University of Southern Queensland

Faculty of Engineering and Surveying

THE ANALYSIS AND REDESIGN OF THE SPRAYCAM SPRAYER TO INCORPORATE FIBRE COMPOSITE PULTRUSIONS

A dissertation submitted by

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Abstract

The University of Southern Queensland along with other centre's around the world are at the leading edge of fibre composite research. Many studies have been conducted into the properties and applications of fibre composite and it is the purpose of the research project to apply these findings to a real world design problem.

This project aims to analyse and redesign the current SprayCam rig. SprayCam is a selective weed spot spraying system used within the agricultural industry. This technology uses a series of cameras operating in the visual spectrum to identify the weeds within fallowed paddocks. These cameras operate solenoids which subsequently spray only the weeds and not the entire field which occurs during conventional spraying techniques. The SprayCam rig is the mechanism that supports the cameras and the other technology and allows them to operate safely and efficiently.

The current design is large and heavy for both its size and also its intended use as a selective weed spot sprayer. It is the belief that the current design overuses materials leading to an over engineered product which also increases manufacturing cost. This project contains two essential facets, the first being the analysis of the current rig design to determine the structural integrity while the second is to investigate the use of fibre composite pultrusions as a means of redesigning the spray rig wing.

In order to complete the analysis of the current SprayCam rig it was first necessary to re-produce solid models of the current wing design to create an accurate basis for finite element analysis (FEA). Considerable research was directed into the appropriate loading constraints which have been identified and discussed in full within the report to ensure the validity of the results. A thorough finite element analysis was conducted on current spray rig design which found that the original wing was indeed over engineered for its use as an agricultural sprayer. The loads which the rig could withstand were much greater than those which it will be subjected to within the field. This result shows an inefficiency of the use of materials within the wing design leading to increased manufacturing cost. Therefore a more appropriate design needs to be developed if the product is going to be competitive in the current market.

In redesigning the spray rig, investigation of all possible avenues would have required significant time and effort. With the University of Southern Queensland at the leading edge of fibre composite research, it was agreed that fibre composite pultrusions would be investigated as a means of both significantly reducing the weight of the spray rig and overcoming existing design flaws. There is currently a great deal of research conducted into the properties of fibre composite pultrusions and it is the purpose of this project to apply this research to a design situation.

Many issues including costing and joining techniques needed to be overcome so that a possible design could be completed. Through use of finite element analysis it has been shown that fibre composite pultrusions are a feasible alternative to the original steel design. Significant weight savings have been shown to be a possibility with only a minimal increase in cost.

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I would also like to thank my family and friends for their support over the past year as it is very much appreciated.

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Nomenclature

σ_B	Bending Stress	Pa
δ	Deflection	mm
R_e	Reynolds Number	-

Glossary

2-D: Two Dimensional.

3-D: Three Dimensional.

ANSYS: ANSYS is a computer software package which is able to solve systems using finite element analsysis (see FEA).

Drag Coefficient: Is the ration of the drag on a body moving through a fluid to the product of the velocity and surface are of that body

FC: Fibre Composites

FEA: Finite Element Analysis: An approximation method for studying continuous physical system which is broken into discrete elements interconnected at discrete node points.

Minimum Tillage: The farming practice where only the minimum amount of soil is cultivated <70%

Peel strength: A materials ability to resist forces that can pull it apart by separating a flexible surface from a rigid surface

RHS: Rectangular Hollow Section

USQ: The University of Southern Queensland

Chapter 1 - Introduction

1.1 Outline

This project aims to complete two major tasks. The first is to analyse the current SprayCam Spray Rig with the use of Finite Element Analysis (FEA) to determine its suitability as a boom for its purpose of selective weed spot spraying. The second aim of the project is to provide a suitable solution for the redesign of the SprayCam Spray Rig to reduce weight. This will be done by investigating novel solutions for the use of pultruded fibre composites within the design. After extensive research a proposed design was developed and subsequently analysed to an acceptable level i.e. for weight, strength, feasibility, rigidity etc.

1.2 Introduction

Fibre composite pultrusions are lightweight, high strength, rigid materials that have many advantages over conventional engineering materials such as steel. Vast research has been conducted into the properties of fibre composite pultrusions and it is for this reason that this project will seek to apply this research to an engineering problem such as an alternative design for the SprayCam Spray Rig.

SprayCam was developed by Rees Equipment Pty Ltd which is a market innovator in selective broad acre weed spot spraying. Over the last 15 years spot spraying technology has become very useful in the agriculture industry with general trends toward minimum tillage and in-turn more intensive spraying applications. This spot spraying system utilises light in the visual spectrum to identify green weeds in fallowed land. These cameras identify a green weed and trigger solenoids which open nozzles to only apply herbicide to the weed. This means that only a small area of the paddock is actually sprayed allowing the cost to be dramatically reduced, enabling farmers to either reduce the total amount applied or use higher concentrations of herbicide than previously possibly with only minimal increase in cost. With more control over application rate and the total amount applied, the ability to eradicate chemically resistant weeds is greatly improved at significantly reduced cost.

The only drawback of the Rees SprayCam system is that the cameras need to be shielded from sunlight, in particular from infrared light which can 'blind' the cameras. As a non-shielded spraying system, SprayCam system is marketed as night time only camera and solenoid control system that can be mounted on to farmers existing booms. The existing rig design for daytime spraying creates an artificial darkness by the use of hoods over the spray rig. The requirement for hoods adds a lot of additional weight to this design when compared to other spraying systems currently available on the market today.

1.3 Problem Statement

It is the view of the chief engineer at Rees Equipment Pty Ltd that the current rig or boom system is overdesigned. This view is based on its weight when compared to other sprayers of the same size. It is the purpose of this project to explore the possibility of using fibre composite pultrusions to create a structure which is much lighter than the original design. While ensuring no physical characteristics are changed that could affect the efficiency of the machine and its capability of completing the same task as it was originally designed. If the weight of the wing structures can be reduced, further work can then be done on redesigning the other sections of the sprayer until a refined cost and weight effective solution is found.

1.4 Objectives

This project aims at investigating the use of fibre composite materials in the redesign of the Rees sprayer to reduce weight. In order to satisfactorily complete the project, the following objectives needed to be completed:

- Convert the current 2D AutoCAD Drawings into a 3D model (using SolidWorks)

- Conduct an initial finite element analysis (FEA) on the current wing design of the Rees Spray Rig. This includes detailed calculation of loads that act upon the machine during operation. This will also validate the hypothesis that the original structure is overdesigned
- Investigate and analyse the wing structure with the use of fibre composite sections as the main wing frame as an option to significantly reduce the weight without sacrificing the operation of the machine.
- Investigate different methods of joining each composite together and also other accessories currently attached to the wing of the sprayer.

1.5 Summary

The following report aims to capture the work done in redesign of the SprayCam Spray Rig to reduce weight by the use of fibre composite sections. The following chapter will introduce the relevant background information required to understand the importance of the SprayCam Sprayer in the agricultural industry. This chapter will investigate the vast issues associated with the spot sprayers use in the agricultural industry and how the use of such technology is changing farming practices.

In Chapter 3, a literature review provides information used for the basis of the technical aspects of the project. It will present the investigations conducted into the use of fibre composites including properties and advantages of the material along with how some of the disadvantages can be overcome. One such disadvantage which needed to be overcome is that of the joining techniques used to join pultrusions. This chapter will also investigate suitable loading cases for the analysis to be used on such agricultural equipment along with appropriate techniques to conduct an accurate finite element analysis.

The method of obtaining the most accurate results for the tasks to be completed within the project will be outlined within Chapter 4. This methodology chapter will not only investigate the tasks which need to be completed to reach the objectives of the project but also the best means of obtaining these results.

Chapter 5 is divided into two main sections. The first section will investigate the design analysis of the original steel sprayer, while the second will examine the proposed composite wing design. Within each section the findings of the finite element analysis and other relevant technical details will be presented.

Chapter 6 will discuss the results of the design analysis in further details and explain what the results mean for the outcome of the project.

Chapter 7 will conclude the report; it will outline the findings of the report and will include any future work which will be needed to be completed to ensure an optimum design is developed as a competitive alternative to not only the current SprayCam Sprayer but also other selective spot sprayers in the current market.

Chapter 2 – Background

2.1 Introduction

This chapter aims to provide awareness of issues surrounding the project. It serves to establish information about the importance of the SprayCam Spot Sprayer in the agricultural industry. Non-technical information is presented in this section so that readers can gain an appropriate knowledge of the topics that surround the project. Topics that will be covered include minimum tillage practices and how its adoption leads to the increase in application of herbicides to agricultural land. The history of the SprayCam spot spraying system will also be outlined so that the reader has all the relevant information required to understand the issues surrounding the products.

2.2 SprayCam History

SprayCam is one of the original selective weed spot sprayers in the agricultural industry. SprayCam is manufactured by Rees Equipment Pty Ltd, named after its founder Mr James Rees and his son and product developer Mr Steven Rees. The technology of selective weed spot sprayers became popular after the adoption of large scale minimum tillage operations throughout Australia. Minimum tillage along with the benefits of selective weed spot sprayers will be investigated in the following sections. However, briefly the SprayCam system utilizes the visual spectrum to identify the green weeds against the colour of the soil and the stubble. Once a desired target has been identified through various algorithms, an electrical current is sent to a solenoid controlled nozzle which triggers over the target applying chemical the identified weed. Due to the system using the visual spectrum it is very sensitive to natural light from the sun, therefore the cameras are only able to be used during night hours unless the SprayCam Rig with its hood system is used. SprayCam utilizes large overhanging hoods which restrict enough light for the camera system to be used during the daylight. With the reduced availability of analogue componentry the technology within the cameras was redeveloped to a fully digital system. This has reduced the cost of the system and is planned to assist in maintaining a competitive advantage within the marketplace.

Over the past year considerable money and effort has been injected into the company to undertake the redevelopment of the technology within SprayCam to bring it into the 21st century and allow it to become competitive with others within the market. The current system is still not available to operate during the day however a more refined design has been achieved which is extremely effective at identifying weeds within the field if darkness is achieved. Other competitors find it difficult to identify problem weeds such as fleabane due to its small, matt coloured leaves. However this does not appear to be an issue in the redesigned SprayCam system as it is able to identify such problem weeds.

The SprayCam camera system which identifies and sprays the weeds is currently being marketed as a night time only spraying system that can be added to any spraying system a farmer may use. It is the view of the company at the present time to then produce a well-rounded package, which includes a spray rig that allows the cameras to work at all times of the night and day.

The current spray rig that is used for testing operations was built and designed in 2003. It is currently a one-off machine as the development program was temporarily abandoned as digital technology advanced. Now with the redevelopment of the camera system completed, the requirement for an improved spray rig has become a priority. The current machine is very heavy in comparison to other systems of similar size and it is therefore the view of the Directors of the company that a lightweight, cost effective solution be developed to increase the popularity of the system in the marketplace.

2.3 Minimum tillage

According to the Agricultural Machinery Study Book 2011, over the past years the agricultural industry has moved towards more sustainable practices to improve both the environment and profits. One of the main shifts has been towards zero or minimum tillage practices. This involves only minimum disturbance of the soil at planting time. It is also referred to as conservative tillage meaning that only minimal ground disturbance occurs (usually 70% of the surface is left untouched). This leaves the undisturbed soil and stubble from previous crops remaining on top of the ground dramatically reducing moisture loss, erosion and loss of soil structure.

In conventional farming practices, the land could be tilled 3-4 times to control weeds and prepare the seed bed. Each time the soil is tilled, up to 25mm of valuable moisture is lost. For farmers in marginal rainfall areas this can become a major problem for the following season’s crop. Whereas with the adoption of minimum till farming the moisture is retained within the ground by the mulching affect that the previous season’s stubble produces. This retention of organic matter also helps to improve the soil. Organic matter is a fundamental building block in the soil structure and without it the soil will begin to degrade. Organisms within the soil also feed on this matter and help to aerate and improve the soil, all leading to increased productivity for the farmer.

The increasing cost of fuel is a major contributing factor for farmers changing to conservative farming. The cost of tilling the soil 3-4 times becomes very expensive when looking at Table 1.

Average Fuel Consumption Rates (Diesel) for Agricultural Operations (adapted from AGR2302 lecture slides)	
Activity	**Fuel Usage**
Ploughing	18 l/ha
Cultivating	6 l/ha
Discing	12 l/ha
Rolling	4 l/ha
Power Harrowing	8 l/ha
Light Harrowing	4 l/ha
Spraying	3 l/ha

Table 1 Average fuel consumption for agricultural applications

Source McChesney (1981) & Bone *et al* (1996) cited in Chen AGR2302 (2011)

The reduction in moisture levels, increase of fuel prices and a desire to become more environmentally friendly all became major problems for farmers and hence the move towards the adoption of minimum tillage farming. Since the conventional means of tillage to control weeds is no longer used in minimum tillage operations, farmers have turned to chemicals to control this problem. This has led to an increase in chemical applications applied to each paddock to control weeds. This can become rather costly as the entire paddock needs to be sprayed with herbicides.

The cost related to spraying large areas has become so high that farmers have investigated different options to offset this input cost. One option is to only apply a rate of chemical they feel will adequately perform the required task. Since only the minimum amount of chemical is applied some problem weeds may continue to survive and may require additional applications of herbicide. This can lead to some weeds building a resistance to the applied chemicals. Therefore it is important that the correct amount of herbicide is applied to ensure that susceptible weeds are not able to become resistant to common chemicals.

With the adoption of minimum tillage operations and the need for increased passes of the sprayer along with decreased tillage operations, farmers have recognised the need to control where the machinery drives within the paddock (AGR2302 2011). The agricultural machinery study book (2011) also outlined that research has found that up to 80% of soil compaction occurs on the first pass. If heavy machines such as tractors pass over the entire field then high levels of compaction occurs to large areas of the cultivated land. It is therefore extremely important that only the minimum amount of passes occur over a field to ensure the maximum return possible of the remaining area. Some of the advantages associated with these practices include (Lecture Notes AGR2302, 2011):

- Crop yield increases especially in dry seasons
- Decreased input cost
- Preserves soil structure

To successfully control traffic, a quality GPS auto pilot is required to ensure that every pass exactly follows the previous. Initial setup costs are quite high for these system and to achieve 2cm repeatability accuracy the cost in 2010 is approximately $28 000-$30 000 per machine (Vanderfields 2011). However for broadacre operations such accuracy is not required and therefore cost can be reduced. For example 30cm accuracy can be obtained for $15 000 which for many broadacre applications such as spraying, will be sufficient. It is estimated that across Australia at least one million hectares are under controlled traffic saving farmers about $20 a hectare in input costs and improving yields by about one tonne per hectare (AGR2302 2011).

Figure 1 Control Traffic (Source AGR2302 lecture notes, 2011)

2.4 Use of Spot Sprayers

Spot sprayers are the name given to chemical applicators that only apply chemical to a specific area. These weed detecting sprayers provide a cost effective solution to the conventional methods of applying chemical across the entire paddock. Each nozzle is electrically activated over the weed ensuring that only small areas are sprayed, in some cases farmers report using 80% less chemical than conventional methods of broad acre spraying (Crop Optics 2008). In conventional spraying techniques the likelihood of some weeds gaining a resistance to herbicide increases as outlined in the previous section. This is caused by repetitive but limited application of chemicals to a field. Research conducted by the DPI in Northern NSW has shown that the average weed cover in fallow paddocks is as low as 20% of the paddock area meaning that often 80% of the herbicide is applied to bare soil and ultimately wasted. This practice, when used for broadacre operations is inefficient, expensive and environmentally unsustainable (CropOptics 2008). Alternatively, with the use of spot sprayers this wastage can be dramatically reduced leading to major savings for farmers.

To gain an understanding of the current chemical usages which are used during conventional spraying techniques Mr Jason Redgewell, a farmer located at Talwood

(Southern Queensland), was interviewed to give some idea about the application rates which farmers are using. The most common chemical that is used for the control of weeds within the fallowed fields is Glyphosate which is used as a knock down herbicide of a wide range of annual and perennial weeds found across Australia. The second chemical extensively used is Ester (a 2-4-D based chemical). On average, he sprays 25 000 - 30 000 hectares of fallowed land every year with the use of Glyphosate and Ester. "As a guide we would budget for 2 Glyphosate plus Ester application and 1 Glyphosate only application," Mr Redgwell explains. In today's market Glyphosate sells for around \$3.30/L, down dramatically from \$7.50 in November 2007 (A Gidley-Baird, 2008) while Ester sells for around \$8.80/L.

Mr. Redgwell explains that the standard rate for the Talwood region of Southern Queensland is 1.4L/ha of Glyphosate and 600ml of Ester, while the Glophosate-only spray is a little heavier at about 1.8L/ha. He also explains that a wetting agent is also used to improve the efficiencies of the active chemicals.

From this information it is possible to calculate the savings a farmer may achieve with the use of spot sprayers. With conventional spraying techniques the cost to spray fallowed land three times over a season is approximately \$28.25/Ha. It should be noted that these rates are only general estimations over many seasons. Depending on the seasonal rainfall a paddock may require as low as 1 or as many as 5 passes. Redgwell goes on to say that it is difficult to put a price on chemicals as it also depends on the size of the weeds that are being targeted.

As mentioned by the DPI of NSW, savings of up to 80% have been identified in ideal situations where little weed cover is present. If more realistic figures are used for example 65%, the savings can be easily calculated. From the calculated figures for the use of spot sprayers, chemical cost could be reduced to around \$18.36/Ha. As a result, significant savings can be produced with the use of selective spot sprayers.

With such savings possible due to the reduction in chemical costs, one option available to farmers is to increase the chemical application rates. This ultimately means that each weed will receive increased levels of chemical while not exceeding the manufacturer's standards of acceptable application rates. Alternatively, more expensive chemicals targeting specific weeds can be used without major cost disadvantages. At the end of the day this finally means that that a better knockdown rate will be achieved reducing the risk of chemical resistance becoming an issue (Cropoptics 2008).

2.5 Chapter Conclusions

This chapter has provided the reader with the relevant background information required to understand the concepts that surround the project. It aims to provide an understanding why the need for selective weed spot sprayers has arisen since the adoption of minimum tillage practices within Australia. It also outlines the advantages these sprayers have over conventional methods of spraying an entire field, when the weed coverage area is only a small percentage. It is therefore not hard to see that significant chemical savings can be achieved with the use of such spraying technologies.

Chapter 3 – Literature Review

3.1 Introduction

This chapter aims to provide the reader with information used for the basis of the technical aspects of the project. It present the investigations conducted into the use of fibre composites including properties and advantages of the material along with how some of the disadvantages can be overcome. One such disadvantage which needed to be adressed is that of the joining techniques used to join pultrusions. This chapter will also investigate suitable loading cases for the analysis to be used on such agricultural equipment along with appropriate techniques to conduct an accurate finite element analysis.

3.2 Fibre composites

Composite materials are the combination of two or more materials to achieve properties (physical, chemical, etc.) that are superior to those of the constituents (Barbero 2011). There are many different methods of using composite materials with in the engineering discipline. However fibre composite pultrusions will be investigated in this report as an alternative to the use of other common engineering materials such as steel. According to Wagners Composite Fibre Technologies (Wagners), an industry leader in the design and manufacture of fibre composite products, this material is generally easy to assemble, flexible and durable, and as a result it is increasingly considered for use in government and industry infrastructure projects. Pultrusions are currently being used in a range of areas including construction and wind turbines with great success as alternatives to conventional construction materials. Little or no research has been conducted into the use of such materials in the agricultural industry and therefore other areas of the engineering disciplines were analysed to gain the required knowledge of the fibre composite industry.

Fibre composite materials offer a range of advantages, the most significant of which is its superior strength to weight ratio. The following table is taken from the Buchanan Advanced Composite (BAC) website (2011) who are manufactures of advanced composite structures in Toowoomba. The table illustrates the strength to weight ratio advantage that fibre composite materials have over conventional materials such as metals.

Table 2: Comparison of composite materials to other metals (Source BAC 2011)

	Material Type	Tensile Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm3)
Carbon Fibre	High Strength	160-270	3500	1.8
	Intermediate Modulus	270-325	5300	1.8
	High Modulus	325-440	3500	1.8
	Ultra High Modulus	440-600	2000	2.0
Kevlar (Aramid)	Low Modulus	60	3600	1.45
	High Modulus	120	3100	1.45
	Ultra High Modulus	180	3400	1.47
Glass Fibre	E-glass	69	2400	2.5
	S-glass	86	3450	2.5
Aluminium		72	400	2.7
Titanium		110	950	4.8
Steel	Mild	200	450	7.2
	High Strength	200	1200	7.2

BAC goes onto note that the advantages of composite materials can be further exploited to give a structure that is of the same strength but of significantly less weight. This saving can be up to 3-5 times greater than using metals.

At only a fraction the weight, and up to six times the strength, it is not hard to see why fibre composites are becoming more widely used in industry. Some of the other advantages fibre composites have over more tradition materials were outlined by Taylor (2009) and include:

- High tensile strength
- Heat resistance
- Thermal Behaviour
- Chemical Resistance
- Moisture resistance
- Fire resistance
- Electrical resistance

3.2.1 Pultruded Fibre Composites

Fibre composite pultrusions are made up of two main materials, the matrix and the reinforcement. The reinforcement material is made up of fibres which provide the majority of the stiffness and strength. While the matrix binds the fibres together and allow loads to be shared between fibres and between the composite and the external loads and supports (Barbero 2011).

According to Strong (year: unknown) the process of fibre composite pultrusion was developed in the 1950's by W. Brant Goldsworthy. The word pultrusion is derived from "pull" and "extrude". It is a continuous process where materials are pulled through a heated die. It is this continuous nature of the process which allows for high production rates of the final product.

3.2.2 Raw Materials

As mentioned above the two materials required to produce FIBRE COMPOSITES pultrusion process are, a liquid resin mixture (containing resin, fillers and specialized additives) and flexible textile reinforcing fibres.

The selection of the correct reinforcing fibres for the specific design task is a critical consideration as these fibres determine the core mechanical properties such as tensile strength and stiffness of the composite. The cost, density, compressive strength and fatigue characteristics are also determined by the reinforcing material. Common fibres used in industry include glass, carbon and aramid (Kevlar) type reinforcing (Taylor 2009). The fibres are in the form of roving and mat and are shown in the following figure:

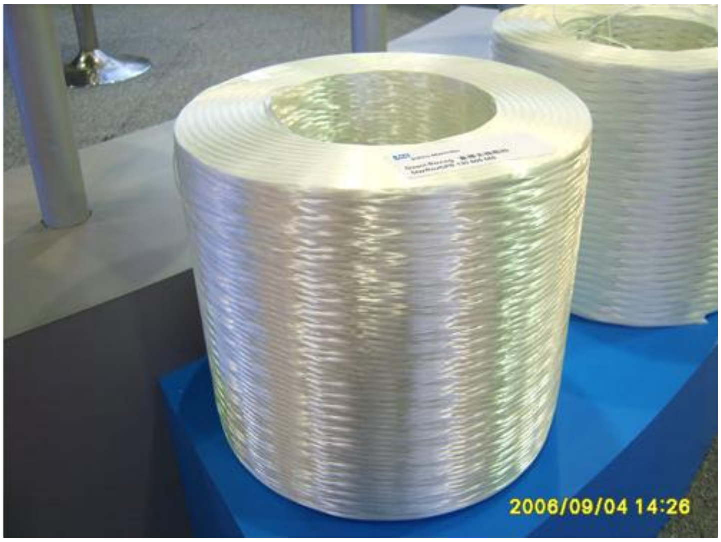


Figure 2: Typical glass roving before the pultrusion process

Source: http://image.made-in-china.com/2f0j00cCztvaeBaVkE/Glass-Fibre-Assembled-Panel-Roving-E-Glass-.jpg

As mentioned above, fibres carry the majority of the load applied to the fibre composites. However, on its own the fibres are unable to withstand compressive or shear loads. It is the task of the polymer matrix (resin) to bind the fibres together into a cohesive material allowing loads to be transferred between fibres and evidently the entire material (Taylor 2011).

3.2.3 Pultrusion Process

As described above, pultrusion is the continual process whereby constant cross sectional profiles are created. The process usually requires less labor than other processes and is capable of high production rates.

The process can be described by the following technique and is clearly illustrated in Figure 3.

1. The first step in the process involves the reinforcing fibre's leaving the roving racks. This stage requires a large area as the roving racks housing the fibre stands are large in size. These fibre's then enter the pre-former which

locate the reinforcement in the appropriate location according to the design specification. This also ensures the roving does not become tangled or twisted

2. These dry materials then enter the injection chamber where they are wetted by resin under high pressure.
3. Once the wet material enters the die, heat is added so that the thermosetting process begins. This heat initiates the hardening of the composite in the curing process. The heat causes the composite to shrink ensuring the final product frees itself from the die, leaving a final product in the shape of the die.
4. The cured specimen is then pulled by a reciprocal action which allows the composite to be continuously made to an almost infinite length.
5. The composite is cut to the required length to facilitate transportation by the use of moving cut-off saws which clamp themselves to the continually moving section to ensure the pultrusion process is not stopped in any way.

