection obtained is 1.5 inches. The weight of the structure is 6.804 kg, and the price about $2,000. This deflection is not acceptable as it does not meet the required value of less than 0.1 inches. Although the price was below the budget, the deflection is too high. The team decided to recalculate the critical values with an I-beam. The dimensions the beam would need in order to achieve the required deflection has a moment of inertia of 1.474·10^{-6} m^{4}or higher. After researching, it was discovered there was no carbon fiber beams available with a sufficient moment of inertia and as such, a custom beam would have to be made. Further Research showed that making a custom beam would be expensive and as a result it was concluded that carbon fiber was not a valid solution.

References

[1] 80/20 Inc. the Industrial Erector Set. (2003). *80/20 Design Tools*.[Online]. Available:

http://8020.net/Design-Tools-31.asp [2011, October 07].

The reference is the Company's commercial website. This Company designs and manufactures aluminum frames and accessories. The manager of ACS referred the team to the 80/20 inc. website. The website contains SolidWorks drawings of the current beams cross-sectional area. Finding and downloading the required design will give the team the opportunity of saving time while designing the cross section and conducting the FEA simulations on it.

[2] M.P.Roura, (2011, November 1). (SolidWorks Drawings).

[3] Division of Allred & Associates Inc. (2011, January). *Dragon Plate* [Online]. Available:

www.dragonplate.com [October 10, 2011].

This website shows all kinds of shapes and sizes of carbon fibre beams and rods. It is useful for the project because it provides all the necessary data of carbon fibre such as Young's modulus and density.

[4] F.P.Beer, E.R.Johnston, J.T.DeWolf and D.F.Mazurek. "Deflection in beams," in *Mechanics of Materials*. New York, 2006, pp 529-605.

This chapter explains how to calculate the deflections in beams that are differently supported. It shows how to calculate a beam with an equally distributed force with two supports, the case we are dealing in our project.

Appendix D – Selection Criteria

Each of the concepts the team considered had their own advantages and disadvantages. The team put together two matrices that were used to examine what the best design options to pursue would be. The first table shows the screening matrices of the four options. Weighting values are based on initial considerations assuming no change of scales will occur in the final design.

TABLE II: SCREENING AND SCORING MATRIX FOR REDESIGN OF THE SUPPORT STRUCTURE

	Design Option			
Selection Criteria (Weight)	Fill Hollow	Redesign Cable	Carbon Fiber	Redesign Structure
Weight (5)	0	+	+	0
Ease of Manufacture (4)	-	+	-	+
Ease of Set-up (3)	0	-	+	+
Ease of Use (3)	+	0	+	+
Aesthetics (4)	+	-	+	-
Sophistication (2)	0	+	+	-
Sum +	2	3	5	3
Sum -	1	2	1	2
Sum 0	3	0	0	1
Net Score	1	1	4	1
Rank	2	2	1	2
Continue?	Yes	Yes	Yes	Yes
Total Weighted Score	3	4	13	4
Rank	4	2	1	2
Continue?	Yes	Yes	Yes	Yes

The follow matrix compares the use of load cells and scales for increasing the maximum weighing capacity. From the results acquired from this it was decided to continue looking into each of the options.

TABLEIII: SCREENING AND SCORING MATRIX FOR SCALES VS. LOAD CELLS

	Design Options	
Selection Criteria (Weight)	Scales	Load Cells
Ease of Use (3)	+	-
Accuracy (5)	0	+
Ease of Manufacture (3)	+	-
Ease of Set-up (4)	+	+
Ease of Reading (2)	+	0
Maximum Capacity (5)	0	+
Aesthetics (4)	0	0
Sophistication (2)	0	+
Sum +	4	4
Sum -	0	2
Sum 0	4	2
Net Score	4	2
Rank	1	2
Continue?	Yes	Yes
Total Weighted Score	12	10
Rank	1	2
Continue?	Yes	Yes