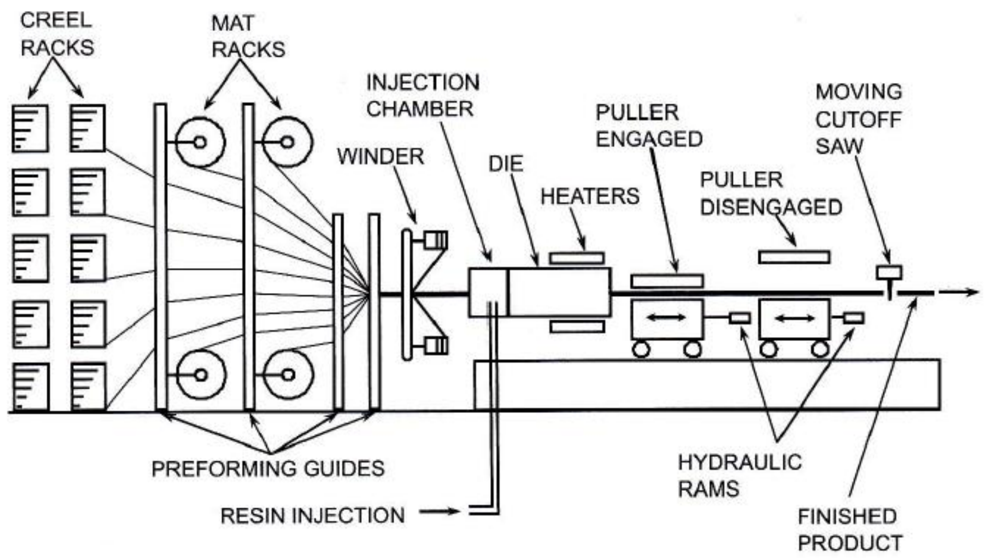


Figure 3: Pultrusion process (Source Barbero 2011)

Fanucci (1992) along with Krolewski (1986) have shown that when creating advanced composite parts the pultrusion process is the lowest cost process when compared to filament winding and prepreg hand layup. The studies showed that the pultrusion process is as low 26% of that of prepreg hand layup and 41% less than filament winding. These are also views shared by Barbero (2011) who goes on to say that the cost of production is low however the major cost of the process is in the equipment. This is why pultrusion is ideally suited for high volume applications.

These production rates vary greatly depending on the cross-section being molded and also the type of machine being used. Barbero (2011) explains that on average a standard beam cross-section can be produced at about 2 meters per minute. He also states that the process limits the wall thickness allowed in sections to 12mm when using standard conduction heaters as curing limitation and intraliminar cracking can occur

The advantages of using composite materials are vast and varied. The main motivation for using such materials is the possibility for weight reduction and also corrosion resistance. However these are not the only reason for designers to use this material. Other advantages include high specific stiffness and strength.

Weight reduction is one of the most important characteristics that motivate designers to use composites within their design (Barbero 2011). The combination of the fibres and the polymers which make up the matrix, both have very low densities ensuring that the final product is not only very strong but also lightweight. This strength is produce from the combination of the two materials. Alone these materials would serve very little use, the fibres have a high strength/weight and stiffness/weight ratios however cannot support compressive loads. However, the polymers bind the fibres together producing a strong lightweight material.

3.2.4 Pultruded Fibre Composite Material Properties

As mentioned in previous sections, fibre composite materials have many advantages over conventional materials such as steel. The following graphs give a representation of the properties of fibre composites when compared to other conventional materials.

Density

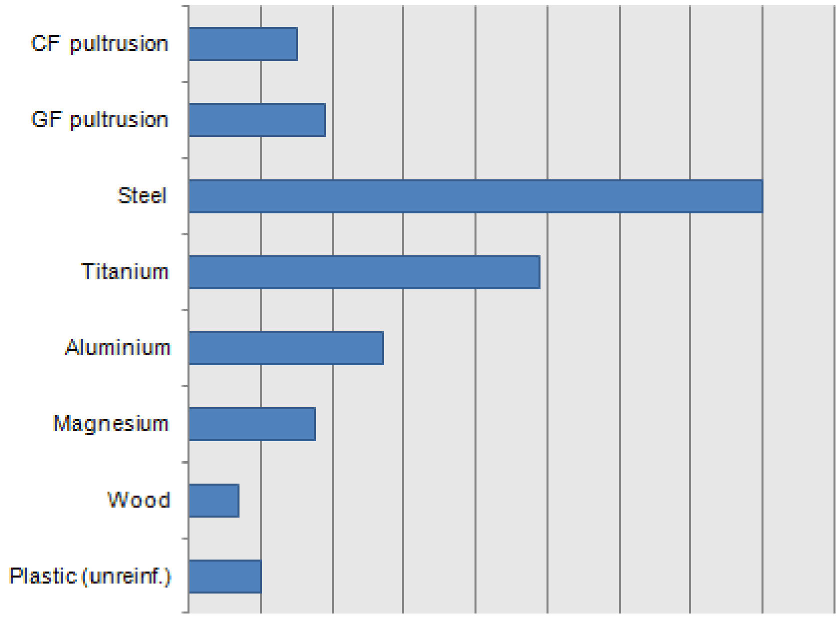


Figure 4: Density Comparison (Source Excel Composites 2010)

Stiffness

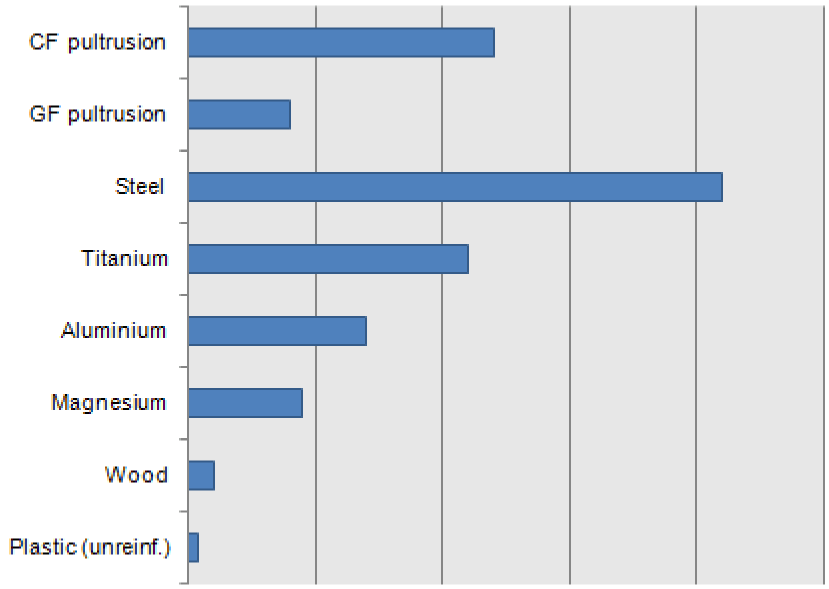


Figure 5: Stiffness comparison (Source Excel Composites 2010)

Stiffness can also be refered to as the Elastic Modulus or in engineering terms, stess/strain of the material. It is a measure of how much the material will deform at a certain load. As can be seen, fibre composites do not compare favourably to steel. However a better comparison can be made between the materials when considering the specific stiffness properties. Specific Stiffness is a means of determining a material's relative stiffness compared to that of other materials. It is defined as:

$$Specific\ Stiffness = \frac{Elastic\ Modulus}{Density}$$

It can be seen that when analysing this property the fibre composites perform favourably when compared to steel.

Specific Stiffness

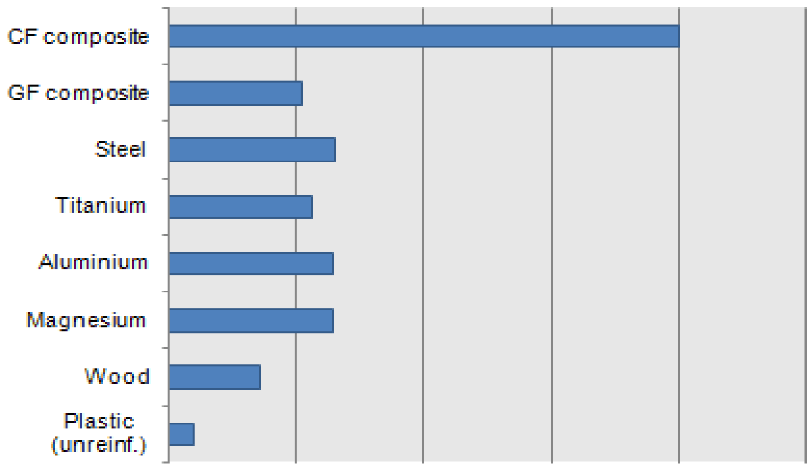


Figure 6: Specific Stiffness comparison (Source Excel Composites 2010)

Strength

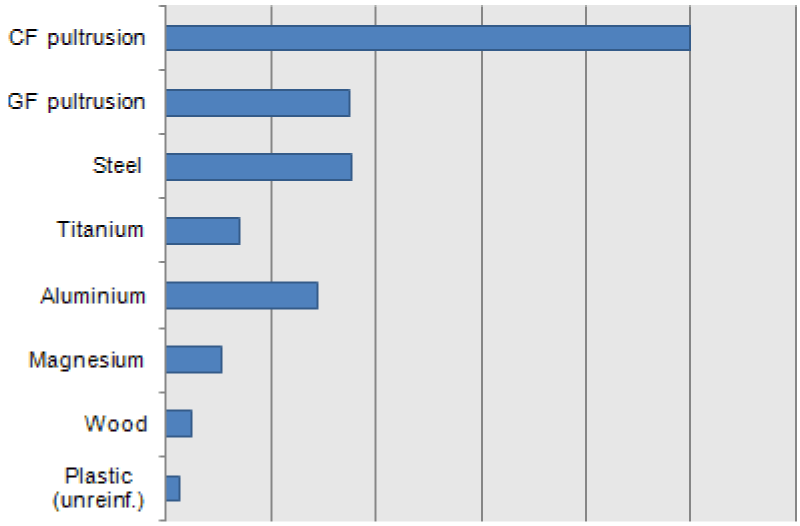


Figure 7: Strength comparison (Source Excel Composites)

Once again the strength of fibre composites are comparable to those of steel. However, when comparing the specific strength that is strength/density, composites will be far superior to those of steel due to its low density property.

Fibre composite pultruded specimens are anisotropic materials meaning that the material properties vary with orientation. Anisotropic materials may be homogeneous but properties change depending on the orientation along which the property is measured (Barbero 2011). This is very critical in the design process to ensure that the engineer is fully aware of these properties and ensures the design takes full advantage of this. The data regarding the material properties of the pultruded composite will be gained through internal reports produced by the Centre of Excellence in Engineered Fibre Composites (*CEEFC*), located at the University of Southern Queensland. Due to industry confidentiality, this data will not be disclosed within this report apart from the most basic material properties required to complete the finite element analysis.

Depending on manufacture of the composite, these material properties can vary greatly. However basic properties can be obtained by knowing the volume fractions of each material that makes up the composite. This can be done by the equation.

$$V_{Matrix} = \frac{Volume\ \ of\ Matrix}{Total\ Volume}$$

$$V_{Fibre} = \frac{Volume\ of\ Fibre}{Total\ Volume}$$

From these fractions an approximation of density can be obtained.

$$\rho_c = \rho_f V_f + \rho_m V_m$$

(Source Barbero 2011)

Research conducted by Taylor (2009) at the University of Southern Queensland investigated the mechanical properties of pultruded fibre composites. His research involved determining the ultimate tensile strength along with producing a model of the fatigue life of such materials.

The results of the ultimate strength results produced mean results of 564.5 MPa. However when designing a project such as the spray rig it is not only the ultimate strength of the material that is important, it is also the fatigue strength. The ultimate strength is the ability of the material to withstand a single cycle of the load, whereas the fatigue strength of a material is its ability to withstand failure created by cyclic loading. Simply, fatigue can be described that at higher loads the material will fail with lower cycles while lower loads will fail at much higher cycles. This phenomenon can be seen in the figure below which was developed by Taylor (2009) as a model of predicting the fatigue strength of pultruded fibre composites.

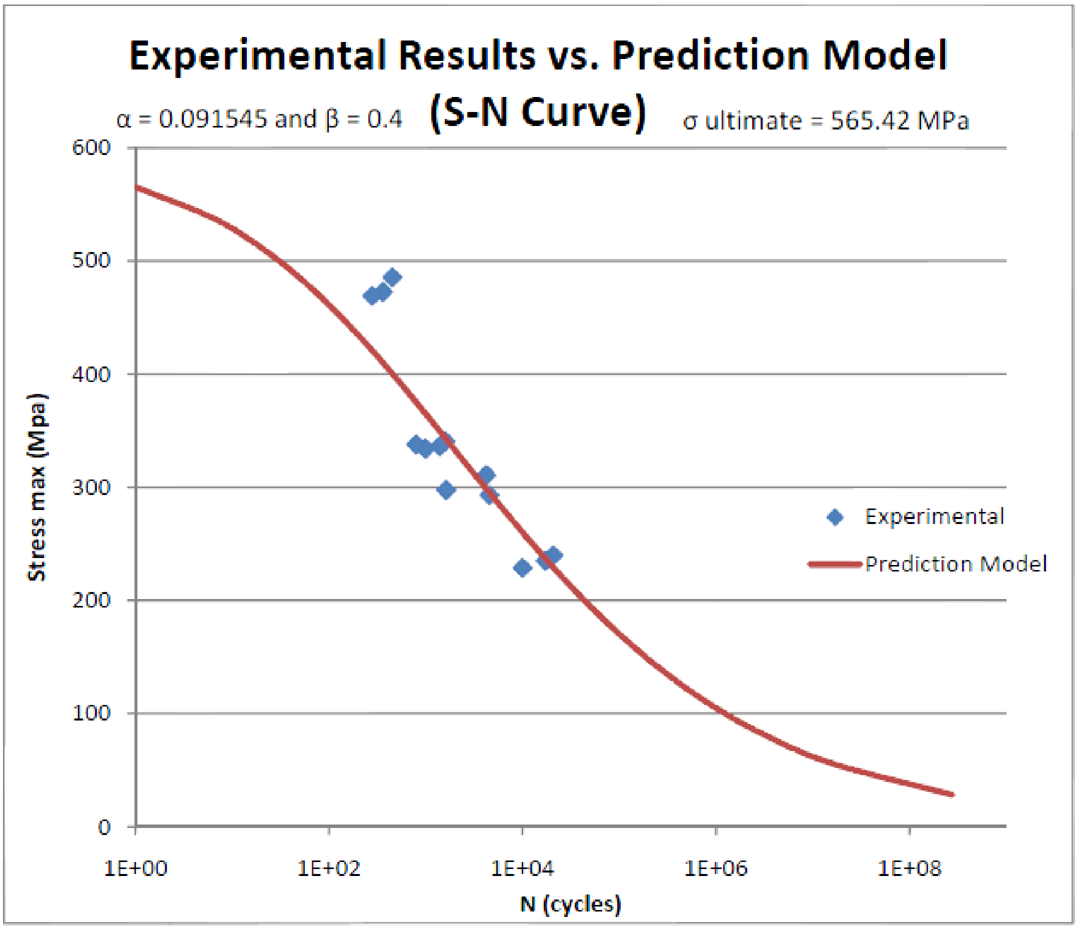


Figure 8: Experimental vs Theoretical Fatigue Strength of Fibre Composites

Source Taylor 2009

The fatigue strength of steel is usually assumed to be approximately half that of its ultimate strength. This fatigue strength is defined as the stress that the material can withstand for an infinite length number of cycles. However, when comparing this to the figure above it can be seen that the fatigue strength of the fibre composites is much lower than those achieved by steel. In fact unlike steel, fibre composites do not show any signs of having a fatigue limit, meaning that they will eventually fail with time even at small loads. Therefore careful consideration must be taken in determining the suitable design limits to ensure failure does not occur due to fatigue. Dr Jayantha Epparaachchi a lecturer at the Univeristy of Southern Queensland and an expert in the field of fibre composites explains that a suitable limit to design to is approximately 25% of the ultimate strength of the fibre composite. However, he also went onto say that it is good practice to use a life of 10^7cycles to 10^8 when designing for such a project. Therefore when analyzing this graph a life of between 75-100MPa would be suitable for the design of the sprayer. However there are many variables to consider when designing for such a task especially when using composites. It is for this reason that Mr Mario Springolo of Wagner's uses full scale testing of new designs. This includes creating a full scale model of the design then testing with real world loads to determine the life of the design. This is the most effective means of ensuring the material will endure the conditions faced during operation.

3.2.5 Issues with using fibre composites

It is obvious from the above information that fibre composites are an extremely useful material and have the ability to be used in a wide range of areas. However from the literature reviewed there are still a number of areas that the composite industry needs to address before they are used more widely in industry.

3.2.5.1 Cost

Goldsworthy (1995) along with Van Erp *et al* (2000) outlined cost as the single most important factor in the development of engineering structures. For a composite material to be used there must be no financial disadvantage to the project for selecting this material. Failing to do so has been a major problem for the composite industry. It is not a surprise that the costs of composite are greater than those of similar materials such as steel.

It has been noted that one area for reducing the cost of using composites is in correctly designed structures. "Smart design is by far the biggest cost saver in composite part production" (Robinson, 1991). This therefore requires new and innovative designs from engineers to exploit the full potential of composite materials. As Busel (1997) explains that to use composites to their potential, it is a combination of both what you use composites for and putting them in the right place. It is that "putting composite elements where you need them will be up to the skill of the engineer and will determine the future of composites" explains the ENG 8808 Study Book (2008, pp1.18).

3.2.5.2 Availability of design and material property information

According to the ENG 8808 study book (2008), numerous sources (Ballinger 1992, Wilkinson and GangaRao 1993, Scalzi *et al* 1998) have all identified that there is a lack of availability of comprehensive database of material and design properties. If designers do not have this comprehensive data easily accessible then the likelihood of them using the material decreases greatly in favour of more traditional materials. One of the causes of this lack of information is the wide array of constituents available for the manufacture of composites. This leads to an equally wide array of material choices all with differing properties. These properties are difficult to obtain from manufactures which lead to the need of testing by individual companies to determine these properties. However it should be noted that the ENG8808 Study Book (2008) explains that manufactures do supply material information in the form of technical data sheets. However these are only an initial introduction to the material and are not suitable to be used in an engineering situation. USQ completed tests on a range of different specimens from varying manufactures and found that the data presented, in some situations are not an accurate depiction "real world test", but merely conducted in idealised laboratory test. Each of the five specimens was subjected to testing to determine the maximum tensile stress and associated strain at failure. The tests were carried out in accordance with testing standard ISO 527. The following table demonstrates the variances within the test results when compared to the published results.

Property	Published Value	As Tested	Standard Deviation
Maximum Stress (Mpa)			
Resin A	86	63	4
Resin B	76 – 83	75	4
Resin C	86	81	1
Resin D	69 - 76	71	0.7
Resin E	83	78	3
Strain at Failure (%)			
Resin A	6.5	2.45	0.28
Resin B	7 - 8	3.20	0.39
Resin C	5 – 6	4.95	0.93
Resin D	10 – 12	6.46	1.20
Resin E	4.2	2.80	0.29

Figure 9: Comparison of reported resin tensile properties with experimentally determined values for a range of vinyl ester resin systems, (Source ENG8803 Study Book 2008)

As can be seen there is a large difference between the two sets of data. This is extremely alarming for the engineering profession as these published values vary greatly to the real world test. This is very disappointing, however not unusual as Pfund (1999) also reported similar findings. This practice needs to be rectified to gain the trust of engineers so that the industry can reach its full potential.

3.2.5.3 Education

It has been identified by the ENG 8808 STUDY BOOK (2008) that successful exploitation of the full potential of composites will hinge on the transfer of knowledge into the general engineering community. It goes on to say that engineers must be trained in all aspects of material selection, material specification, product specification and quality control. This will help to ensure that engineers recognise composites as another material in their arsenal.

Another problem facing the industry is in the education of the consumers. The use of composites is a relatively new area and many consumers are wary of new developments. During a consultation with an engineer from Felco Manufacturing

Pty Ltd in Toowoomba QLD (manufacturers of fibre composite products) the manager explained that the job of the engineer is not only to design the most suitable engineering solution but to also market the product. This is because it is hard to convert people from conventional materials such as steel to a product such as composites. This view is also noted in the DIAB sandwich handbook which discusses the issues with introducing a new material to an industry. The major opposition to the use of the material is through the conservative and ignorance of people. It also validates the claims that the only way to overcome this resistance is to teach and convince these opponents.

3.2.6 Joining Methods

The use of fibre composite will require dramatic changes to the design of the spray rig wings which in turn may change how they connect to the existing centre structure. It is for this reason a range of varying joining methods need to be investigated to determine the correct method for each situation.

Joining is one of the most difficult problems associated with the design of a fibre composite structure as Strong and Beckwith (1997) explained, "the Achilles heels of composites are its joints." This is a view also shared by Mr Norm Watt an experienced professional in the area of fibre composite manufacture who explained in a private consultation, that the most difficult tasks to be completed with the redesign of the spray rig will be the joints. However it must be noted that it was also mentioned that it is not impossible. Strong and Beckwith (1997) go onto explain that many composite structures are relatively simple to design however much time and effort must be devoted to designing suitable joints. When considering the suitable joint there are two main types to be considered; mechanical and adhesive or for further effectiveness a combination of both can be used.

Mechanical joints are usually conducted with the drilling of a hole between the two materials that are to be joined. The mechanical fastener would then be placed between the two materials and tightened in a certain fashion. For example a nut is tightened on a bolt and threads on a screw pull the material together, pins rely on interference joints while rivets pull on themselves to create a sufficient connection.

The determining factor for which mechanical method to use, is the strength of the material at the joint location. For example Strong and Beckwith (1997) explain that if the material is weak in compression then a nut and bolt would only cause the material to crush. It is for this reason in some situations a stiffer material such as metal is placed inside the structure to give it the strength it needs in compression. Also if the material is weak in shear then a screw may not be useful. This type of joining is not affected by surface finish and therefore no surface treatment is required to create a sufficient joint.

At any joint location, stress concentrations usually occur due to the rapid change in the materials geometry. This needs to be factored in when designing a structure and can be a major problem if not identified, especially if the structure is designed to its engineering limits. There are a number of options that engineers have to accommodate these stress concentrations. Good designs will usually accomplish this by increasing the number of fibres at the joint location. This can be done by increasing the size or thickness of the material, adding more fibres or reinforcing the joint with a non-composite material such as metal or wood strips.

Some long term considerations when using mechanical joints include; fatigue, corrosion between the fastener and the composite as well as the admission of water through the joint itself.

Mechanical fasteners are usually metallic and therefore contribute to the overall weight of the structure. As a result there has been a trend towards the use of lightweight materials such as aluminum and titanium. However both these materials are expensive when compared to traditional fasteners.

The advantages of using such products include; reliability, simplicity and ease of inspection. In addition, these materials don't usually create an issue with temperature limitations in the joint structure. Any limiting factor involving heat is most often due to the composite itself.

Another example of mechanical joints described by Watt's was the use of collars and sleeves to join two or more sections together. This is particularly useful when joining composites that have the same geometric cross sections. This is the process of one geometry fitting inside of a collar/sleeve which then is able to be connected the other piece/s of geometry in the structure. This method of joining similar geometric sections together is used extensively in the wind turbine industry for joining turbine blades to the rest of the structure. Due to its common use there is a great deal of research available on this technique of jointing.

Adhesive joints can usually be classed into the following types; structural, hot melt, pressure sensitive, water-based and radiation cured (Strong and Beckwith 1997). The considerations when choosing the correct method are the cost, the service environment, the application and the type of composite being bonded.

When choosing any adhesive the first consideration is whether the composite and the adhesive are compatible. This will ensure that the joint between the materials are optimised. In general the closer the chemical nature of the adhesive and the composite, the better the joint will be.

Unlike mechanical joints when considering the correct adhesive joint, environmental factors must be analysed to ensure the most effective material is used. This includes the temperature, solvent and moisture levels, loads, UV light and expected service life of the joint.

All adhesives require a certain amount of surface preparation with some more strict than others. The manufacturer will usually provide these specifications and they should be strictly followed. These specifications will also contain the time required to form a suitable joint. Some types of adhesive may have a relatively short cure time while others require clamping and exact curing procedures to form the required bond.

There are a number of other ways to improve the effectiveness of adhesive joints. To ensure a sufficient joint the adhesive must be applied to the entire surface of the joint, this is called wetting up. To increase the efficiency of the bond, the two surfaces must be clean of any debris, grease and other contaminants. This bond is also improved with mechanical interlocking between the small irregularities on the surface of the composite and the adhesive. This can be achieved by roughening the surfaces, followed by cleaning of any contaminants from the surface. Once the surface has been properly treated and cleaned the time elapsed should be kept to a minimum to ensure recontamination is avoided.

Once both surfaces are prepared, the adhesive may be applied. There are many different methods of applying adhesives depending on the form the adhesive possesses. These forms include liquid, pastes, powders and even sheets

The curing of the joints often requires a specific process depending on the adhesive being used. These techniques include curing with heat (most common), moisture, evaporation of the solvent and exposure to UV light.

The advantage of using adhesives to join composites together may vary greatly but the effort required to produce these joints is well rewarded. One such advantage is that of the relative flexibility of the adhesive when compared to the composite. This provides for a certain amount of shock absorption that would otherwise not be possible. Another advantage is the self-sealing nature of the adhesive joints. This protects the joints from moisture that could otherwise damage the integrity of the structure. The most obvious advantages however, are that of the saving weight and the distribution of forces over a greater area. Strong and Beckwith (1997) add that an often overlooked advantage of adhesive joints is the ability to connect often complex geometry given its ability to naturally distribute forces.

3.2.6.1 Joining Steel to Fibre Composites

The decision to connect fibre composite wings to an existing steel centre section resulted in a significant level of research into various composite to steel jointing methods.

As mentioned in the previous section on mechanical fastening techniques much research has been conducted into the design of suitable joining techniques of composite wind turbine blades to steel rotor hubs. This research is headed by the Sandia National Laboratories where many useful experiments have been conducted and documented. Metzinger and Guess (1999) conducted research into the mechanical properties of bonded lap joints between steel and composite material. In research conducted at the Sandia National Laboratories Metzinger and Guess (1999) investigated tubular connected lap joints similar to those in Figure 10 below.

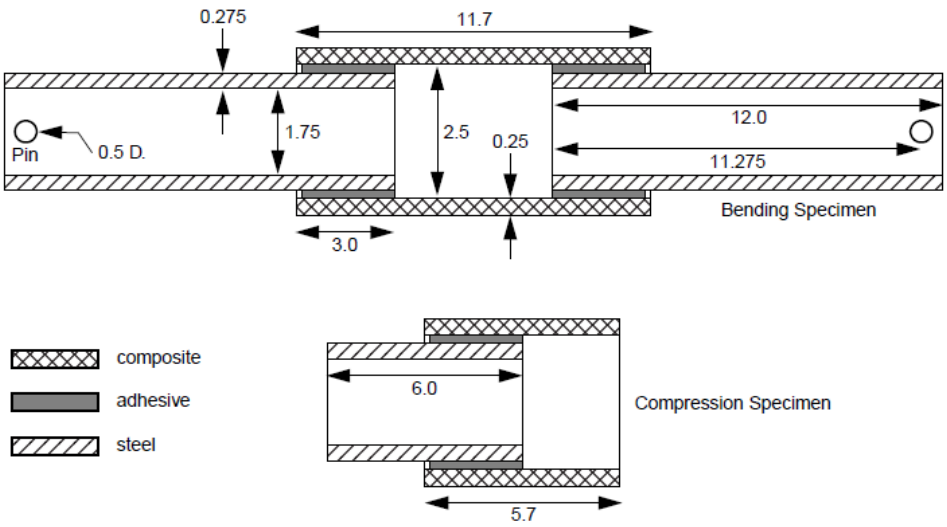


Figure 10: Test configuration of lap joint, (Source Metzinger and Guess, 1999)

The investigation consisted of a range of experiments including compression and tension testing along with bending fatigue tests to determine the modes of failure of the bonded lap joint. Their research showed that this type of joint had significantly higher strength when in tension than in compression. The results of the compression tests showed that the joints were able to withstand an average of half that of the specimens that were tested in compression. Through inspection it was found that of the specimens that were placed in compression, the adhesive had completely debonded from the steel adherent. The investigation showed that this was in fact due to the peel stress on the adhesive. However, on inspection of the tensile tests the composite adherent had actually failed and not the steel adherent debonding. This showed that the tensile joint did not actually fail and explained the reason for the strength in tension being comparatively high.

These results were also verified with fatigue testing where the joint was subjected to repeated alternating stresses. These tests revealed that the failure occurred due to the debonding from the steel adherent on the compression side and not the tension side. These results verified that these lap joints show far more strength in tension than compression.

In another study conducted by Metzinger and Guess (1997), it was found that different geometric designs can affect the strength of these lap joints. Tests were conducted on similar geometry to Figure 11 and the effect of geometric changes to the area as outlined within the square box to the right of the drawing. Focus was placed on three different joints which included a baseline, additional adhesive and tapered steel generating a taper adhesive seal. In each case a common method was used in applying the adhesive.

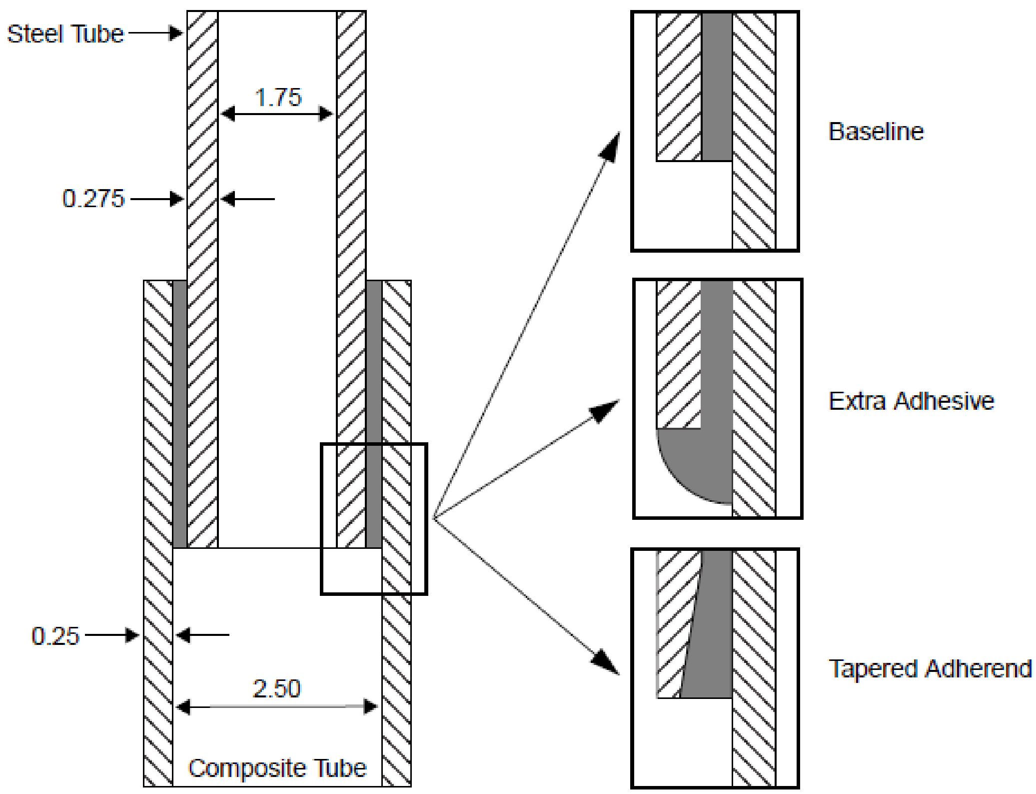


Figure 11: Configuration of compression testing of lap joints, (Source Metzinger and Guess 1997)

It should be noted that this study conducted by Metzinger and Guess (1997) was only for compression as they were primarily focusing their research on the effects of geometric changes to the joint. The results obtained should not be considered representative of tensile testing.

Through their research they found that that the common baseline joint failed at slightly higher loads than that of the tapered steel joint. For both failure modes the adhesive once again debonded from the steel. This is the same as the result found two years later in the test outlined previously. These two experiments can therefore be successfully compared to each other. The research conducted into the geometry of the joints found that the extra use of adhesive significantly increased the load which the joint can withstand. This addition of adhesive creates enough resistance to the peel stress so that the actual join does not fail. On inspection with ultrasonic testing it was found that the ultimate joint failure resulted from the composite delaminating at the end of the test specimen.

Further investigation into the two experiments showed that in both cases the same steel size and composite materials were used. Therefore it is possible to directly compare the findings to obtain results determining whether the addition of extra adhesive can improve the compression strength to a point similar to the tensile strength outlined in the first experiment.

Figure 12 shows that the compressive strength of the joint is significantly lower than the tensile strength.

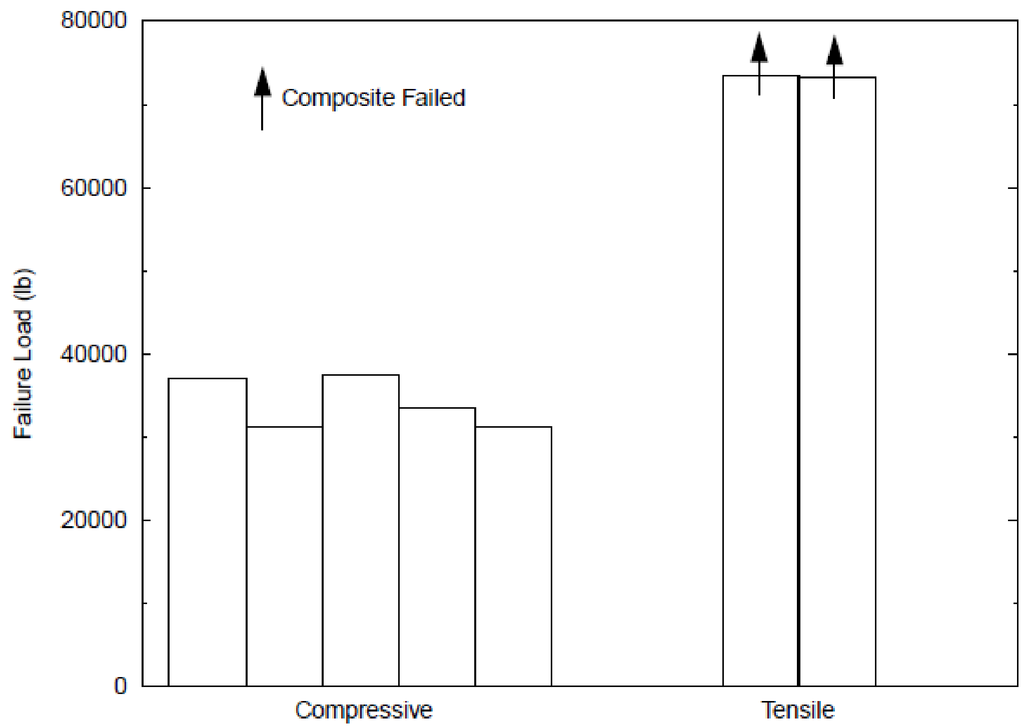


Figure 12: Comparison of tensile and compressive strength specimens, Source Metzinger and Guess (1999)

As stated earlier the difference in strength is very significant and can be attributed to composite material failure in tension compared to debonding in compression joints. However, Figure 13 illustrates that the poor compression strength can be overcome to a point where the composite material fails, just like the tensile joint, by adding extra adhesive to the end of the joint.

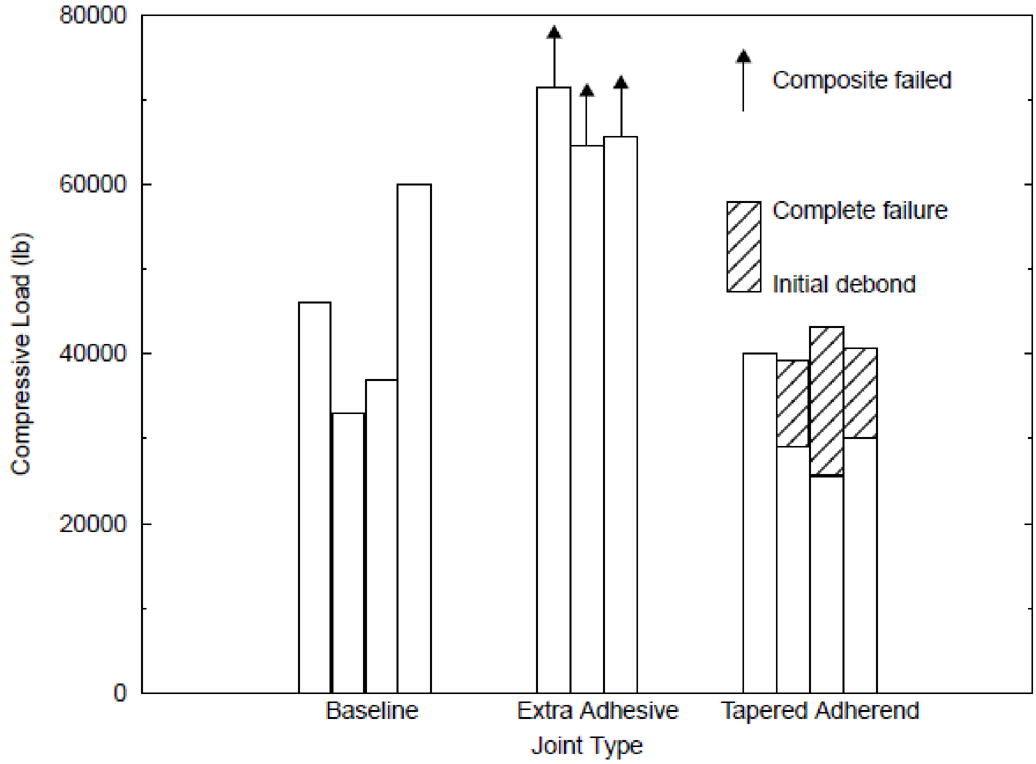


Figure 13: The effect of different geometry on the compressive strength of a lap joint, Source Metzinger and Guess (1997)

From these tests it can be seen that the major problem with bonded lap joints is that the compression strength of such joints is far less than that of the tensile strength. However, through experimentation it can be seen that the compression strength can be significantly increased with the addition of extra adhesive as in Figure 11. In the test specimens this increased the strength of the joint to a point where the composite failed and not the joint.

The fatigue strength of these same joints were also analysed by Metzinger and Guess (1999) with the results outlined in Figure 14. These results illustrate that the fatigue strength of the three different geometries vary greatly. Again, it is clear that the additional adhesive significantly increases the fatigue strength of the joint in compression.

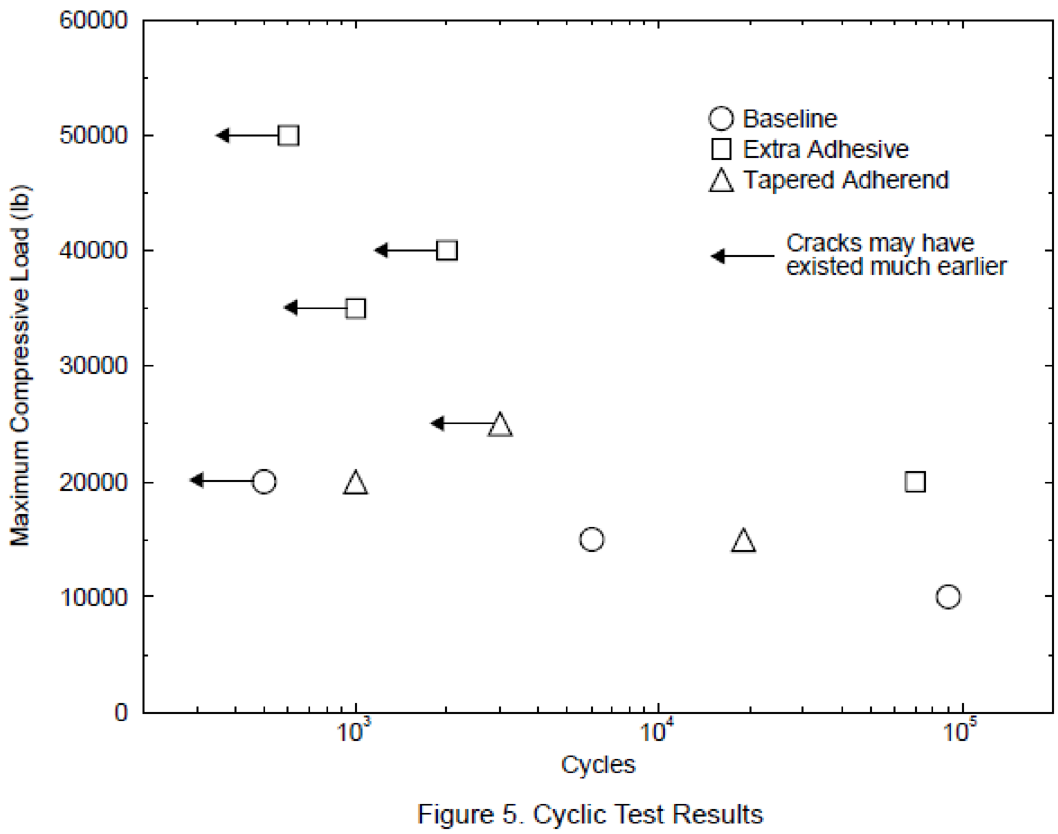


Figure 14: Fatigue Strength of the lap joint with varrying geometries

Source Metzinger and Guess (1997)

This literature review clearly indicates that lap joints are a viable option when considering connection methods for steel and composites. Also that the addition of extra adhesive to the end of the joint is a very useful tool when designing lap joints to overcome the issue of poor compressive strength. This last technique should be used to its full potential to ensure maximum strength and life is obtained by the structure.

In both investigation the same adhesive, Hysol EA 9394 was used; a two part adhesive that shows high strength characteristics. There are many more adhesives available to complete a similar task and these should be investigated to ensure the correct adhesive is chosen for the current task.

3.3 Loading conditions for the analysis

3.3.1 Dynamic loading cases

To conduct a suitable Finite element analysis of the spray rig wing design, it was necessary to determine all the appropriate forces that may act on the spray rig while it is in operation. Each wing is required to support itself. This includes the hood sections, the frame structure, camera holders and hood linings. These loads are easily determined statically however each load case changes when considering dynamic loading.

When considering dynamic loading you normally think of an object colliding with another. However in the case of the spray rig this is not the most important issue. The major dynamic load case is that of the motion applied to the frame when moving over rough or uneven cultivation. The wing will tend to bounce during travel and short falls with sudden stops causes sharp increases in the load applied. According to Siegel *et al* (1965) this sudden impact load produced can be found by twice the static load. This is a view also supported by Shigley (1963). However, he goes on to say that this is a conservative approximation. It was determined that in this analysis, twice the static load will be appropriate.

3.3.2 Wheel rolling resistance in the field

Another major load case on the wing of the spray rig is that of the rolling resistance of the wheels. Throughout the research conducted, three sources of calculating rolling resistance were identified. The first method of determining the force required to overcome rolling resistance was presented by Hibbeler (2007) who describes the phenomenon that occurs when the wheel passes over the soil. This method of predicting the force is very useful when gaining understanding, however to calculate the actual results becomes difficult to achieve without sufficient tests. The second method of calculating the force is presented by the Agricultural Machinery Study Book (2011) which presents the Gee Clough equation created through experimental data specifically designed for the agricultural industry. The final method which will be investigated within this report was outlined by Professor

Edward McKyes of McGill University, Montreal an expert in the field of soil mechanics who has also written many books on the topic of agricultural mechanics

Firstly the method by Hibbeler will be discussed to ensure a sound background of the topic is presented. As mentioned, Hibbeler presents the phenomenon in way that is very easy to understand and describes the way in which a wheel/cylinder deforms the surface of which it rolls. If a rigid (or solid non-deforming) cylinder rolls over a rigid surface at a constant velocity the normal force exerted on the surface of the cylinder acts tangential to the point of contact. In this case, since the two objects are perfectly rigid this force is directly upward through the centre of the cylinder as shown in the following diagram.

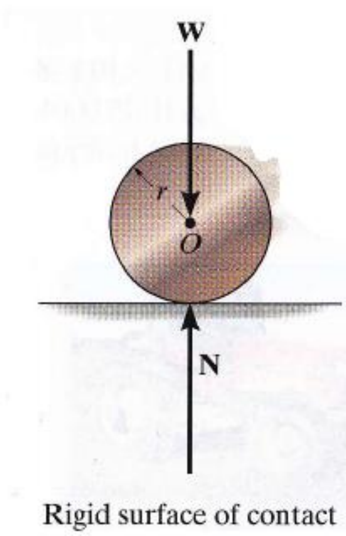


Figure 15: Effect of rolling resistance on two rigid bodies

As can be seen from Figure 15 above, there is no force retarding the direction of motion and therefore the cylinder will continue to move at a constant velocity if not acted on by other forces. Unfortunately in the real world this is not the case and the two bodies cannot be assumed to be rigid. Hibbeler continues to explain the effect of rolling resistance by describing a cylinder that is extremely hard while the surface is relatively soft. The weight of the cylinder creates a force on the surface which causes it to compress. Figure 16 below, shows this compressive action and also the forces that this creates on the cylinder.

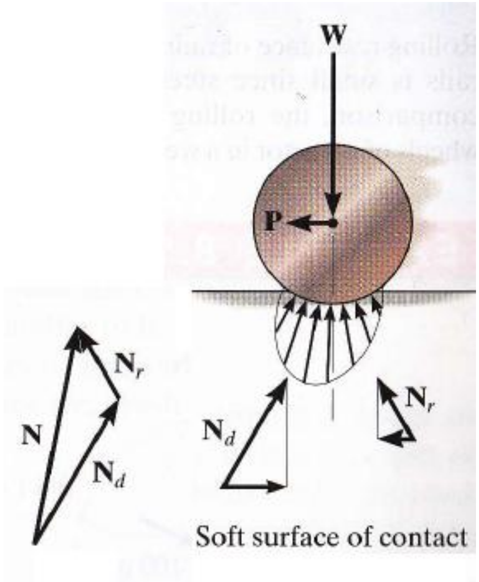


Figure 16: Forces created the cylinder compressing the surface Source Hibbeler 2007

As the cylinder rolls over the surface, the material in front retards the movement while the material behind is restored and tends to push the cylinder forward. However these two forces are not equal, the force acting on the front of the cylinder is always greater. This can be seen by the resultant force **N** in Figure 16 which is against the direction of travel. Therefore a force **P** must be applied to the cylinder to maintain motion. Hibbeler continues to explain that this force is the primary reason rolling resistance occurs however there are other less obvious factors that contribute to the retarding force. These include heat loss and also if the weight of the cylinder is great enough, permanent surface deformation (compaction) is created, storing energy in the material. The analysis of the system is also shown by Hibbeler. For the system to be in equilibrium it is important to consider the resultant force **N** as concurrent with the driving force **P** and acts at an angle of theta ($\boldsymbol{\theta}$) with the vertical. These forces are more adequately shown in Figure 17 below.

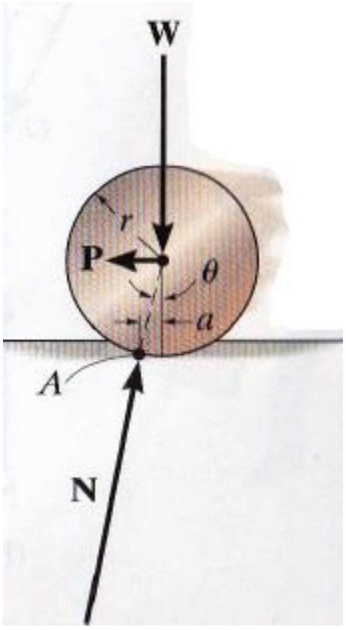


Figure 17: Forces acting on the cylinder Source Hibbeler 2007

To calculate the force **P** required to overcome the rolling resistance the moments are to be taken about **A** which gives

$$Wa = Pr$$

Since the deformation is generally very small in relation to the cylinder's radius, cos(θ) is approximately 1.

Therefore

$$Wa \approx Pr$$

or

$$P \approx \frac{Wa}{r}$$

Where *a* is termed the *coefficient of rolling resistance,* and measured in length. This dimension is extremely hard to determine since it depends on such parameters as rate of rotation of the cylinder and elastic properties of both materials.

The second method on analysing the rolling resistance is presented in the Agricultural Machinery Study Book, the Gee Clough equation. This method uses the properties of both the tyre and the soil conditions that the machine will encounter to calculate the corresponding Rolling Resistance. It can be presented as follows:

$$C_{RR} = R/W = 0.049 + 0.287/M$$

Where:

C_{RR} = Coefficient of Rolling Resistance;

R = Rolling Resistance, N;

W = Vertical load on the wheel, N;

M = Tyre mobility number

The tyre mobility number can be determined by the following equation:

$$M = \frac{CI \times b \times d}{W} \times \sqrt{\frac{\delta}{h}} \times \frac{1}{1 + b/(2 \times d)}$$

Where,:

b = tyre section width, m;

CI = cone penetration resistance, kN/m

D = undeflected tyre diameter, m;

h = tyre section height, m;

W = vertical load on the tyre, kN;

and δ = tyre deflection, m

For the above equation δ/h is usually taken as 0.2 (Agricultural Machinery Study Book 2011). From the research undertaken, smaller wheels and higher tyre pressure increases the rolling resistance. It is therefore easy to see that the larger the diameter of the wheel the less rolling resistance occurs. This is very useful in this project as the current wheels are rather small which will create a large force on the machine. It was also found that the rolling resistance increases in direct proportion to the vertical load on the tyre. Therefore with a smaller vertical load on the wheels less force will occur on the structure. This is extremely important to consider when analysing the composite structure to ensure the correct rolling resistance is used.

A cone penetrometer is a device used for estimating the strength of the soil. It is a function of soil moisture content, soil density and clay ratio. Values range significantly from 100kPa for weak field conditions (e.g. wet seedbed) to 2Mpa for strong field conditions (e.g. dry grassland) however the average field condition is between 300kPa to 1Mpa. For the analysis of the spray rig, cone penetrometer readings that create the greatest resistance should be used ensuring that the wings can withstand such forces.

The final method of determining the rolling resistance of agricultural machinery was obtained through private communication with Professor Edward McKyes of McGill University, Montreal. Professor Mckyes has produced numerous books regarding agricultural equipment along with soil mechanics. His approach is a simplified approach when compared to the other methods presented. He has concluded that pneumatic tyre rolling resistance is usually about 2% of the machine weight plus a force related to sinkage into the soil and is described by the following relationship:

$$R = W\left(\frac{z}{d} + 0.02\right)$$

Where:

R = rolling resistance force

W = total vertical force from the wheel to the ground

z = tyre sinkage in the soil

d = overall tyre diameter

After analysing the methods presented in the different sources, it was decided that the second method of calculating the rolling resistance is more suitable in this situation and that the third method would be used to validate the Gee Clough equation. The first method assumes only small deformation of both tyres and surface. With the given situation, any deformation can be rather large as wet soil will deform a great distance so this method was discounted. While the third methods which was analysed will be used as a means of checking the results obtained by the Gee Clough equation.

3.3.3 Wind resistance

According to Fox, Pritchard and McDonald (2009), drag can be defined as the component of force on a body acting parallel to the direction of relative motion. Drag can be divided into two types; friction and pressure. This is a view also shared by Kreith, Manglik, Bohn (2011) who explains that drag force is the sum of the pressure and friction forces. Pressure drag is caused by the airflow over the surface which creates areas of varying pressure also known as turbulence in the wake of the moving object. This turbulence creates a force that opposes the direction of motion. Pressure drag depends on the shape of the shape of the object and this drag can be reduced with techniques known as streamlining.

The second type is friction drag which describes the interaction between fluid (air) and the surface. It is the same as any interaction between two objects or surfaces which is known as friction.

To determine the force created by the wind on the sprayer each wing can be assumed as a half cylinder. This is then easily calculated as tables are readily available for drag forces of a cylinder. Once a force is determined for a full cylinder this can be halved to find the force exerted on the sprayer by drag. This method was also verified by Mrs Ruth Mussad (6 June 2011) an expert in the field of fluid dynamics.

The *drag coefficient* can be calculated by the equation

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}$$

Where:

F_D = Drag force

ρ = Density of the fluid

V = Velocity of the fluid

A = Frontal projected surface area, and

C_D ,can be calculated by the figure 9

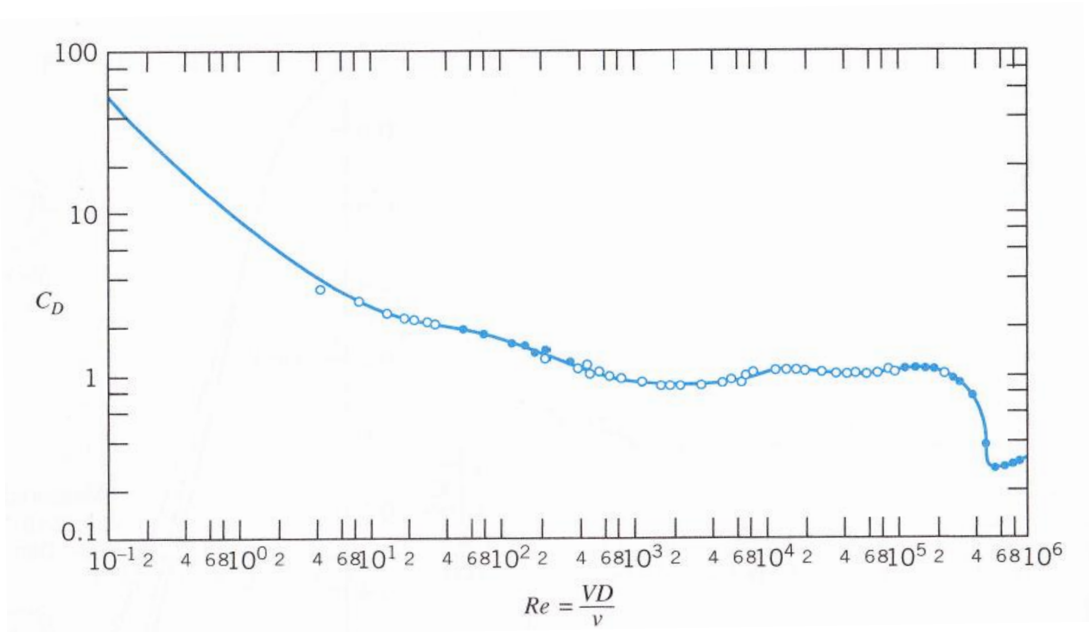


Figure 18: Drag coefficient for a smooth circular cylinder as a function of Reynolds number,

(Source Fox *et. Al . 2009)*

Once the coefficient of drag is determined it is a simple step to rearranging the equation and determining the force exerted on the structure. It should be noted that the force calculated from the equation acts at the midpoint of the structure and any analysis conducted on the design needs to take this into account.

3.4 Conducting a sound Finite Element Analysis

According to Snook (2008), Finite Element Analysis (FEA) is "*a method used to approximately predict the behavior of a continuous physical system by solving a finite number of algebraic equations that describe a mathematical model of some equivalent idealized system."* To produce accurate results using this method it is important that accurate assumptions be made regarding the physical system that is being solved. As Snook explains, a finite element analysis is only as good as the underlying assumptions on which the analysis is made. To ensure the analysis is as accurate as possible, a list of important processes that must be completed to ensure the validity of the results. These have been taken from the Computational Mechanics and Design Study Book 2008:

- The model must be chosen to correctly model the real system.
- The computer package/software and solution technique must correctly analyse the model.
- The mesh must adequately model the real geometry.
- The mesh must be suitable for the element type and problem domain.
- The material property must be accurately known.
- Sufficient elements must be chosen to give accurate answers to the mathematical model
- Modelling of the loads and boundary conditions should be accurate
- The interpretation of the results should also be sound

To ensure all these steps are taken, it is important that sound engineering assumptions are made through appropriate research and previous engineering experience. Often the process of finite element analysis is an iterative process, requiring many attempts to obtain satisfactory results. Therefore it is recommended by the National Agency for Finite Element Methods and Standards that for each analysis a report be conducted so that the relevant assumptions and other important information are documented for future reference.

According to the Computational mechanics in design study book (2008), an important feature of any FEA analysis is that the obtained results are verified by another means even if it is to determine the correct magnitude. This can be done by simple hand calculations for both the maximum stresses and deflection. The following equations were taken from the Structural Design Study Book 2011.

The maximum stress within a beam can be calculated by the following equation:

$$\sigma_B = \frac{My}{I}$$

Where:

M = is the maximum moment created within the beam

Y = is the distance from the centroid of the section to the outer most edge of the section where the maximum stress will occur

I = the second moment of area of the cross section.

The maximum bending moment created by the UDL's on the structure can be calculated by the following equation:

$$M = \frac{\omega L^2}{8}$$

Where:

ω = the magnitude of the UDL in N/m

L = the length of the beam.

Likewise it is a relatively simple task to determine the maximum deflection within a beam by the use of the following equation to compare the results to the FEA and determine the level of accuracy. Through the use of simple hand calculations it is also possible to determine the deflection within the beam. This maximum deflection can be calculated by the following equation (Structural Design 1 Study Book):

$$\delta = \frac{5}{384}\left(\frac{\omega L^4}{EI}\right)$$

Where,

E = Youngs Modulus, Stess/Strain, of the material.

3.5 Chapter Conclusions

This chapter addresses and explores the issues surrounding the project. Fibre composites have many advantages over conventional materials such as steel however with these advantages come disadvantages. The issues such as cost, availability of material property data and also education are all issues that need to be addressed when using fibre composites. Joining methods were also found to be a major issue when using fibre composites. However, it was found that through sound engineering research these issues can be overcome to provide a suitable solution.

To conduct a suitable analysis it is vital the appropriate load cases are applied to the structure. These have been significantly researched and analysed so that the most appropriate load scenarios can be applied in finite element analysis. Additional research into FEA has highlighted the need for suitable assumptions and the requirement for appropriate documentation so that improvements can be made in future analysis.

Chapter 4 – Methodology

4.1 Introduction

This chapter leads the reader through the tasks within the project that need to be completed to a satisfactorily standard to ensure that the original design objectives are obtained. To ensure that the proposed design exceeds the objectives and requirements of all parties involved with the spray rig, a set of parameters and associated constraints will be investigated.

Outlining the design methodology early in the project allows one to be clear on what exactly is the basis of the design and to develop a set of procedures by which outcome can be judged against the objectives.

Once the general objectives and specifications have been identified the procedure for analysis will be outlined for both the original and the fibre composite designs.

4.3 Design Specification

The design specification is a set of parameters which are put in place so to ensure the final design fulfills the desired requirements. The design of the new spray rig must still be able to function in the way in which allows the SprayCam system to operate at optimal efficiency and in the manner that it was originally designed. The final design should fulfill the following criteria:

- Be able to be used in the same way as it was originally designed without sacrificing any functionality.
- Must be able to support current accessories such as hoods, camera holders and wheel structures. The initial investigation into redesigning the sprayer will maintain the current hood and wheel structure as a means of time saving for this project. Future investigation should be directed toward wholesale changes in design as there are several obvious changes that could be made.

- Must be able to maintain structural integrity during operation so that stresses do not exceed acceptable levels.
- Deflections are to be kept to a minimum so that optics are not affected by a change in focal length.
- Ultimately the spray rig is a tool which the business owner needs to make a profit through selling economically viable units. Therefore the cost must be of an acceptable level when compared to original design and also the competitor's products.

4.3 Overview of tasks to be completed

Considering the original objectives of the project, a range of task can be developed to ensure the project is completed to an acceptable level and in a timely manner.

1. **Objective 1: Convert the current 2D CAD Drawings into a 3D modeller.**
   To determine if the original design was in fact over designed, a number of tasks needed to be completed. At the start of the project there were basic 2D drawings which were required to be modelled in a 3D package. Solid Works 2010 was the chosen software as it is currently used by Rees and also in many other local businesses. By using this program new skills can be developed which will be valuable in future projects conducted by the author.

2. **Objective 2. Conduct an initial finite element analysis (FEA) on the current wing design of the Rees Sprayer. This includes detailed load calculation that acts upon the machine during operation. This will also validate the claim that the original structure is over designed.**

   Once the 3D model of the current spray rig was developed it was then possible to begin the Finite Element Analysis (FEA) on the wing structure. This FEA was conducted using ANSYS: a powerful modeling software that is readily available for use at the University of Southern Queensland. It is possible to conduct high level analysis with multiple load scenarios critical for the analysis of the

Spraycam system using this program. These load cases were determined through the information obtained within the literature review. When conducting the FEA it is important to conduct a sound finite element analysis as outlined within the literature review to ensure the results obtained are accurate and a true representation of the system being analysed. Once this analysis has been completed it is then possible to study the results and determine whether in fact the original design has been over designed for the purpose of a selective spot spray rig.

3. **Objective 3. Investigate and analyse the wing structure with the use of fibre composite sections as the main wing frame as an option to significantly reduce the weight without sacrificing the operation of the machine**.

   Once the original design had been analysed with ANSYS it was then possible to begin the analysis of the proposed composite design. The current version of ANSYS available at USQ does not permit the analysis of fibre composite materials and therefore was not able to be used for this analysis. A proposed design needed to be developed so that it would satisfy the Design Specification (Sec 4.2) and create a viable alternative that could be then analysed in a suitable FEA software. Strand 7 was chosen as the most suitable software due to its availability at USQ. Although Strand 7 is a more basic FEA package when compared to ANSYS, the composite solver which is used is very good and produces accurate results for the purpose of the project. This Strand 7 analysis will utilize the plate element function which produces detailed results of the stresses and deformations that occur within the structure during the loading scenarios which will be applied.

   To analyse the structure using fibre composites it will be required to know the material properties of the pultruded sections. As discovered during the literature review, these can be very difficult to determine from the information provided by manufacturers. It is for this reason data will be obtained from a “CEEFC internal report” which lists these properties and also the testing procedure that was used to obtain the results. Due to confidentiality issues these will not be disclosed within this report apart from the most basic properties that will be used in the analysis.

Once a proposed design has been sufficiently analysed costing data will need to be completed to compare the new composite design to the original. To complete a thorough and accurate analysis would take much time and professional skill to complete to a high level. It is for this reason only a basic costing analysis will be conducted on the cost of material for both the original and the new composite design. This is obviously not a comprehensive analysis and will require much more effort if a composite design were to be built as many factors are not included.

4. **Investigate different methods of joining each composite together and also other accessories currently attached to the wing of the sprayer.**
   The literature review discussed the difficulties associated with joining techniques of pultruded composites. As a result significantly more effort is required in this area of the design process. Without adequate joining methods the design of a composite spray rig is not viable. However through the review of literature it was discovered that there has been a great deal of research done in this area which will be of significant use when deciding on the most suitable joining methods.

4.4 Selection Process

Since a range of decisions will need to be made within the project a method of making these decisions will need to be developed. The report will investigate a range of problems that are faced when completing the project using composite pultruted sections to reduce the weight of the Spraycam Spray Rig. After research into a proposed solution has been completed, it may become immediately clear that the proposed solution is not viable. On the other hand, research may uncover multiple solutions to any one problem. In scenarios such as this, decision matrices will be used as a tool to evaluate the proposed solutions. This is an effective approach to ensure that no proposal is overlooked in the process. The weighted merit system has been investigated and has been shown to produce the most reliable results. This system works by designating the design specifications a ranking (high number = high importance). Each design will then be ranked against these parameters and depending how well they meet the requirements will be given a number (high number, the better the specifications were met). This number will then be multiplied by the level of importance to give the overall grade. This system works well when compared to other methods such as the "Merit System" which rates each design against non-weighted criteria. In this case each criterion is given the same amount of importance as each other, providing unsuitable answers if the one criterion is more critical than another.

4.5 Chapter Conclusions

When performing a project such as redesigning the SprayCam Spray Rig, it is important to have a clear understanding of the tasks that are required to be completed. These have been outlined within this chapter including the specifications which need to be completed so that the proposed design can be analysed to ensure that it meets the requirements outlined by the manufacturer and business owners.

The method of selecting the most appropriate fibre composite section has been outlined and also the selection process used to determine the correct solution to an identified problem. With these key processes outlined the basis of the analysis of the proposed fibre composite design can now be conducted with the knowledge that the acquired results will be of an acceptable standard.

Chapter 5: Design Analysis

5.1 Introduction

This chapter highlights the results obtained by the analysis of both the original design and the fibre composite wing design. It outlines the process taken to create the appropriate finite element analysis including all the appropriate calculations of the loading cases and also the issues which were overcome in producing the desired results.

5.2 Analysis of current design

This sections aims to provide the reader with suitable information that was used to create results obtained in the Finite Element Analysis of the current SprayCam Spray Rig. It includes many sections which have been investigated to ensure a thorough analysis of the system is completed. It includes details of the major features of the current SprayCam Spray Rig along with its competitors in the current marketplace. Calculations of the load cases and position of these loads are all defined and the appropriate calculations regarding these cases are presented. This section includes the restraint conditions that were used to ensure the analysis provides the most accurate results. Following these sections, the finite element analysis results of the current spray rig are presented including all results obtained.

5.2.1 Current Design

The current Rees cameras have recently undergone considerable redevelopment to improve their accuracy at detecting and spraying weeds. The technology requires highly moderated light sources to operate at the optimum level and operating the camera system during daylight hours is not possible without the use of a specialized hooded spray rig which produces artificial darkness. The current design utilises large over-hanging hoods covered in thick black plastic on the front and rear of the machine to prevent light penetration. These covers sufficiently reduce the amount of light entering the machine so that once the sprayer is in operation, there is no costly stopping and starting to recalibrate the sensors.

The current 18 meter Spray Rig was designed in 2003 and has been in use since its manufacture. It is a very large machine in comparison to competing spray booms as it is required to significantly restrict natural light entering the camera zone. Weighing more than 2 tonne the complete Rees SprayCam System is considerably heavier than others in the market. Depending on farmers operation the machine can be used as an 18m or 16m sprayer. The 16m size works very well with farmers who use 8m planters or a factor thereof e.g. 16m, as the same wheel tracks can be used to ensure ground compaction is kept to a minimum. Whereas the 18m machine can be used comfortably where farmers use 12m as two passes of the sprayer is equivalent to 3 passes of the planter. The design was originally taken from a larger machine, a 24m wide sprayer and reduced to its current form as a pre-production unit. The difference between the two wing sections are the addition of an extra set of wheels located further out on the wings and an extra 3m section. This allowed the buyer to choose a suitable width machine for their desired farming application. Being designed to be a larger machine makes the current machine much heavier than it needs to be. However this also has its advantages, since owners have the opportunity to change the size of their sprayer if the need arises. If for example a new 12m planter is bought to replace an 8m machine then the operator can either choose to maintain the current machine or upgrade it to a larger 24m sprayer. As mentioned in Chapter 2 many farmers have adopted controlled traffic approaches to minimize traffic across their paddock and therefore the 24 m machine would ensure no additional wheel tracks across the field. The 24m machine would be the most popular machine for many farmers as it enables them to cover more ground faster with the larger machine.

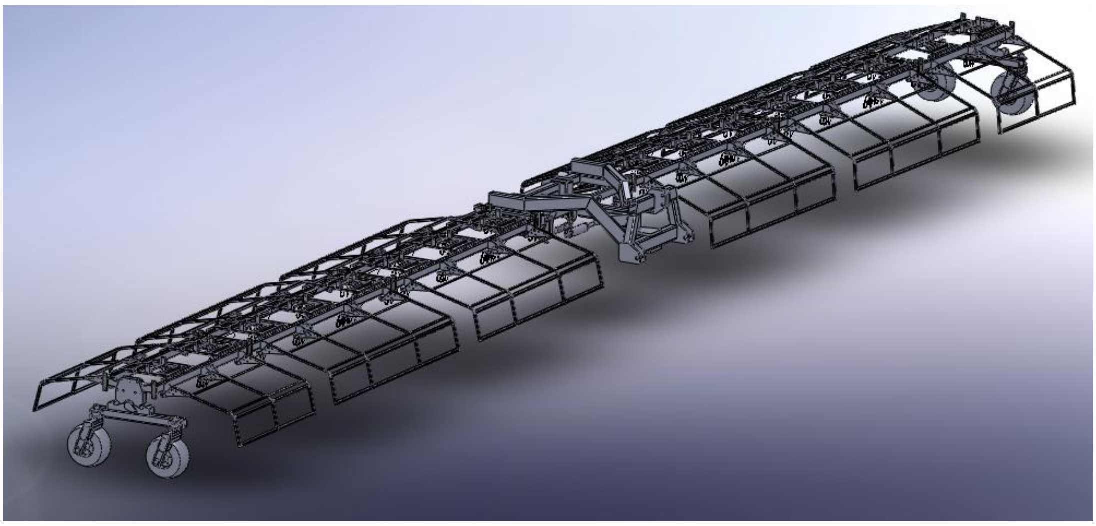


Figure 19: The SprayCam Spray Rig

The current design consists of a 2m wide centre section which is connected to the tractor via a three point hitch. This centre section is then connected to the wings on either side. Located at this connection are pin joints Figure 20 which allow each wing to pivot up and down as the machine moves over undulating conditions.

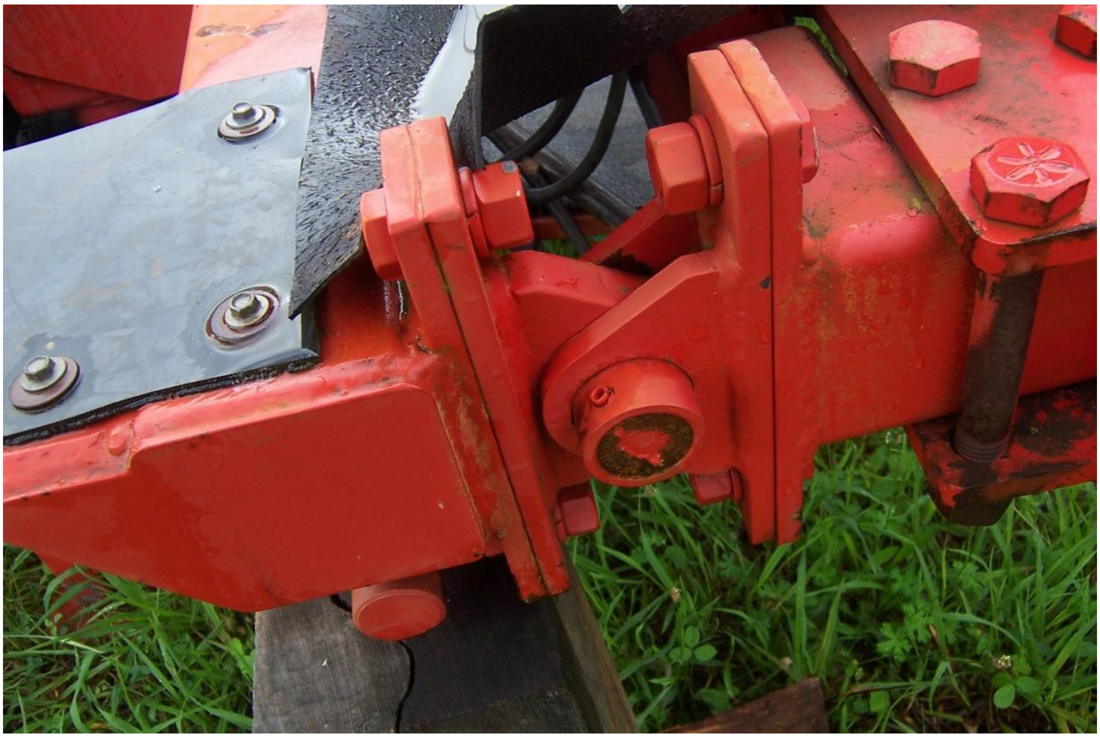


Figure 20: Wing Pivot Point

To ensure the machine can be transported from one paddock to another, the entire wing sections fold behind the centre section allowing for easy transportation. This is illustrated in Figure 21.

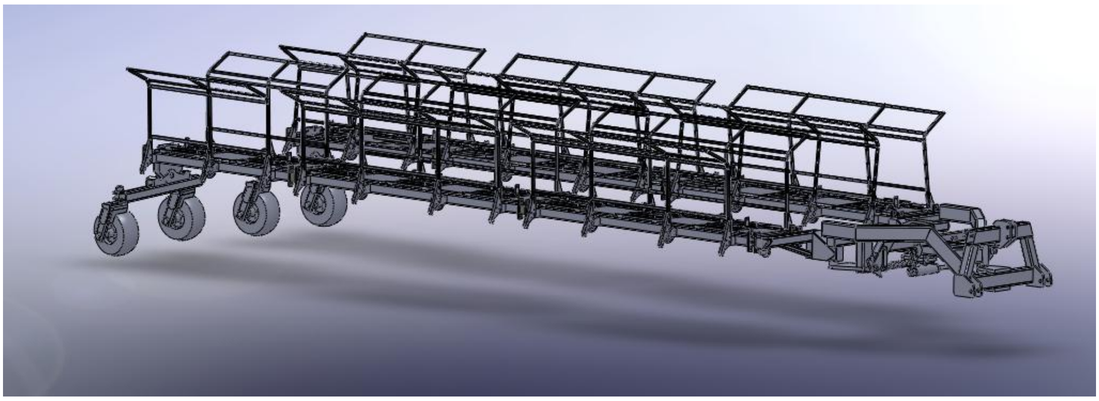


Figure 21: Sprayer in transportation mode

To allow the wings to go from the operating position to the transportation mode the current design incorporates a wing locking mechanism which is used to secure the wing in position whilst in operation. This locking system is shown in Figure 22. When a hydraulic cylinder extends, pins on the wing lock into position. This cylinder remains in the extended position whilst in operation ensuring that pressure is maintained on the wings so that they do not return to the transportation position. If an obstacle is struck by the wing, the design allows the springs shown to compress and release the wings so that no major damage occurs to the machine. To release the wing for transport it is as simple as contracting the hydraulic cylinder which lessens the force required to release the wing and the operator drives forward folding the wings to the transport position. This system allows the operator to choose the amount of force which is suitable to ensure the wings remain in place during operation. It is recommended that only slightly more pressure is added to ensure that the system releases when required without any additional stress occurring to the design.

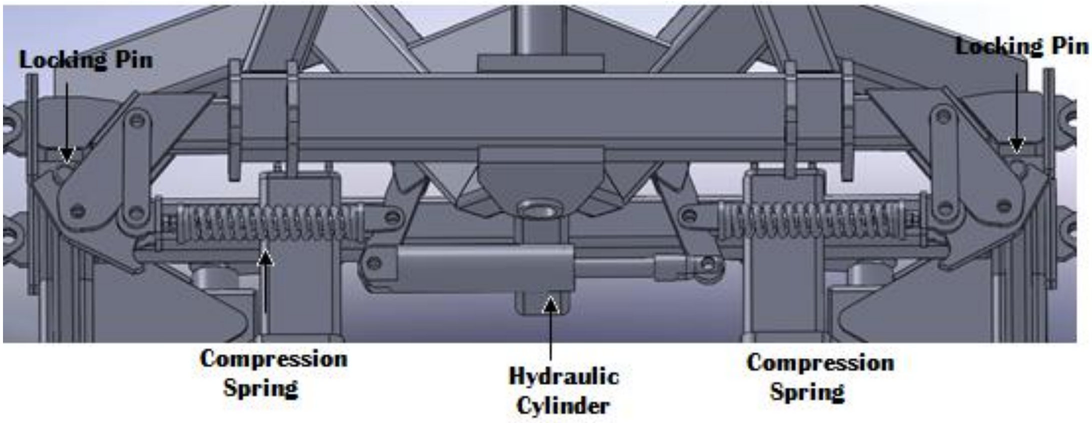


Figure 22: Locking Mechanism

To create a stronger more rigid wing structure the original design incorporated a stiffening member beneath each main wing structure. From investigations into the original plans and drawings available it is believed that this member was an addition to the design and was not originally accounted for within the design. Comments passed on from the business owners suggest there was a problem with deflection in the wings which affected camera performance. The addition of this 'brace' adds additional stiffness to the structure to ensure deflection is kept to a minimum during high levels of stress. The main reason for this is so the cameras maintain a focal length of 1m and to ensure the design does not prematurely fail due to fatigue. To ensure this deflection did not become a problem engineers devised a solution that utilized a series of RHS beneath the structure that housed a thick metal rod which is connected on the inside and outside of the wings frame. This effectively created an inverted truss which could act against the dynamic force acting downwards during operation ensuring a much stiffer frame is produced.

If required this technique of strengthening and stiffening of the structure may be further utilized in the development of a composite design to further reduce weight while maintaining the structural integrity of the final design

5.2.2 Existing Designs

The spot spraying industry is a relatively small area of the agricultural industry as the initial capital cost is quite high. There are two main competitors in the current market place; Weedseeker and Weedit. These two technologies utilize the infrared spectrum to identify the weeds within the field. These technologies allow the machine to operate at all periods of the day or night. However calibration is an issue during the day with sensors having to be re-calibrated many times to account for varying levels of infrared produced by the sun throughout day.

Unlike the Rees cameras these designs can be attached to original sprayers that farmers own and therefore chemical application can occur at any time of the day or night without the need for custom made sprayers.

Figure 23: The Weedseeker design (Source CropOptics 2010)

It may seem obvious from the information presented in the above section that the Rees technology suffers substantial limitations in the face of competition with other spot spraying systems. However, the competing technology does come with its draw backs. From information obtained by Mr. Steven Rees the Weedseeker along with Weedit do come at a high price of approximately $6000-$6500/m compared to the expected cost of the SprayCam System at $1500-2000/m. Furthermore to allow the existing sprayers to operate during the daylight hours, the sensors need to be recalibrated numerous times to account for the varying levels of infrared at different times of the day. Therefore with the use of a cost effective spray rig design the SprayCam system can effectively compete in the current market.

5.2.3 Solid Model

As mentioned in Chapter 1, the first objective of the project is to convert the current basic 2D Drawings into a more comprehensive solid model. Solid modeling has many advantages over 2 dimensional drawings which include ease of conducting an FEA and also any problems regarding interferences can be clearly identified.

To successfully conduct an accurate finite element analysis using ANSYS, it vital that an accurate solid model is created to ensure the accuracy of the results. Once the model has been created with a suitable modeling package it is a relatively simple task of importing the model into the FEA package to begin the analysis.

The second advantage of using a solid modeling package to produce designs is that many discrepancies that may exist in the design are more clearly visible through part rotation etc. This includes any interference that may occur with the design. Problems with a design can be clearly identified early in the design process meaning that changes in the design can be conducted before any prototype or production design is made. Unlike 2D drawings where it is very difficult to visualize such problems; time and money can be saved by the use of solid modeling software.

Much time and effort was required to complete the entire 3D model of the SprayCam Spray Rig. The chosen program was Solid Works as this is the program used by Rees Equipment as well as many other companies in the engineering industry. It is seen as the industry leader and it was for this reason the software was chosen over others as it gives the opportunity to gain new skills that will be of an advantage in the author's future career.

To ensure the solid model created is of use for future research and development conducted by Rees, the model must be of a high standard and quality. This requires all drawings to be competently converted from the 2D drawings into the 3D software.

With almost one hundred separate drawings it was vital to allocate a suitable numbering system to each drawing. The system that is used is a common method in industry assigning each drawing either a -100, -200, -300 series parts. The -100 series parts are drawings that are required for the final assembly. While the -200 drawings are sub-assemblies that will later be used in the final assembly, while the -300 series drawings that will be placed into the sub-assemblies e.g. bushes.

Developing the parts required to create the final assembled spray rig took several months. Over this time it was found that many of the required measurements were omitted from the current 2D drawings. Fortunately, the pre-production unit was available for measurements of dimensions and little time was lost.

Like the omitted dimensions, the solid model revealed problems with the current drawings. Assembly of the drawn parts began with small errors; however, as mentioned previously solid modeling can reveal problems with designs that may otherwise go unnoticed. This is particularly true during the assembly of the locking mechanism. The 3D model clearly showed that the locking pin would be interfered with before it was able to completely lock into position. During manufacturing this problem was most likely identified and as can be seen in Figure 24 below, a small area (circled in black) was removed so the latch could operate correctly.

Figure 24: Modification to sprayer design after the design completion

This is a major advantage of the use of solid modeling software as it greatly improves the accuracy of designs. However this is not the only advantage as it also improves the speed of design and manufacture. The above fault would have caused extra time and delays to the manufacturing process if unidentified during the design stage. While this was only a small problem other errors may not be as easily fixed causing lengthy delays to manufacturing, emphasizing the importance of 3D modeling.

5.2.4 Load Cases

Suitable loads will be applied to the wing structure to obtain reasonable results from the FEA. This section will calculate the appropriate forces acting on the sprayers wings according to the literature reviewed in Chapter 3.

As been noted in the current design section of this report, varying levels of release pressure can be placed onto the wings by changing the compressed length of the springs (shorter the springs = higher release force as can be calculated by the equations used to calculate the spring force). The compression force of a spring can be calculated by the using two parameters, '*k'* the spring constant (N/m) along with the distance of compression '*x*' from the original resting condition. With the simple equation F= kx, the force can be calculated. Since the initial length of the spring can be altered via the tightening of adjusting nuts there is a wide range of forces that can be created by the system. The force stopping the wing from releasing can also vary as contacting surfaces rust together making movement very difficult. It is for this reason that it is recommended that the operator conduct field test on this release force so that only adequate forces are applied.

For the analysis of the wing structure it will be assumed that the release force of the locking mechanism is only slightly larger than that of the force required to hold the wing in its normal operating position. This will ensure that if any obstacles are encountered during operation, the wing will release minimizing any damage to the sprayer.

5.2.4.1 Dynamic Load

From the literature reviewed, a suitable load case for the dynamic forces applied to the wing while in operation e.g. bouncing over uneven ground will be twice that of static load. This doubling of the static load is produced by creating acceleration due to gravity that acts on the structure that is twice that of the normal $9.81m/s^2$. It is also important that this doubling effect is also added to the load created by the hood section as well. This involves multiplying the total static load by two. Shigley (1963) however found that this is a conservative estimate and therefore will ensure that the structure can withstand all operations in the field.

5.2.4.2 Wheel Rolling Resistance

Within section 3.3.1 the information and equations required to determine the rolling resistance forces created by the wheels were discussed and outlined. The method that was chosen as the most suitable after reviewing the literature for use in this application is the method of using the Gee-Clough equation. However as a method of verifying the results the approached outlined by Professor Edward McKyes of McGill University, Montreal was also used.

To determine the rolling resistance of the spray rig's tyre it is necessary to determine the tyre mobility number. This is a dimensionless parameter that takes into account the size and geometry of the tyre (Diameter: 0.521m & Width 0.2m) as well as the operating conditions of the soil. The final parameter that determines the mobility number is the vertical load on the tyre. The greater this vertical load the greater the rolling resistance will be. Due to the lack of available measuring devices at the location of the spray rig the Solid Works feature of measuring the mass will be used to determine the load on the wheels.

The load on each wheel was determined by finding the mass of the total wing section which then can be used to find the reaction supports at the wheels. Once this load is determined the wheel structure load can be added to gain the vertical load at each wheel.

It should be noted that the load on the wheels will vary with the creation of a new composite design and therefore, so will the rolling resistance created by these wheels. Meaning that the forces created by the wheels need to be recalculated with the new design load of the composite wing structure.

The tyre mobility number can be determined by the following equation

$$M = \frac{CI \times b \times d}{W} \times \sqrt{\frac{\delta}{h}} \times \frac{1}{1 + b/(2 \times d)}$$

Where:

b = tyre section width, m; 0.2m

CI = cone penetration resistance, kN/m

D = undeflected tyre diameter, m; 0.521m

h = tyre section height, m;

W = vertical load on the tyre, kN; 2.3882kN per wheel, and

δ = tyre deflection, m

The rolling resistance will be calculated in the worst case scenario that the wing may be subjected to. This will occur when the wheels enter a very wet muddy area. The cone penetrometer reading in such a soil reading is approximately 100kN/m according to the Agricultural Machinery Study Book 2010. Utilising these values the Tyre Mobility Number can be calculated as follows:

$$M = \frac{100 \times 0.2 \times 0.521}{2.3882} \times \sqrt{0.2} \times \frac{1}{1 + \frac{0.2}{2 \times 0.521}}$$

$$M = 1.637$$

It should be noted that this rolling resistance that is created by the wheels would be a worst case scenario since a 100kN.m cone penetrometer reading is for extremely wet muddy soil. Since the application of this machine is a selective spot weed sprayer the machine will not be used in such situations and therefore will very rarely if ever encounter such environments. However it is still very important that this be investigated as it is not possible to control the actions of an end user.

Once the mobility number has been identified the rolling resistance can be determined by the following equation as presented in Chapter 3:

$$Rolling\ Resistance = \left(0.049 + \frac{0.287}{M}\right)W$$

$$RR = 535.714N/Wheel \text{ or } 1071.43\text{N}/\ Wing$$

As mentioned verification of this force was also conducted using the approach outlined by Professor Edward McKyes:

$$R = W\left(\frac{z}{d} + 0.02\right)$$

Where:

R = rolling resistance force

W = total vertical force from the wheel to the ground; 2.3882kN

z = tyre sinkage in the soil

d = overall tyre diameter, m; 0.521m

The tyre sinkage is difficult to measure in varying soil conditions however on soil located near Cecil Plains on the Darling Downs of Southern Queensland the sinkage of the soil is approximately 50-100mm.

Using an approximation of 100mm as the sinkage of the soil, the equation presented by Proffesor Mykes produces the following results:

$$R = 1.89\left(\frac{0.100}{0.521} + 0.02\right)$$

$$R = 507N/Wheel$$

When comparing this result to the original method of using the Gee Clough equation the results are very similar and it can be assumed that the results obtained by these methods are an accurate representation of the loading case.

As discussed in the literature review, one of the major contributing factors to rolling resistance is the load which the wheels are required to carry. Therefore any change to this load will change the rolling resistance which the wheels create. So to correctly analyse a new spray rig made of fibre composites it is necessary to identify the new load which the wheels will carry and in turn the new rolling resistance.

5.2.4.3 Wind Resistance

As outlined in Chapter 2, determining the wind resistance on the spray rig wing can be conducted by considering each wing as cylinder then simply halving the force to gain the desired load on the wing due to wind resistance. The following equation can be used to determine the force on the wing

$$C_D = \frac{\left(\frac{F_D}{\frac{1}{2}\rho V^2 A}\right)}{2}$$

Where:

F_D = Drag force

ρ = Density of the fluid which for this analysis is taken at its most dense state which is 1.252 kg/m^3

V = Velocity (m/s) of the air traveling over the surface of the sprayer at its operating speed of 24km/hr however 30km/hr will be used to ensure speed variations are accounted for.

A = Frontal projected surface area, and

C_D, can be calculated by Figure 18 on page 44

The parameter of Reynolds number (R_e) can be determined by the following equation

$$R_e = \frac{\rho U_\infty D}{\mu}$$

Where:

ρ = Maximum density of the air

U_∞ = The maximum free stream velocity of the air

D = Diameter

μ = Absolute viscosity

The varying properties of air have been taken from Bohn, Manglik and Kreith, 2011, Apendix 2, Table 28

Substituting all the values into the Reynolds equation,

$$R_e = \frac{1.252 \times 8.33 \times 2.435}{17.456 \times 10^{-6}}$$

$$R_e = 1.4553 \times 10^{-6}$$

Reading the C_D from Figure 18 gives a result of 0.25

Substituting this value into the coefficient of drag formula gives a drag force of 423.081 N.

This is the total force over the entire section of each wing and therefore when conducting the analysis of each wing this load should be applied at the mid section of the structure.

5.2.5 Load Positioning

To accurately simulate the loads outlined in section 5.2.4 it is important to position them at the correct location on the structure.

Since the force created by the wind resistance acts over the entire section of the wing (a universally distributed load), the combined force when acting as a point load will act at the centre of the structure. When selecting a face for a load to act upon in ANSYS the load is set to occur in the centre of the face. Because this load does not occur at the centre of any face it is important to relocate the load to the midpoint of a geometries face. This can be done by using the following equation.

$$Relocated\ load = \frac{Original\ distance\ from\ pivot\ point}{New\ distance\ from\ pivot\ point} \times original\ load$$

Therefore, to relocate the wind resistance force (3917.5mm) to the two meter wing section whose midpoint is 6917.16mm from the pivot point, the new force acting at this location will be 3917.5/6917.16mm multiplied by the original smaller force. This same method will be used to relocate the force created by the rolling resistance to a suitable location to give more reliable results.

It is important that the load created by the hood structure is applied correctly in order to simulate the machine whilst in operation. Loads on the hood were investigated in two different locations. The first was to give a more basic analysis where-by the entire load of each hood was placed at the midpoint of each section. This can be seen in the following diagram. This method will more closely represent the load cases that will be applied to the Strand 7 model.

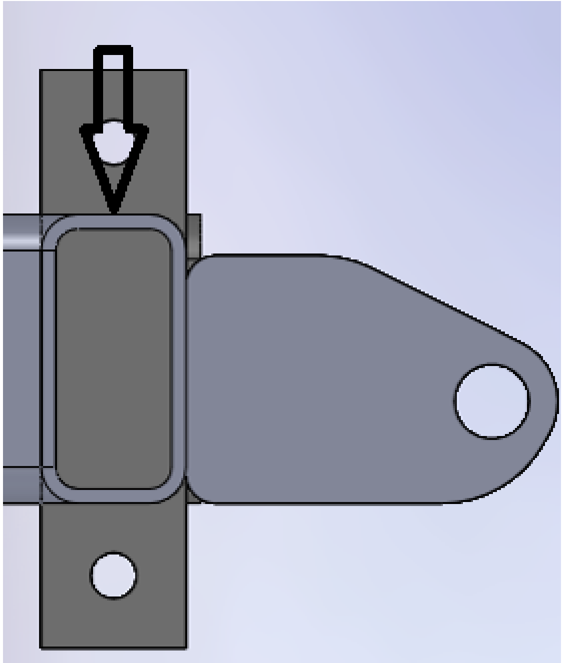


Figure 25: Load case 1

The second method used was to include the hood pivots within the design. The pivot point housings positioned the load 105mm away from the RHS. This creates both a downward load and also a moment onto the RHS as shown in the below figure.

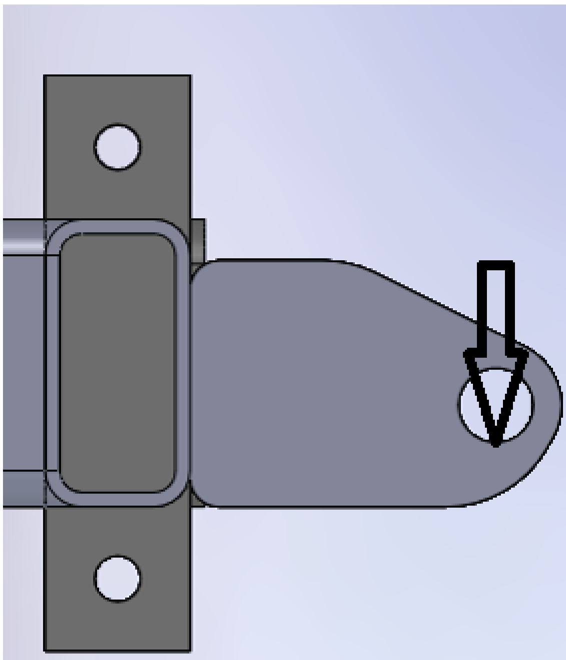


Figure 26: Loading Case 2

The load was distributed evenly over all pivot points and across the wings frame. Both these methods were compared to determine validity of the results that would be gained by the Strand 7.

The final load case to be placed upon the structure is the force created by gravity. This force is applied to all bodies within the finite element analysis and as mentioned in the previous section, it should be doubled to factor in the forces created by dynamic load. This acceleration was then applied to all bodies within the analysis in the negative Z direction (i.e. downward).

5.2.6 Support Positioning

Both ANSYS and Strand 7 offer a vast array of options when determining suitable support methods. To ensure accurate results are obtained through the finite element analysis correct, support reactions are required to simulate the supports that occur on the machine. The wing structure is supported at either end of the frame; located at the outside of the wing the wheels support the frame preventing any rotation and any vertical motion. While on the inside, a pin joint allows the wing to rotate about the axis of the joint but does not allow any linear motion to occur in any of the three dimensions.

To simulate the pin joints, transverse movement in all three dimensions are restrained while the same is done to the rotational movement in all directions except for the dimension in the direction of travel (Y-direction) as shown in Figure 27. The movement allows the wing structure to move up and down to follow the contours of the land without placing unnecessary strain on the machine. It also ensures that a constant height is maintained across the wing at all times keeping the weed detecting cameras in focus and working at their optimum height. In conjunction with this support the reactions located at the outside of the wing restricts linear motion in the Z-direction(Up and Down) while the other two dimensions are allowed to freely move, whilst rotation is restricted in all directions due to the wheel structure preventing this from occurring.

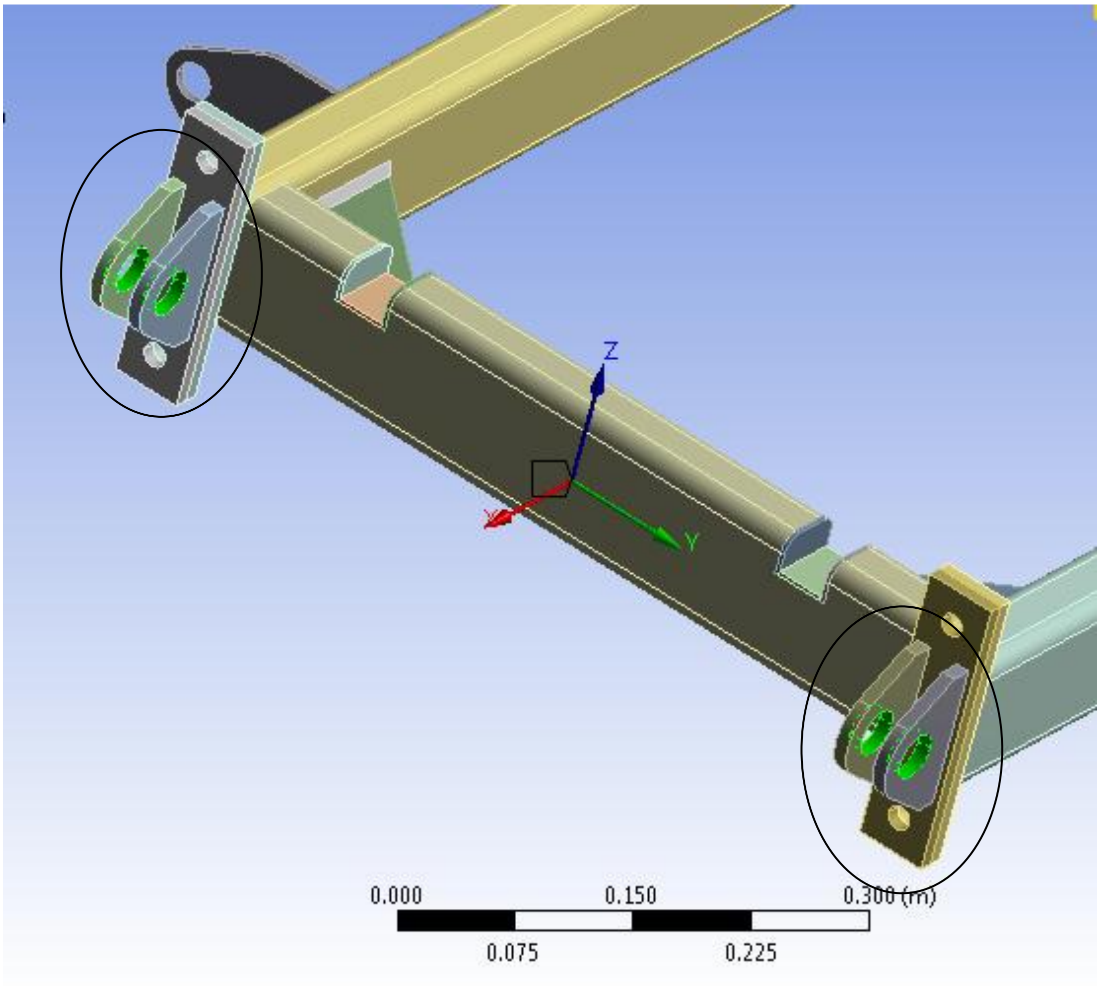


Figure 27 Axis location for pin joint assembly

5.2.6 Verifying the finite element analysis results

Through the literature review it was discovered that FEA simulations analyse all models with relative ease, however the quality and accuracy of the results may be questionable until other methods are used to verify them. The method that will be used for this project will be the use of a simple bending moment equation to calculate the bending stresses within a beam. The calculations do not require in depth analysis as they are simply a tool to verify whether the results of the FEA are suitable.

For this simple analysis a single beam will be analyzed to verify the results. Since only one of the beams in the analysis will be analysed it is expected that the results obtained will be of a higher magnitude than those of the FEA.

Since the load created by the hood structures is applied at 1 metre spacings over the length of the sprayer, it is possible to consider the total load which they create as universally distributed load (UDL) over the whole beam. This method is verified by the Structural Design 1 Studybook which shows that if a load is applied frequently enough over the length of a beam then the loads can be transformed to a UDL. This is not the only UDL that acts upon the structure. The load created by the weight of the beam should also be applied in the same way, remembering that loads should be treated as dynamic, effected with an acceleration twice that of gravity.

The stress within the beam can be calculated by the following equation which has been taken from the Structural Design 1 Study Book 2010:

$$\sigma_B = \frac{My}{I}$$

Where;

M = is the maximum moment created within the beam,

Y = is the distance from the centroid of the section to the outer most edge of the section where the maximum stress will occur, and

I = the second moment of area of the cross section.

The maximum bending moment created by the UDL's on the structure can be calculated by the following equation:

$$M = \frac{\omega L^2}{8}$$

Where;

ω = the magnidtude of the UDL in N/m

L = the length of the beam.

Once these values have been calculated it is possible to compare the results to the FEA to determine the level of accuracy.

Through the use of simple hand calculations it is also possible to determine the deflections within the beam. This maximum deflection can be calculated by the following equation (Structural Design 1 Study Book):

$$\delta = \frac{5}{384}\left(\frac{\omega L^4}{EI}\right)$$

Where;

E = is Youngs Modulus, Stess/Strain, of the material.

I = Second Moment of area

5.2.7 Current Design Finite Flement Analysis

As mentioned in the Chapter 3, ANSYS was used as a Finite Element Analysis technique to obtain the results required for the task. To gain a suitable analysis it was important to complete many FEA's to improve accuracy. Manual verification ensured the validity of individual elements and in turn the validity of the final outcome. This process was carried out by investigating different load scenarios and then applying them to the analysis. This verified not only the load scenarios but also the model itself by ensuring any problems associated with its creation were identified.

As mentioned in section 5.2.6 the load created by the hood structures would be analysed by two methods which were outlined in this section. The two different approaches gave varying results, which will be outlined below.

The first setup to be analysed (Load Case 1) was to apply the load of the hoods directly to the top and middle of each section. The results of the FEA are shown in the following three figures.

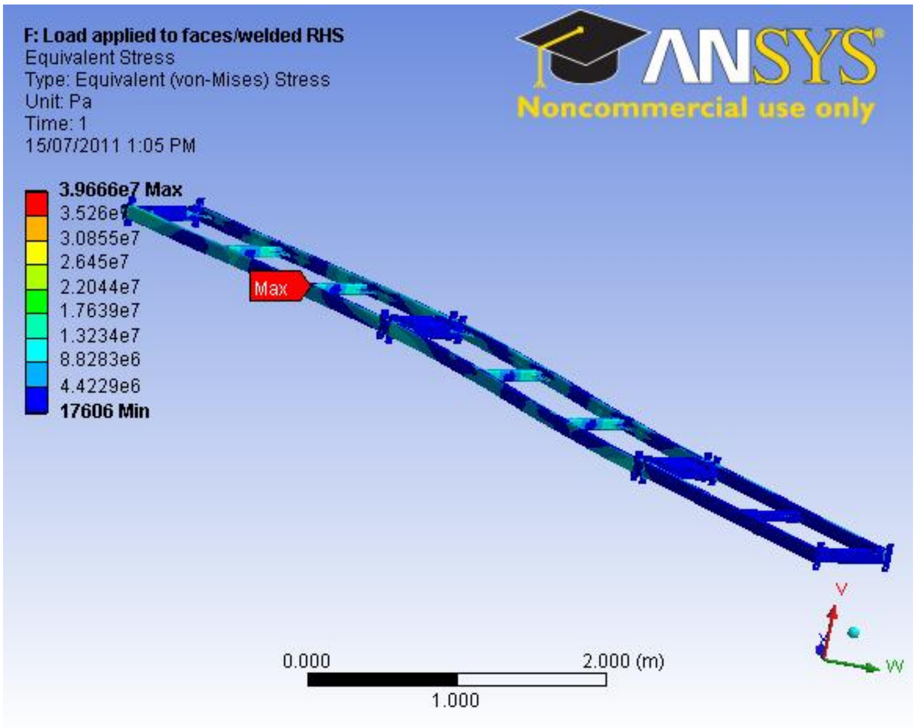


Figure 28 Stresses created within the wings structure loading case 1

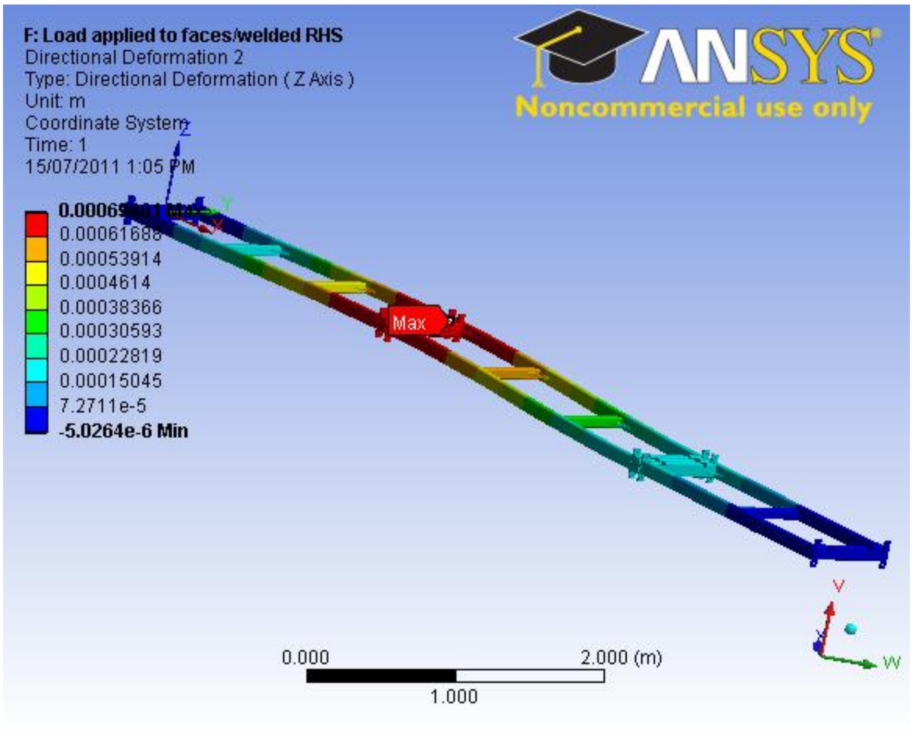


Figure 29 Deformation in the 'Z' direction during load case 1

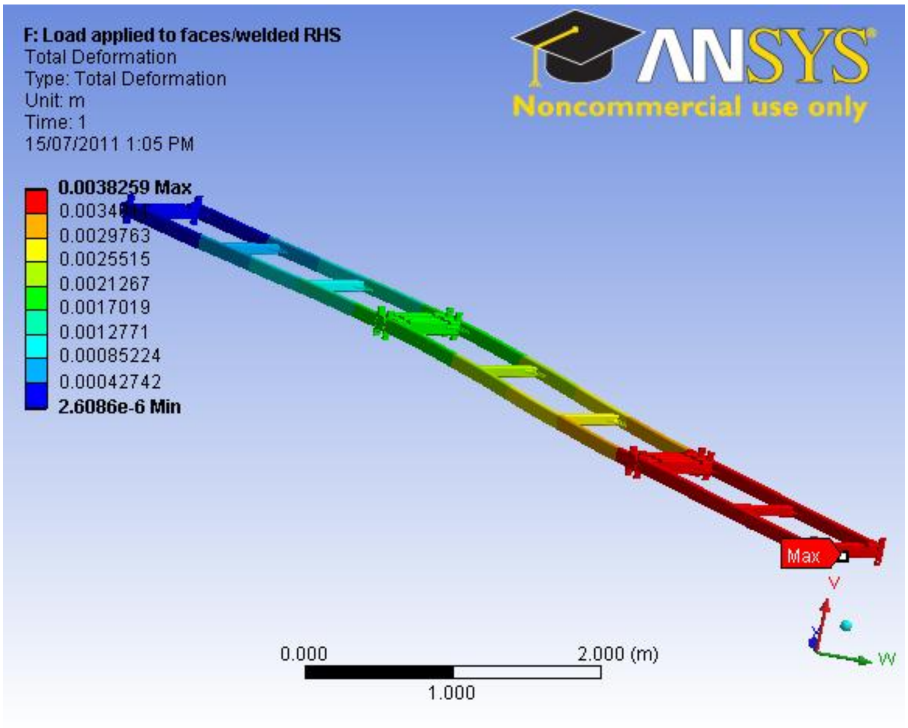


Figure 30: Total deformation of the structure during load case 1

As mentioned, load case 1 is a basic analysis which allowed any locations of interest to be identified. This ensures that all support positioning is accurate and correct, load cases are applied in correct locations and are suitable.

On inspection of the two deformations (Figure 29 and Figure 30) it can be noted that the maximum defections occur at positions that are acceptable for such loading and support positioning. The maximum deformation in the z direction occurs towards the center of the structure which is to be expected. However the total deformation occurs at the end of the beam which likewise is expected. This latter deflection is created by rolling resistance of the wheels as well as wind load acting on the structure. The stresses that these deformations create on the structure would be expected to create a greater stress on the structure as in this orientation the frame is only supported at one end, similar to a cantilever with a length of almost 8 metres.

The stresses that the three load cases produce on the structure produces a maximum stress towards the pinned end of the structure and the side where the structure is in tension due to the rolling resistance and drag force. These forces create the maximum stress at the pinned joint end while the forces created by the mass of the wing and the hood section create a maximum stress near the midpoint of the structure. Once these two are combined the maximum stress occurs somewhere between the centre and the pinned joint. This is shown by the Finite Element Analysis in Figure 28.

Simple bending stresses (σ_B) were then developed on a single beam to determine if the magnitudes of the stress were correct. This is yet another means of verifying the results produced by the FEA. Although the stresses that will be calculated are an approximation they give some indication of whether the model is correct. It is expected that these approximations will be higher than the FEA since only a single section of RHS is being analysed instead of the entire section.

Through the use of the equations outlined in Chapter 3, the bending stress can be calculated as follows:

$$\sigma_B = \frac{\left(\frac{280 \times 8^2}{8} + \frac{215.6238 \times 8^2}{8}\right) \times 0.05}{\frac{0.05 \times 0.1^3}{12} - \frac{0.04 \times 0.09^3}{12}}$$

$$= 1.142 \times 10^8 \ Pa$$

$$= 114.2 \text{ MPa}$$

From the above calculations it is easy to see that the assumption that the magnitude of the stresses calculated by this method would be larger than those of FEA, is correct. Although the calculation is considerably higher than those of the FEA this would be expected since only a single beam is analysed without any of the extra bracings to provide extra strength and support.

Through these simple analyses, it can be seen that setup of the Finite Element Analysis produces results in the correct location, direction and with reasonable magnitude.

Since this method of verifying the FEA showed that the results obtained were of a suitable magnitude, it is therefore possible to continue with the other FEA's to determine more accurate results.

Load case 2 was then applied to the frame. As mentioned it involved the load of the hoods being directly applied to the pivot points. This gives the analysis a more representative load case than the first and therefore more accurate results. The following figures illustrate the results that were obtained.

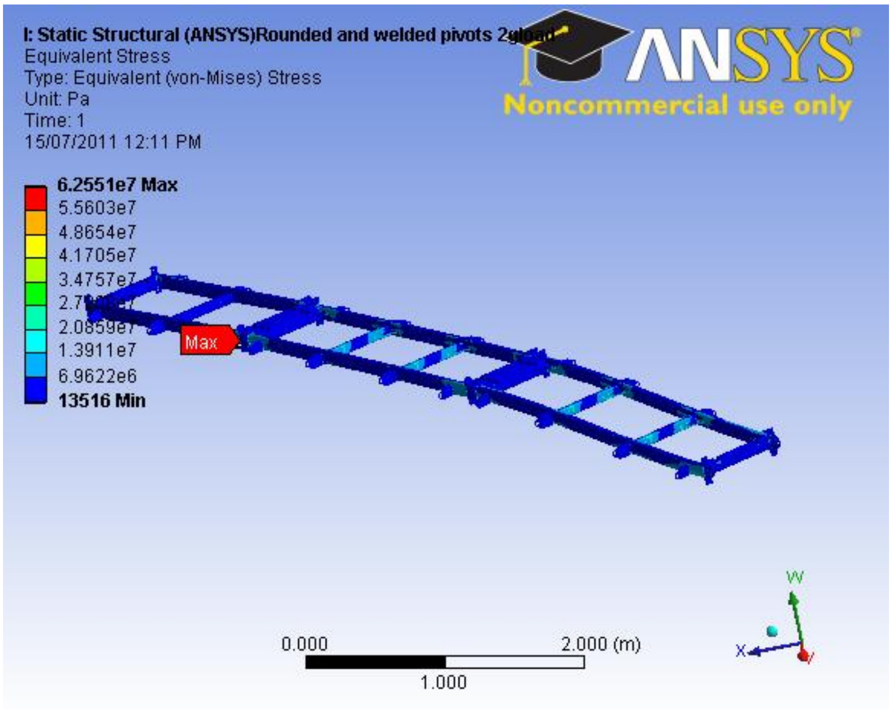


Figure 31: Stress created during load case 2

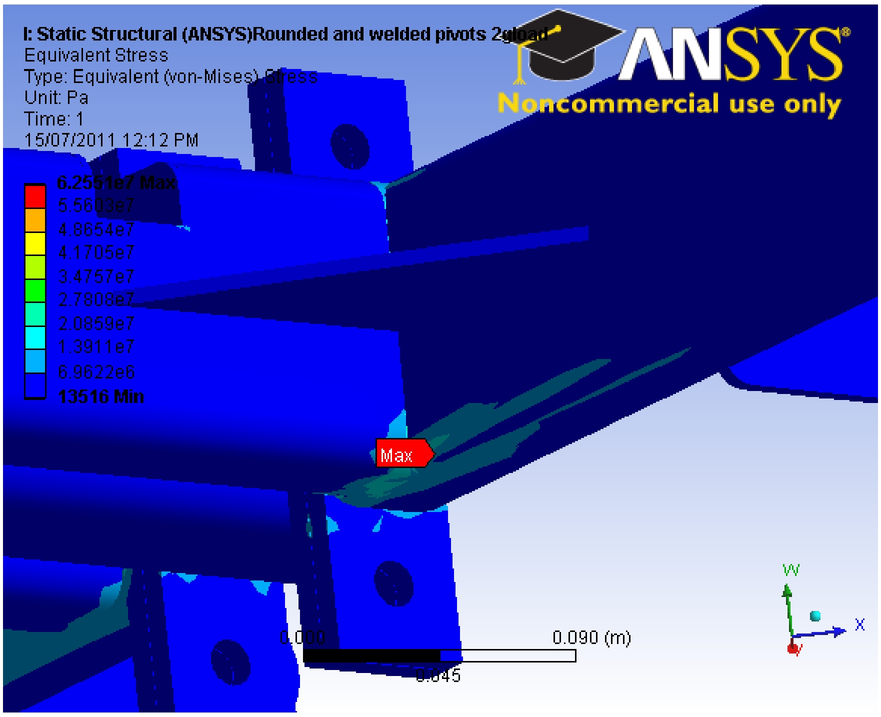


Figure 32: Maximum stress within the frame during load case 2

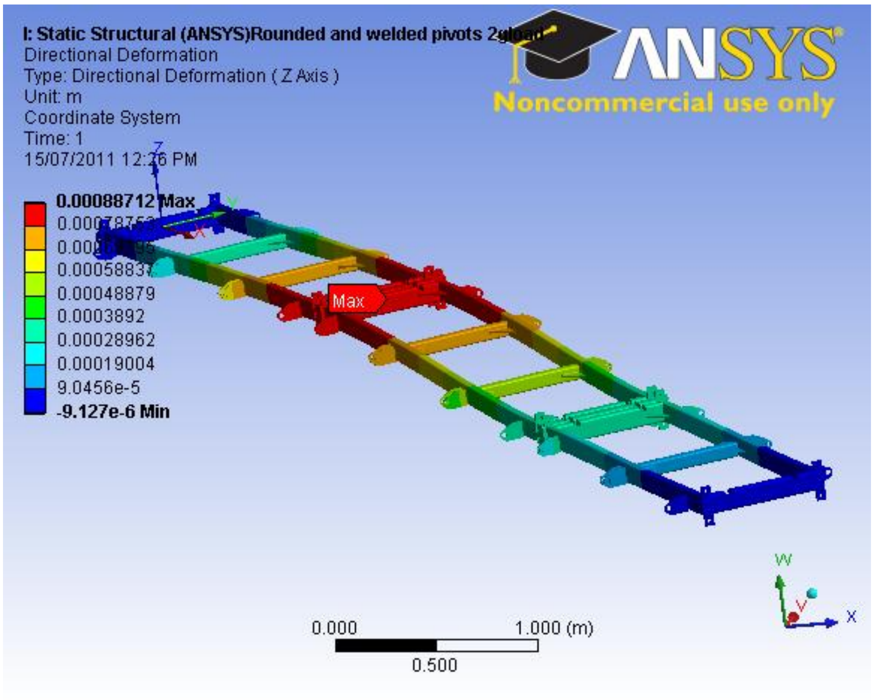


Figure 33: Maximum deflection in the Z direction during load case 2

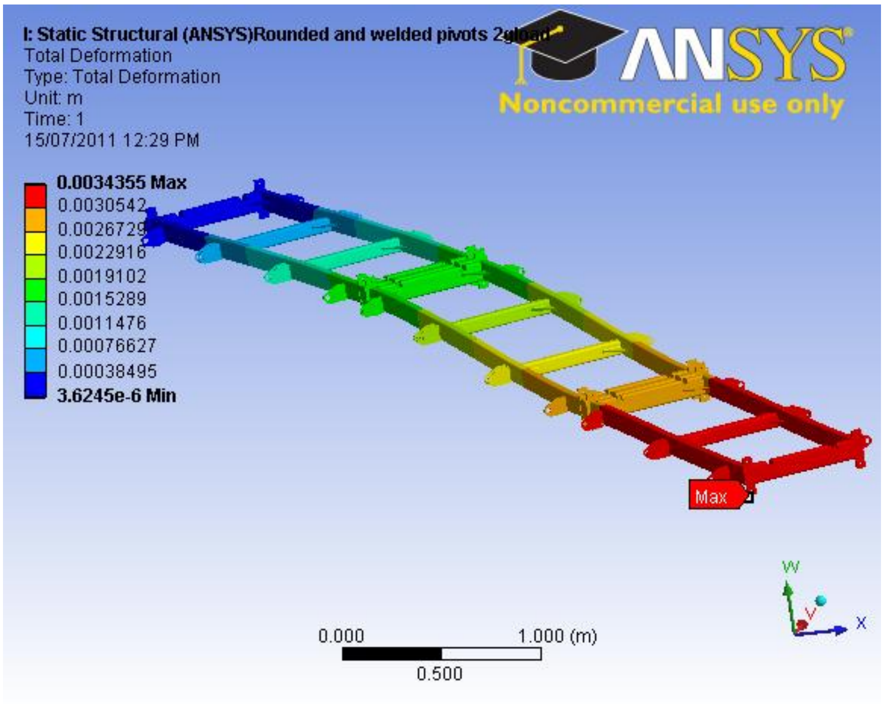


Figure 34: Total deformation during load case 2

It can be seen that the results obtained by this load case creates higher stress on the wing's frame than that of load case 1. The maximum stress increased to 62.5 MPa up from 39.7 MPa. Such levels of stress show that the original design has a factor of safety of no more than 4 if assuming the steel has a yield strength of 250 MPA. A safety factor of 4 is rather small when compared to the usual factors which are used within the agricultural industry. Such factors are used in tough conditions when unexpected loads may be applied to the design. Therefore this industry has a reputation for over designing much of their equipment which leads to large and heavy equipment being produced. However I feel it a better to compare the design to other sprayers, where loading cases are known and predictable, a safety factor of 4 is rather high and is acceptable. It was identified within the previous Section 5.2.1, that a stiffening member had been added to the existing design of the sprayer after it had been manufactured. This member ensured the structure did not deflect causing the cameras to lose focus and affect the quality of the spraying application. The analysis shows only very small variations in the deflection and would therefore believe this to be a precautionary measure as the old camera design was very sensitive to changes in height. I believe that this would not be an issue with the redeveloped digital cameras as this is no longer such a large issue

5.2.8 Issues overcome during the FEA process

There were many issues to be addressed to ensure the validity of the finite element analysis. The largest of which was to ensure that all joints were correctly welded in the model. Problems were found with the SolidWorks software which did not allow for welds to be produced in specific areas where RHS was butt joined to each other. An example of this is illustrated in the following figure.

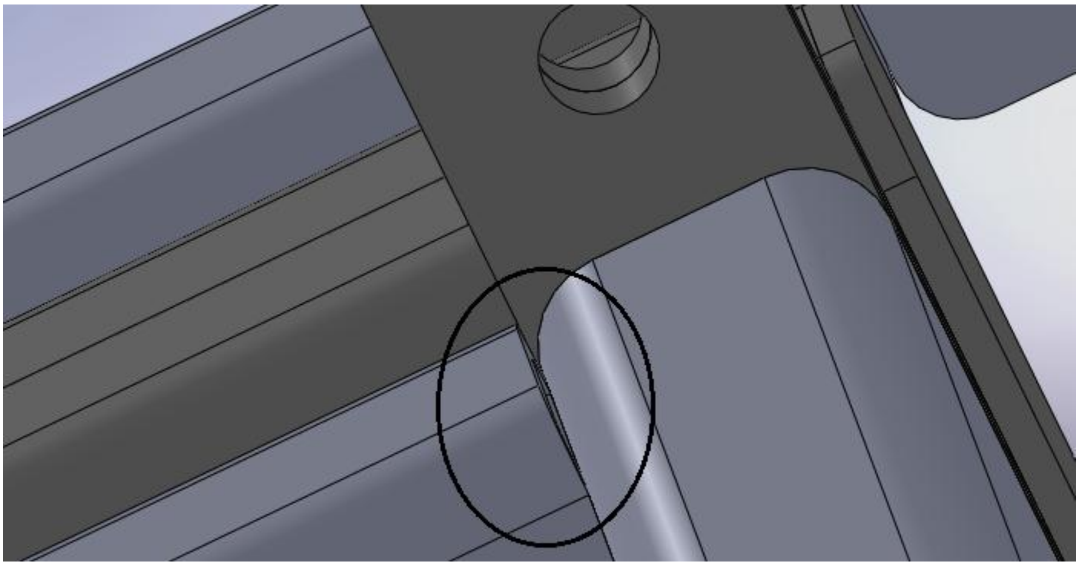


Figure 35: Example of SolidWorks inability to weld this type of joint

An attempt was made to rectify this through the SolidWorks Help Centre to no avail. Advice was provided that the newest version of the software contained a modified welding tool to assist with this error. However installation and use of this tool was unable to complete the weld as desired. ANSYS analysis was consequently conducted with the known problem occurring within the geometry. As expected the results that were obtained showed high stress concentrations at the areas outlined above. As a result this issue required some attention to ensure the validity of the results.

The only option available was to model the weld with series of sketches and extrusions so that area could be filled with material that resembles a weld. The final outcome is shown in Figure 36 below.

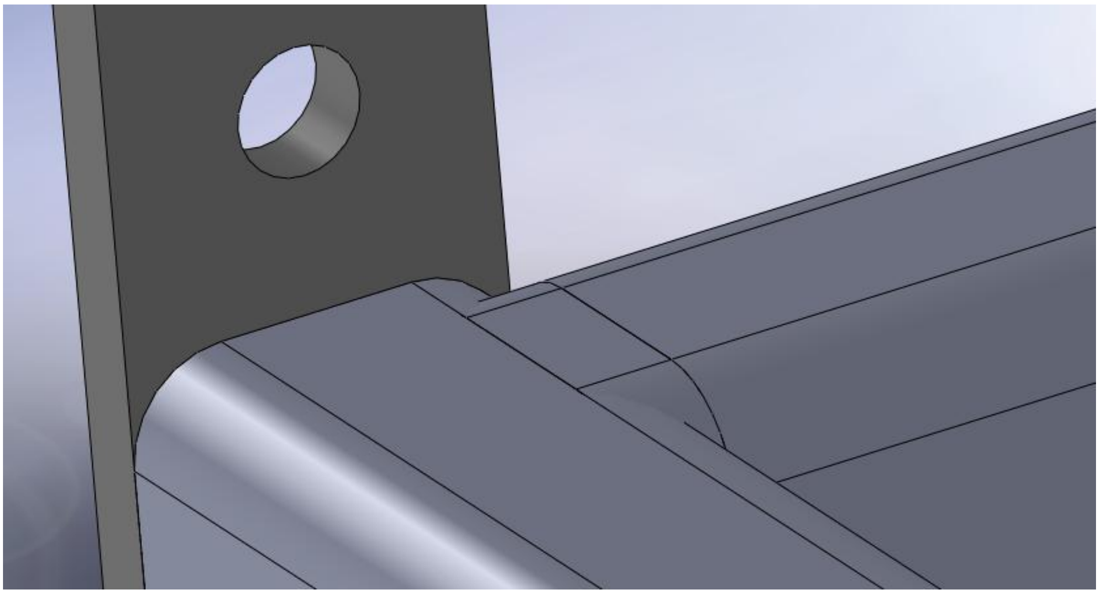


Figure 36: Welded area

Although this is not totally representative of a true weld, the results obtained within the ANSYS analysis were much more realistic than had occurred without the use of this technique. Adding this material to fill the area that was unable to be represented by the SolidWorks software ensures that the major stress concentrations were removed from this location and the loads were distributed more evenly throughout the frame.

Another area that would be a cause for inaccuracies within the results obtained by the FEA, would be the locations where the three individual segments are joined together. In the real world scenario these are bolted together creating a connection around the bolted joint. However within the analysis that has been presented within this report, the software assumes that at each section is a single material comprising of no joints. To analyse this more accurately, a contact region around the bolt hole should be created allowing the analysis to correctly simulate the joint's behavior. However, the significantly more complex analysis would have questionable advantage over the single material method. For example if the bolts were to fail, stronger bolts could be used deeming the connection to act almost as a single material. Therefore for the purpose of this analysis the more accurate method of analysis will not be used unless either time permitted or the bolted area became of significant importance. It is known that the location of the high stress areas were not in this area and therefore the method of analysis can be assumed accurate.

5.2.9 Current Design Analysis Conclusions

The current SprayCam Spray Rig has been analysed to an acceptable standard to determine whether the original assumption of over design for its use as a selective broadacre spot sprayer is valid. This original hypothesis has been proven accurate by the FEA. It is common practice with the Agricultural industry to over engineer many of their products, and when comparing the SprayCam sprayer to other sprayers this level of safety seems excessive. If this project were to analyse another piece of agricultural equipment, for example a plough, a safety factor of four would not be suitable. This is due to the unpredictable nature of its loads which it encounters e.g. hitting large rocks. However the sprayer operates in more predictable circumstances and it is for this reason large safety factors are not needed.

Since it has been found that the original SprayCam system is over designed for the purpose of an agricultural sprayer, the conclusion can be made that the current design could be modified to make better use of materials. Both the large heavy hood structures used to block light for the cameras and the lineal weight or the main beams are clear indicators of inefficiency. By significantly reducing the weight on these components the loads acting on the structure would also be reduced enabling a similar strength design with the use of less material. It may also be assumed that the current design of a large rectangular section rather than the more common truss system (in competitive rigs) does not make the best use of the material on offer. These issues will be discussed in further detail in Chapter 6.

5.3 Fibre Composite Design

Due to the time restraints of the project, the original hoods and other accessories will be utilized to create a suitable design of a composite wing for the SprayCam Spray Rig. For the new composite design to be able to make use of the existing components, the structure must be of a similar design to the original. This includes a large rectangular frame to ensure that the current hood structures can easily be modified to fit the new design. Within the analysis of the current SprayCam Spray Rig in section 5.2, it was discovered that the current design does not efficiently utilize the materials available. Steel and composites are two very different materials with composites having a very high specific strength/stiffness when compared to steel. This means that over the length of the wing the composite may be more suitable in carrying the load of its self and also the accessories, than that of a steel design.

For a new composite design to meet the original objectives of the project, it is vital that the design work seamlessly with the current design. This means that it can utilize the existing hood structure along with the current centre section.

5.3.1 Geometry Selection

As discussed in the literature review, pultrusions can be made in many different constant cross sectional profiles. For the purpose of this project the profiles listed by Exel Composites were used to determine the most suitable cross section for the use in the wing structure of the spray rig. This company was chosen as the University of Southern Queensland regularly utilises their products and in addition, the tests conducted by Taylor in 2009 involved the same materials.

Table 3 below provides properties of the range of SHS and RHS profiles that are available to be considered in the analysis of the new spray rig wing design.

Table 3: Pultruded cross sections to be considered

Dimensions			Density (kg/m)
Width (mm)	Height (mm)	Thickness (mm)	
75	60	4,5	1.80
75	75	6	2.95
100	100	4	2.75
100	100	6	4.06
101	51	6,3	2.26
101	51	6	3.15

Not all these sections will need to be analysed for possible selection as this would require more time than is available for this project. Therefore careful selection of the most appropriate sections to analyse needs to be conducted to ensure the appropriate selection is made. It is difficult to determine a single section for the starting point for the analysis of the fibre composite. Many factors will determine which section is chosen for the final design; the major two are strength and the sections ability to work with the other sections of the wing structure e.g. joints.

To estimate a suitable section with regard to strength, it is important to look at the directions which cause the greatest stress in the material. From observation it can be noted that a large proportion of the load that needs to be supported is in the y-direction or parallel to gravity. This means that sections with the greatest load carrying ability in this direction will be those with the largest cross section in this direction.

The second parameter which was investigated was the ability for the section to be easily joined to the original section. To allow the composite wing structure to function most effectively it is important that the joining techniques used in the assembly are suitable to withstand the load that will be applied to wing during operation. Research has shown that this is a difficult area of composite design and time should be taken to carefully design joining methods that can operate effectively.

The joints with the largest stress will be the two located on the inside of the wing where it joins to the centre section. Here the wing is needed to pivot, allowing the wing to follow the contour of the land. Through consultation with the supervisor of the project, it was determined that the use of composites in this section would not be a suitable option as there are many changes in geometry required and any composite only joining method would be significantly expensive to produce. In addition, the stresses at these locations are among the highest found within the structure so a strong design was needed to ensure the integrity of the spray rig.

Following the literature review into the techniques used by the Sandia National Laboratories for joining steel and fibre composites with lap joints, it was decided that this method of joining the wing to the centre frame was the most suitable. Their research conducted on the lap joints used in composite wind turbine design, uncovered that through the use of slight changes in the geometry of the lap joint, the usually poor compressive strength of steel/fibre composites joints can be considerably increased. Slight changes, which included the addition of adhesive to select regions, showed dramatic increases in strength to a point where the composite failed instead of the joint.

As a result the most appropriate solution was to use a steel to composite lap joint. This would involve the composite cross section sliding into a steel section where it would be glued and joined into position. This would ensure that at the critical location of joining the wing to the centre section, the highest strength design could be used.

Since this joint requires the location a composite material into that of a steel section (or vice versa), only certain combinations will be suitable for this task. During the test conducted by the Sandia National Laboratories the clearance between two materials used for a suitable lap joint was approximately 5mm. It is important that a suitable clearance is allowed to ensure that optimum adhesion occurs. Further work should be conducted on the exact distance that should be used but for this project approximately 5±2mm will be considered adequate. In practice, it is recommended that testing be completed to ensure the adhesion of the joint is sufficient before proceeding with any construction. The lap joint constraint reduces the list of suitable cross sections to three. Each suitable fibre composite pultrusion has a cross section of 100x100mm. These are shown in Table 4 below:

Table 4: Suitable combination of composite to steel lap joints

FC cross section (mm)	Steel Cross section (mm)	Clearance (mm)
100x100x4	125x125x9	7
100x100x4	90x90x…	2
100x100x6	125x125x9	7

As can be seen, the selection of possible sections is relatively small. However, careful consideration should be taken to ensure the most suitable section is chosen to be analysed so as time is not wasted.

The first combination that was discredited was that of 90x90 steel which only creates a clearance of 2mm. I believe that this will be two small to ensure the best possible adhesion of the joint.

With only the choice of two 100x100mm pultrusions left available, it was decided that the 4mm thick section should be analysed first as it provides a significant weight saving advantage (32%/m) over that of the 6mm. If the FEA showed that this section was unable to support the wing then the larger section should be analysed.

Choosing the use of an adhesive lap joint provides yet another benefit over other methods of joining which were found during the literature review. The advantage of using such a joint over other methods such as mechanical fasteners e.g. nuts and bolts, is that the level of stress concentration is reduced. It was found that during operations like drilling, the fibres around the hole become damaged. Since these critical load carrying fibres become damaged and can no longer carry the required load, stress levels dramatically increase. By choosing to use a lap joint the pultrusion is not modified and the load carrying fibres are not damaged during assembly. This reduces the risk of stress concentration occurring at the critical location of the joint. Another advantage of the steel joiner at the end of the wing allows steel gussets to be added if the analysis shows additional strength is required.

Figure 37 below, is an example of the joining mechanism that may be used. The fibre composite pultrusion can be simply pushed into the steel and with the use of adhesives to create a strong join.

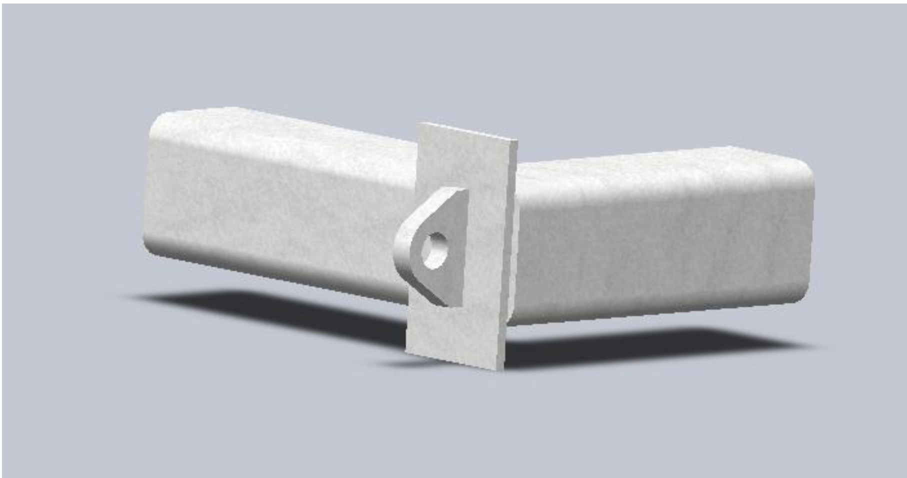


Figure 37: Steel Joint with pivot

Since the method of joining the composites restricted which profiles could be used, the analysis was conducted using 100x100x4mm pultruded fibre composites sections as the main frame for the sprayer. A basic solid model of the fibre composite project is presented in Figure 38 utilizing the steel lap joint connectors.

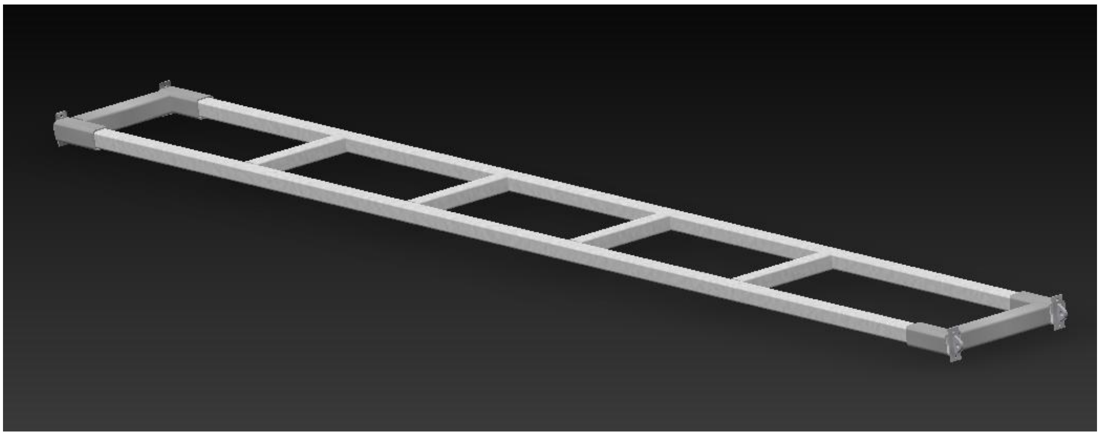


Figure 38: Fibre composite wing model

As mentioned previously the choice of section and its self weight would determine the rolling resistance created by the wheels on the wings. To determine this rolling resistance the change in mass will be calculated which requires the addition of the new composite sub structure plus the mass of the hoods and other accessories located on the wing.

The original frame had a mass of 280 Kg which does not include the hoods or camera covers and the proposed fibre composite design requires a total of 19m of material. The saving in weight can be calculated by the use of Table 3 on page 84 which outlines the mass/kg of the fibre composite pultrusions. As a result the mass of the new composite wing would be approximately 76kg which is a saving of approximately 204 Kg.

With this approximate load of the new composite wing structure now available, it is possible to determine the force created by rolling resistance of the wheels on the structure. By the use of SolidWorks it is possible to determine the load on each wheel to be 1950N creating a rolling resistance of 373.484N/wheel.

It should be noted at this point that the majority of the weight of the composite wing is made up of the original accessories e.g. the hoods and wheel assembly. This means that if time permits further investigation should take place to determine a means of re-developing these accessories so that they are lighter and the weight of the overall design is greatly reduced.

Once the sizing of the composite section is completed it is then possible to continue with the other joints within the wing. The next to be considered is the method of joining the original hood structure to the new composite section. The original pivot points for the hoods were simply welded onto the RHS however this cannot be done with the composite material. A number of options are available as a means of fastening the pivots into position, as was discovered within the literature review. Drilling holes were discounted on the basis that by producing such holes would cause weakness within the fibres around the hole. After considering different alternatives it was decided that a plate would be used to weld the pivot point to then two u-bolts would be used to fasten it together similar to Figure 39 below.

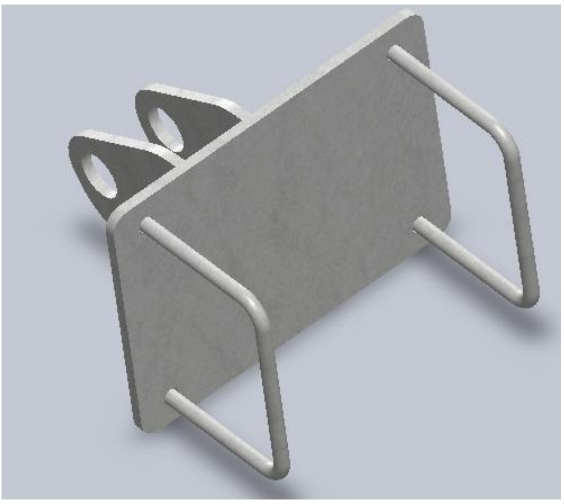


Figure 39 : Hood adapter

The bolts that would be required for this task are square top U-Bolts, which allow for maximum contact with the pultrusion. To determine the size of these bolts it was necessary to determine the maximum load these bolts were required to withstand. Calculating the correct bolt size was completed by using the Fundamentals of Machine Component Design by Juvinall and Marshek (2006). The maximum tensile load which the bolts will be required to carry was determined by the use of a free-body diagram and summing the moments about point 'A'. This method identified the top bolt being in tension, carrying a load of 1050N. The following diagram shows the free body diagram which was used for the calculations.

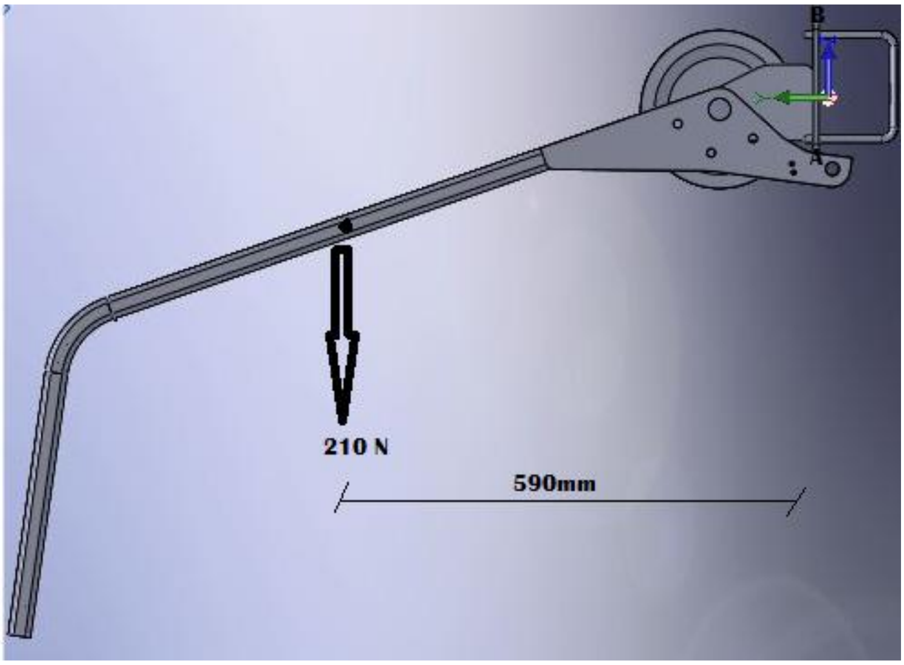


Figure 40: Free body diagram used to determine the tensile stress within the hood connections

By summing the moments around point 'A' it assumes that the system rotates about this point and can give the following equation to determine the force at B.

$$\sum M_A = 0; 0 = B \times 0.118 - 210 \times 0.59.$$

$$B = 1050N$$

Satisfactory fastening strength can be achieved by using a common, relatively inexpensive SAE Class 5.8 bolts with a proof strength of 380MPa and effective cross sectional area of 11mm^2 (Stress=Force/Effective area) if a safety factor of 4 is used. Now this is a very small cross section to be used on such a large size bolt (~100Wx150Lmm). In practice, the smallest diameter U-bolt available with these dimensions is M16. Now this is ample for this situation and should not fail under foreseeable scenarios including any shear stresses created within the bolt. Further investigation and testing should be conducted to ensure that the bolts do not squash the composite if over tightening occurs. Further investigation will be required (outside of the scope of this project) to determine a suitable torque that ensures proper stability of the pivot while not jeopardizing the strength of the pultrusion.

If crushing of the composite becomes an issue when the bolt is fully loaded, it is recommended that bracing be introduced. It was identified within the literature review that to stop composites from being crushed and losing their structural integrity, a secondary material can be placed inside to add the required strength. For example a steel insert or in the case of Wagner's in Southern Queensland, reinforcing made from recycled plastic. This is not only light but also environmentally sustainable.

5.3.2 Adhesive Selection

The difficulties associated with the joining of composite materials and ways to overcome such problems have been mentioned several times throughout this report. Another method of increasing the strength of the joint is through the correct selection of an adhesive. To ensure the correct adhesive is used to connect the fibre composite to the steel, a range of adhesives were chosen that could fulfill this role. Adhesive selection is an important part of the project as it ensures all joints perform at their maximum. All adhesives chosen in

Table 5 below are curable at room temperature as this is the most cost effective solution when compared to high temperature curing which requires the use of specialized equipment

Table 5: Adhesive Properties

Adhesive Type	Peel Strength (N/25mm @ 25^{o}C)	Shear Strength (MPa)	Cure Temp
Hysol EA 9361	111	24.1/5.9 (25^{o}C/71^{o}C)	Room Temp
Hysol EA 9394	22.2	28.9/20.7 (25^{o}C/82^{o}C)	Room Temp
Hysol EA 9360	222	31.7/10.3 (25^{o}C/82^{o}C)	Room Temp
Hysol EA 9396	110	24.1/22.1	Room Temp

From the research conducted by Metzinger and Guess (1999), peel strength was the key to determining whether a joint will fail or not. For the same joint, compressive and tensile stress will produce similar plastic strain however the peel stress will be in the opposite direction. Through their research they found that adhesives were much stronger in tension than compression and this was related to the peel strength, therefore when selecting an adhesive, high peel strength is very important.

While peel strength is very important, shear strength across a variety of temperature is also critical. The spray rig will encounter significant temperature variance and therefore it is critical that properties such as shear strength remain constant and predictable over the expected ranges.In this situation where there is no clear answer to the problem the weighted merit system will be used to determine the most suitable adhesive for the required task with results presented in Table 6.

Table 6: Weighted Merit System of Adhesives

Adhesive Type	Peel Strength (x5)	Shear Strength (x4)	Cost (x4)	Total
Hysol EA 9361	4	2	5	48
Hysol EA 9394	3	5	5	55
Hysol EA 9360	5	3	2	53
Hysol EA 9396	4	4	5	56

By using this weighted merit system it can be seen that the adhesive material best suited to the application of joining the sections together is Hysol EA 9369. It performs extremely well over the range of criteria and will suit this application well. Tests should also be conducted using Hysol EA 9394 which is a relatively cheap alternative to the higher placed Hysol EA 9360. If these tests show deficiencies within the joint then higher quality adhesives should be investigated e.g. Hysol EA 9360, which shows high strength values Research conducted into the strength of joints by the Sandia National Laboratory showed that Hysol EA 9394 was sufficient in overcoming the peel strength which debonded the joints in the wind turbine industry. With the help of geometric changes to joint regions, Hysol 9394 was able to ensure that the joint did not fail but instead caused the composite to fail first. However for the application used to join the composite wing to the steel structure it is believed that the Hysol EA 9396 would be the most appropriate selection

5.3.3 Composite Finite Element Analysis Method

To conduct an accurate Strand 7 analysis more effort is required to gain suitable results then using ANSYS. When conducting the Strand 7 analysis there were two possible methods to achieve desirable results. These include a beam truss element analysis and a plate analysis. Using the beam analysis method the results are very basic, only providing the maximum stresses and deflection at a single point of the structure. Whereas using the plate analysis method, a detailed picture of the stresses at any point along the section is possible. It is for this reason that the plate element method was chosen to conduct the analysis of the structure.

When using the plate element analysis it is vital to create a model which produces the most accurate results. To improve the likelihood of this occurring, meshing of the model should be made as small as possible. It was suggested by Eparaachchi that a maximum mesh size of 10mm be used to ensure accurate results from an analysis of composite materials.

Once the correct model has been developed it is important that the correct material properties are assigned to the plate elements. As mentioned, Strand 7 is capable of producing accurate results for orthotropic materials (having mechanical properties in different directions). There are two methods of creating an orthotropic composite material using Strand 7. The first is to select the orthotropic material from a dialog box provided and substitute the known material data which includes calculating the stiffness matrix. This is a lengthy process which involves a range of calculations to produce the desired results. It takes a large amount of time and effort and introduces potential errors (mistakes) making the results invalid. The second method is much faster and produces results to a similar level of accuracy. It is a two step process which first requires producing a bidirectional ply material. This is an easy step that only requires entering the mechanical properties for the composite. From this step, a laminate can be formed from the ply properties creating an orthotropic material. This second process is much faster and more accurate as no calculation need to be made as this is done by the program. By not having to calculate the properties of the stiffness matrix, as in the first method any potential errors are avoided and therefore a more accurate result obtained. Table 7, outlines the mechanical properties for the composite pultrusions which were obtained through the CEEEFC internal report.

Table 7: Mechanical properties of the pultruded composites

Mechanical Property	**Value**
Youngs Modulus (E_1)	3.15×10^4 MPa
Youngs Modulus (E_2)	7.2×10^3 MPa
Shear Strength (G)	3.0×10^3 MPa
Poissons Ratio (*v*)	0.25
Density (*p*)	1.9×10^{-9} T/mm^3

5.3.4 Load Cases

Ensuring the accuracy of the results obtained during the finite element analysis depends largely on the accuracy of the loads and the positioning of these loads which are being applied to the system. The load cases will be determined by the same method as the original spray rig. Both the wind resistance and the load created by self weight will remain the same as the original design. However the rolling resistance created by the wheels will change due to the reduction in mass of the composites within the new design. Determining this new load will only be an approximation, however the obtained results will be reasonably accurate. The weight of the original hoods and camera covers along with the wheel structures remain unchanged from the original design. It is then possible to add the new composite wing frame to the weight which can be calculated from the information provided by Excel composites regarding the mass/m of their products. By adding these together, along with the weight of the joints a new load scenario can be determined. It was found that through the use of composites the wings frame could be reduced from 281.8939kg to approximately 76kg with a 100x100x4mm section. This reduction in weight results in a significant reduction in the rolling resistance which can be seen in

Table 8.

Table 8: Composite wing loading cases

Load Case	**Magnitude**	**Position**
Rolling Resistance	747N	End
Wind Resistance	211.5N	End*
Gravity	2G	All in the downward direction
Hoods	840N	Centre of each 3m section

Notes:

* The wind resistance has been located on the end of the wing since this is the simplest method of positioning the load. Wind resistance that has been calculated acts at the middle of the wing. Therefore for the load to act at the outside of the wing the load has been halved to ensure the same size load is applied to the frame.

The final load case requiring analysis is that of the load positioning of the hoods. The positioning of the hood loads are difficult to model using Strand 7 analysis and the loads created by these hoods will be analysed using the method which was used by the first FEA of the original spray rig. It was not found to be the most accurate method of determining the stress within the system however due to the time constraints of the project, will be sufficient. In light of this, when analyzing the results of the FEA it is important to remember that these obtained results will be greater than those presented in the analysis.

5.3.4 Composite Wing Analysis

Strand 7 was used for this purpose, as it has the necessary features to conduct such analysis. As previously shown, fibre composite pultrusions are available in a range of different cross sections, therefore it is important the correct section is selected for the analysis of composite wing. The first analysis will be conducted on the 100x100x4mm section wing. This is a relatively light 100x100m section and therefore if required a larger sized section will be analysed if this section is not found to be unsuitable.

Figure 41 below shows the maximum stress within the 100x100x4mm pultruded section. The locations of the load cases are shown together with the location of the supports and the stresses within the wing. The red circle identifies the area of greatest stress

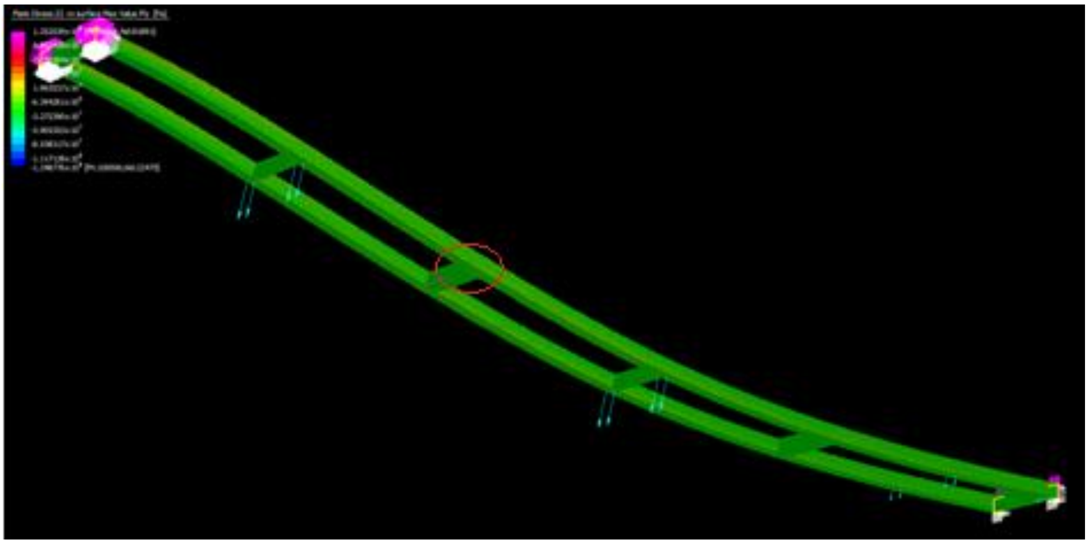
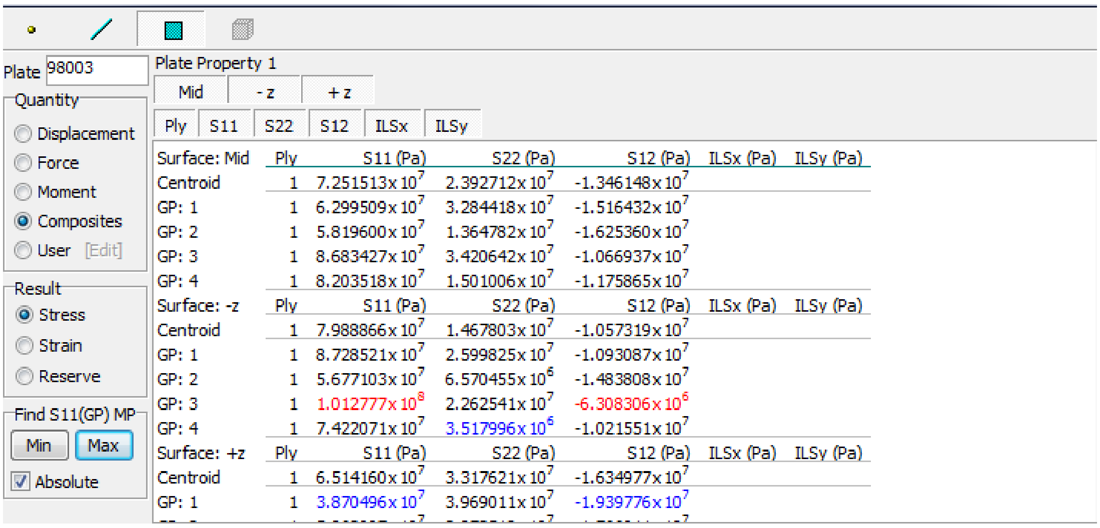


Figure 41: Fibre composite Finite Element Analysis

From the above diagram it is difficult to depict the stress within the truss. However it is possible to depict the support reactions and the load cases that were used in the analysis.

The maximum stresses which occur within the wing are tabulated in the following Figure.



Surface: Mid	Ply	S11 (Pa)	S22 (Pa)	S12 (Pa)	ILSx (Pa)	ILSy (Pa)
Centroid	1	7.251513×10^7	2.392712×10^7	-1.346148×10^7		
GP: 1	1	6.299509×10^7	3.284418×10^7	-1.516432×10^7		
GP: 2	1	5.819600×10^7	1.364782×10^7	-1.625360×10^7		
GP: 3	1	8.683427×10^7	3.420642×10^7	-1.066937×10^7		
GP: 4	1	8.203518×10^7	1.501006×10^7	-1.175865×10^7		
Surface: -z	**Ply**	**S11 (Pa)**	**S22 (Pa)**	**S12 (Pa)**	**ILSx (Pa)**	**ILSy (Pa)**
Centroid	1	7.988866×10^7	1.467803×10^7	-1.057319×10^7		
GP: 1	1	8.728521×10^7	2.599825×10^7	-1.093087×10^7		
GP: 2	1	5.677103×10^7	6.570455×10^6	-1.483808×10^7		
GP: 3	1	1.012777×10^8	2.262541×10^7	-6.308306×10^6		
GP: 4	1	7.422071×10^7	3.517996×10^6	-1.021551×10^7		
Surface: +z	**Ply**	**S11 (Pa)**	**S22 (Pa)**	**S12 (Pa)**	**ILSx (Pa)**	**ILSy (Pa)**
Centroid	1	6.514160×10^7	3.317621×10^7	-1.634977×10^7		
GP: 1	1	3.870496×10^7	3.969011×10^7	-1.939776×10^7		

Figure 42: Maximum Stress within the 4mm section

It was found that in the analysis presented, the maximum stress is located in a similar position to that found in the original steel design analysis with a value of 101 Mpa which is similar to the model predicted by Taylor for acceptable fatigue stress. However in the fibre composite analysis, the location of the maximum stress is more towards the middle of the frame. It has been noted that there is a large load created by the hoods when compared to the self weight of the composite frame. This will lead to high bending stresses at the mid section of the frame which is verified by the higher stress in this location. Unlike the steel design where the stress was towards the pivoting support, the rolling resistance is much less with the composite design and therefore has less effect on the wing structure. Since the location of theses stresses are in accordance with what would be accepted it can be assumed that the location of the loads and supports are correct.

The stress within the majority of the section is relatively low at around 10^6 - 10^7 P; well under the recommended fatigue strength of the composite material. However high stress concentrations occur at the location of the cross supports which can be seen in the following figure. It is believed that these concentrations are a result of the sharp changes in geometry in the Strand 7 model.

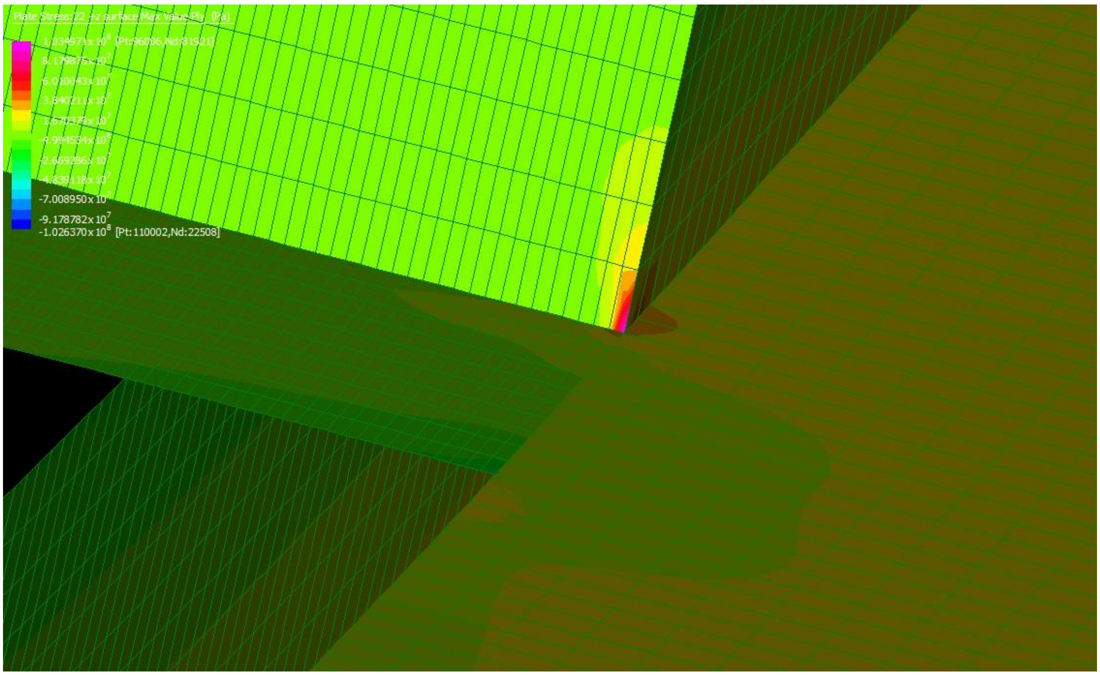


Figure 43: Stress concentration effect

Extremely high stress levels which are evident within the analysis occur at the cross supports. This occurs due to the sharp changes in geometry of the wing. It is well documented that at these sharp changes, stresses increase greatly. This increase is based on St Vennant's principle as at these locations the stress theoretically reaches in-finite levels (i.e. Load/very small area). This may be reduced by the use of smaller meshing as it would allow the stresses to be more accurately modeled and therefore reduce the level of stress within the member. In an actual rig, such sharp changes will not be present and instead the joint will evenly distribute any stress over a greater area of the structure, hence reducing the levels of stress.

It was mentioned that if needed another analysis should be conducted on the system if the stresses within the structure reaches unacceptable levels. The levels within the frame does reach high levels and therefore further analysis was undertaken with a 100x100x6mm section to ensure it is considered for the final wing design. The results of this analysis can be seen in Figure 44 and Figure 45.

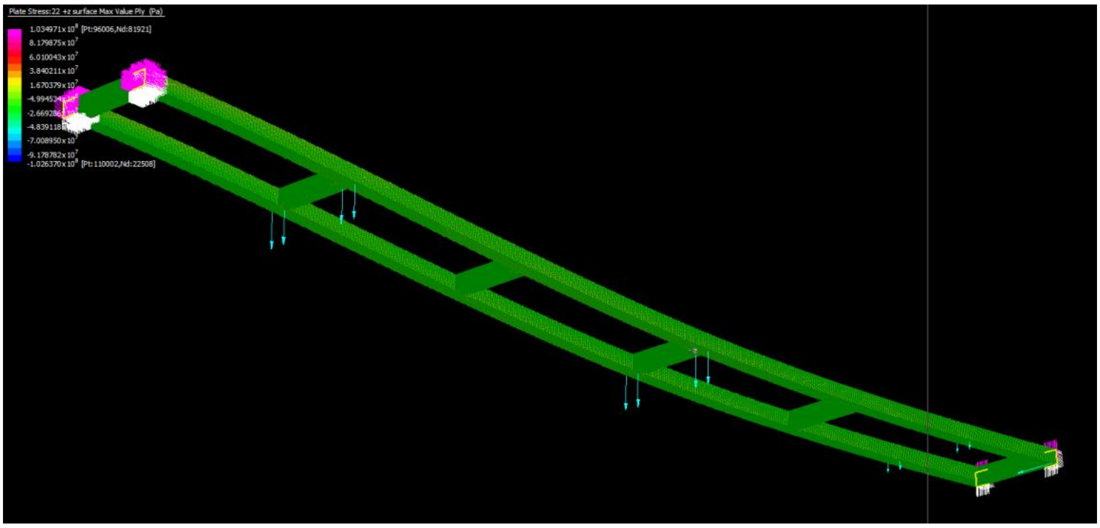
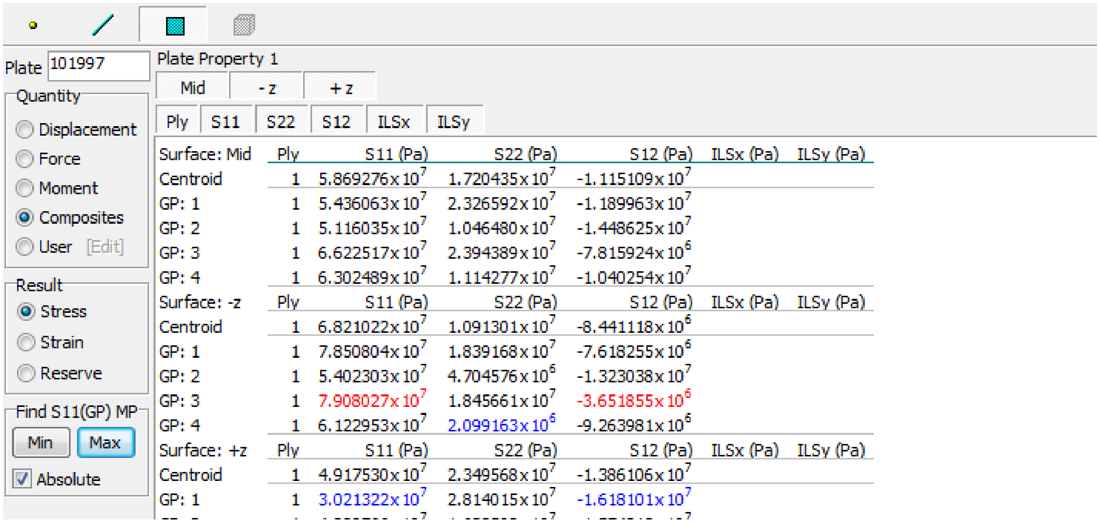


Figure 44: 100x100x6mm finite element analysis



Surface: Mid	Ply	S11 (Pa)	S22 (Pa)	S12 (Pa)	ILSx (Pa)	ILSy (Pa)
Centroid	1	5.869276×10^7	1.720435×10^7	-1.115109×10^7		
GP: 1	1	5.436063×10^7	2.326592×10^7	-1.189963×10^7		
GP: 2	1	5.116035×10^7	1.046480×10^7	-1.448625×10^7		
GP: 3	1	6.622517×10^7	2.394389×10^7	-7.815924×10^6		
GP: 4	1	6.302489×10^7	1.114277×10^7	-1.040254×10^7		
Surface: -z	Ply	S11 (Pa)	S22 (Pa)	S12 (Pa)	ILSx (Pa)	ILSy (Pa)
Centroid	1	6.821022×10^7	1.091301×10^7	-8.441118×10^6		
GP: 1	1	7.850804×10^7	1.839168×10^7	-7.618255×10^6		
GP: 2	1	5.402303×10^7	4.704576×10^6	-1.323038×10^7		
GP: 3	1	7.908027×10^7	1.845661×10^7	-3.651855×10^6		
GP: 4	1	6.122953×10^7	2.099163×10^6	-9.263981×10^6		
Surface: +z	Ply	S11 (Pa)	S22 (Pa)	S12 (Pa)	ILSx (Pa)	ILSy (Pa)
Centroid	1	4.917530×10^7	2.349568×10^7	-1.386106×10^7		
GP: 1	1	3.021322×10^7	2.814015×10^7	-1.618101×10^7		

Figure 45: Maximum Stress within the fibre composite wing

From above it can be seen that the maximum stress within the analysis has been reduced by 30MPa, to 79 MPa. This stress is acceptable when compared to the 10^8 life predicted by Taylor in 2009. However the size of the stress modeled in this analysis would most likely be less than those occurring in an actual design, due to the positioning of the hood structures. As found in the analysis of the original sprayer this loading cases achieved smaller levels of stress than when compared to the analysis of actual loading scenario. However the location of the stress concentration is at a sharp change in geometry at the cross supports. As mentioned earlier such sharp changes in the model creates this stress concentration and by the use of suitable joining methods these increases will be reduced making the analysis to Taylor's model even more favourable.

As mentioned by Mr Mario Springolo of Wagners Composite Centre, it is very difficult to precisely determine the stress which may occur within a composite design. Therefore it is vital that real life tests be conducted to validate the research and the finite element analysis.

The reduction in the level of stress created by using the larger 6mm thick cross section significantly reduced the levels of stress and any practical tests should be conducted on this section first. The analysis of the following costing data should also use this information.

5.4 Costing

Costing plays a major role in the development of a proposed alternative for the SprayCam Spray Rig. It was identified within the literature reviewed that costing can be a major disadvantage of composites and would always be an issue with a wing made of composites. The initial cost of producing the wing will be high when compared to the original design, however the literature reviewed also revealed that secondary costs would be lower when compared to steel. For example, joining methods are much faster than steel and therefore labor costs would be reduced. It is very difficult to produce an accurate costing analysis for a new composite wing design which includes all the necessary information. An accurate analysis would be a very length process and require a lot of knowledge and experience in composite design and use. For this reason, this report will firstly determine the difference in material costs of the composite design when compared to the original steel structure. Labour costs will be estimated against each of the two methods. Importantly estimation process will not include any change in cost attributable to any redesign available for the centre and wheel sections of the wing due to the significant weight reduction. This work is beyond the scope of the project however needs to be investigated to ensure a reasonable cost comparison can be made.

Material costs have been provided by Exel Composites a market leader in pultruded composites. The data has been collected through private consultation with the company's head office in Melbourne.

The standard length the pultrusion is 6m however larger lengths can be obtained if this is a manufacturing requirement. The pricing was determined with the most common mixture of components used by Exel Composites. These mixtures can be varied for each customer's desired requirement, depending on the application and use. A representative for Exel Composites noted that if the requirement arose, other addition such as carbon or Kevlar may be added to add increase strength and stiffness. This adds extra cost which will not be investigated in this report.

Table 9 below illustrates a range of sections which were provided by Exel composites.

Table 9: Composite Pultrusion Costs

Section	Size	Length	Mass/Length	Cost/Length	Cost/kg
Equal Angle	25x25x3.2	6	1.25 kg	$ 58.20	$46.58/kg
Equal Angle	102x102x9.5	6	20 kg	$ 306.60	$14/kg
Channel	203x56x9.3	6	30 kg	$ 408	$13.6/kg
SHS	50x50x6.4	6	12.6 kg	$ 228	$18.09/kg
SHS	76x76x6.4	6	9.6 kg	$ 288	$30/kg
SHS	102x102x9.5	6	20 kg	$ 414	$20.7/kg

Table 9 includes pricing for a range of sections and sizes of pultruded materials which Exel Composites produces. Obviously these are not all the sections which are available and unfortunately a price of the 100x100x6mm section was not available. The representative for the company advised that it was possible to use the costing for the 102x102x9.5 section as a reasonable approximation for the costing of the desired section. Therefore a slightly conservative price of $25/kg will be used to determine the costing of the fibre composite wing. By using this data along with the information provided by Table 3 regarding the density of the desired section, the cost per metre ($/m) of the 100x100x6m section would be approximately $101.25/m (4.05kg/m x $25/kg = $101.25/m).

Assuming that the large 8m lengths can be obtained in a single length the total amount of material that would be required would be.

$$8m \times 2 + 0.462m \times 6 = 18.772m$$

The total cost of composites that would be used in the project is approximately be $1900

Once this costing has been completed it is possible to move on to the material costs associated with the production of the original steel design.

The current spray rig design is produced with two main sections; 100x50x5mm and 75x50x5mm sections within a truss system. The total lengths of each are as follows

100x50x5mm= 2 x 8m + 8 x 0.560m = 20.48m

75x50x5mm= 5x0.560m= 2.8m

The prices of the materials have been sourced through private communications with Metal Corp Steel in Toowoomba. The listed prices are subject to change and therefore the listed prices are only an indication.

Table 10: Material costing of original steel design

Section (mm)	Length (m)	Price/Length
75x50x5	6	$126.50
100x50x5	6	$151.00

The required amount of material for the production of a single wing is:

1 length of 75x50x5mm = $126.50

And 4 lengths of 100x50x5 =$604

Equating to a total cost of $730.50 for the RHS required to manufacture one the wings in the original design.

As has been mentioned, this is only a very basic analysis of the cost of the two projects as neither include the cost of labor or joining techniques. It is purely a material costing exercise, which produces results that which show the composite wing to be considerably higher. It is believed that if the costs of labour were to be included the price difference would reduce due to the lower time required to manufacture joints using the composite material. While there is a material cost difference, discussion with Rees management has indicated that it is not overly significant when considered against the total machine cost. The total machine cost of the current design has been estimated to be in the region of $40-50,000.

5.5 Chapter Conclusions

Through the use of finite element analysis, the original and the new composite design have been compared within this chapter. Before the analysis was completed it was first important to calculate all the important load cases that occur on the wing structures including the rolling resistance created by the wheels and with the drag force of the wing through the air. These loads were calculated by the use of the most suitable equations found within the literature review. Loads were applied to the most suitable location on the wing. The subsequent stresses within both designs were then found by the use of the finite element analysis.

The results produced during the original sprayer analysis showed that the hypothesis that the original design was over designed was correct. A safety factor of approximately 4 was found which is light when compared to other agricultural machinery such as ploughs and planters. However, when considering other sprayers such a safety factor would be considered over engineered. This analysis therefore shows that the current design does not require such large sections and that it would be beneficial to re-engineer the wing sections to reduce weight.

Reducing weight would also have the benefit of reducing the loads acting on the section e.g. rolling resistance.

While it has been noted that this current design of the sprayer may not be optimal, the use of a material such as a fibre composite pultrusion with its superior strength and stiffness to weight ratio, will be better suited to carrying the loads required over the span of the wing. For this project the original frame design has been maintained as this will be easier and cheaper to attach the original hood structures, however these hoods should be investigated and redesigned so that a lighter more effective structure can be produced.

Two different sized cross sections have been analysed as suitable candidates for the use as the frame member; 100x100x4mm and 100x100x6mm pultruded sections manufactured by Exel Composites Melbourne. There are many different sized sections available however the 100x100mm sections have been identified as a section that will be able to be used in the proposed composite to steel lap joint.

Both sections performed well when analysed during the FEA and as predicted the 6mm section performed the best. High stress concentrations were found at the positions where sharp changes in geometry occur. This is contributed to the model, produced in Strand 7, containing sharp joint intersections. This will not occur in a practical design or manufactured machine as the steel lap joints will remove such transitions. Stresses theoretically reach infinity as a load on a very small area produces an extremely high stress contributing to the phenomenon observed in models at these locations. As mentioned the 6mm section performed the best and should be used to carry out further testing.

Mr Mario Springolo of the Wagners Composite Fibre Technology Department confirmed that it is very difficult to determine the suitable stresses which can occur within a composite design as it depends on many factors including the load, the number of cycles and the capacity of the member. By using Taylor's model for the fatigue life, the use of the 6mm section should be sufficient to withstand a loading cycle of in excess of 10^8 cycles, provided high stress concentrations are left out of the analysis (and the design). Mr Springolo also noted that Wagners carry out full scale tests to ensure the product is suitable. This will obviously have to be done with this model as there are many variables within the design and the only way to be sure of the integrity of the structure is to conduct a full scale test.

Costing was also analysed during Chapter 5 of the report and as expected the cost of the composites was higher than that of the original steel design. The costing of materials was the only parameter which was investigated within this section and it would be expected that if further analysis were completed on labour costs, the difference in price of the two designs would decrease.

Through this analysis of a new composite wing design it has been shown that it is indeed possible to produce such a spray rig. However to ensure the validity of the results it would be necessary to conduct a full scale test of the design. This will require more time to produce a design that is readily marketable than one matching the steel design. By the use of the costing analysis it has been shown that the material cost to produce a composite wing would be approximately $1170 more than a steel wing. A proportion of this would possibly be offset through less labour cost during production. Compared to the total machine cost, the analysis indicates that a composite wing could be a potential solution to the desired weight reduction objective provided some re-design is undertaken and an appropriate level of field testing is undertaken.

Chapter 6 – Discussion

6.1 Introduction

To successfully complete this project two main aims needed to be completed. The first was to analyse the current SprayCam Spray Rig with the use of finite element software. This included creating a solid model of the machine, defining the suitable loading situations and finally applying this to the FEA. These tasks have been completed producing usable results that will be discussed within the following section.

The second aim of the project was to investigate the use of fibre composite pultrusions as a means of redesigning the spray rig. A composite design has been investigated and a proposed solution has been produced. Subsequent analysis been completed to determine the suitability of the proposed solution.

The results of both these analyses have been presented in previous chapters while the meaning of these results will be discussed in further detail within this section.

6.2 Design discussion

6.2.1 Original Sprayer Design

To confirm whether or not the current design of the SprayCam System is over designed for its intended purpose, a comprehensive finite element analysis was conducted to determine the properties of this design. This included determining all the appropriate loads which act upon the structure along with applying the appropriate restraints where required.

The literature review process discovered that, when conducting any FEA it is important to verify any results obtained by the use of another method. This was accomplished by the use of hand calculations which can be found in Chapter 5. These calculations produced results which were similar in magnitude to those created by the FEA, although there was some variance. The hand calculations used only basic structural analysis techniques and did not take into account any bracing located throughout the structure. These hand calculations were expected to produce results with higher levels of stress and deflection. From investigation of these hand calculations and the FEA the results obtained were as expected and therefore verifying the analysis which was conducted. As mentioned previously, two loading cases were analysed to validate the obtained results. This comparison was conducted to determine the difference between placing the loads hoods directly on the main beam and placing them on their actual pivot points. The results showed a considerable difference between the two methods which was expected since this method adds a moment to the beam. Since the analysis of the composite wing analyses the structure by placing the load directly on top of the beam, consideration for the increased stresses need to be taken into account.

These results obtained within the analysis of the original design confirmed the original hypothesis, that the current design is over designed for its intended purpose. The finite element analysis showed a safety factor of 4 for the design which when compared to other broadacre sprayers is under engineered. Many other agricultural equipment uses large safety factors as a means of designing against unpredictable loading cases. Through consultation with the chief engineer of Rees this is less of an issue with this design as the loads which are applied are generally expected and therefore such large safety factors are not warranted. However it should also be noted that the loading cases that have been applied to the wing are likely to be more than those that would be applied during normal operation. For example the rolling resistance is produced for wheels in wet muddy soil and the dynamic load is twice that of what the machine is subjected to in normal operation therefore it would be safe to say that the current rig design is over designed

By conducting this analysis it can be seen that the original design is adequate for its intended purpose. However the combination of a high safety of factor and a large heavy design illustrates that the current SprayCam Spray Rig is not an optimal for its design criteria. This heavy machine should be further investigated to improve, cost and its use of materials. Much of the stresses within the design can be contributed to supporting its own weight. Therefore if the size of the sections used within the design is decreased, the loads acting on the wing will also decrease creating a design with similar structural properties. The resulting reduction in weight would also lead to a reduction in compaction of the soil.

6.2.2 Composite Sprayer Design

From the results obtained by the FEA conducted on a new wing made of composite materials, promising data can be retrieved which makes a design made of composites a possibility.

It can be seen from the analysis of the design that Strand 7 is only an idealized model of the real system. Its use to produce a highly complex model would require a lot of time and was outside the scope of this project. As mentioned in the previous section since the loads of the hoods are applied to the middle of each section of the beam the resulting stresses are less than those which would occur in a real wing. Therefore it is vital that further finite element analyses are conducted to ensure the validity of the results. However, from the results obtained it can be seen that the use of composites is a possibility for the final design of a new SprayCam Spray Rig.

The first analysis which was conducted was on a 100x100x4mm cross section. This produce maximum stresses of approximately 100MPa. This stress is slightly higher than the 10^8 life predicted by Taylor (2009) and therefore another analysis was conducted to investigate the properties of the 100x100x6mm profile. The results showed a reduction in the maximum stress to a more acceptable level of 79MPa when compared to Taylor's model. Such a reduction in the maximum stress shows that the 6mm section would be more appropriate for the use as a fibre composite wing.

As mentioned in the Section 5.3, high stress concentrations are located at sharp changes in geometry, namely the intersection of two pultrusions. According to St Vennant's principle at these locations the stress theoretically reaches infinite levels (i.e. Load/very small area). In the actual model such sharp changes will not be present and instead the joint will evenly distribute any stress over a greater area of the structure. The increase in the area for the load to be distributed over will in turn reduce the stress concentration effect.

It is possible to reduce the modeled stress concentration effect within Strand 7 by reducing the size of the mesh which is used. The current minimum size of the mesh is 10mm. Reducing the mesh size however, significantly increases computing time. Given the issue was quite obvious, it did not appear necessary to undertake additional analysis to achieve limited additional benefit.

Aside from these issues of stress concentrations the composite pultrusion analysis shows promising results for machine made of fibre composites. The level of stress within the frame (~10^6 -10^7Pa) is very low when compared to the model discussed in the literature review for the design of composite materials. This would therefore create a design which would endure the given loads for the life of the rig. Due to these low stress levels a design made of composites are a possibility, however, to ensure the integrity of the design, full scale testing should be conducted as a means of validating the results obtained during the analysis.

6.2.3 Joining Methods

Joining techniques were identified within the literature review as one of the main issues regarding the use of fibre composite pultrusions. However it has been found that through the appropriate design tools these issues can be overcome. There are numerous different joints that need to be considered in such a project.

The research conducted at the Sandia National Laboratories in America has provided a wealth of knowledge to this project in regards to joining techniques between fibre composite pultrusion and a steel structure. As mentioned in previous sections, slight changes in the geometry can dramatically increase the strength of an otherwise weak joint. Their results showed that the joint can withstand stresses created within the material of up to 418MPa. This was the stress within the composite material before the test failed. By changing the geometry it was found that it was possible for this failure to occur within the composite material instead of the joint. Since the joint did not fail it can be assumed that the joint can withstand stresses in excess of 418MPa since the tests were unable to determine the breaking point of the joint before the composite failed. By investigation of the composite FEA, at no point within the analysis do the levels of stress exceed this level. Nevertheless these ideas have not been used extensively throughout the industry and therefore further research should be conducted along with testing on such joints to ensure their longevity. This testing should occur within a laboratory with suitable testing equipment to gain data on the strength of the joint for both single cycle stress and the effects of fatigue. This will ensure this method of joining is suitable for such applications. Another method of validating the joint location is by the use of FEA software. This has not been done within this project due to time restrictions but would be a useful means of evaluating the stresses within the joint.

Another area which was considered for joining was the hand layup. This is a method of joining composites which is used in many industries with great results. I suggest this would be suitable for use on the cross members which run the length of the wing. This will reduce weight when compared to steel lap joint while maintaining the suitable amount of strength. If strength becomes an issue, the addition of stronger fibres e.g. carbon or Kevlar would be considered as an alternative as these would produce the required strength necessary for joining the two sections together.

Since this project is investigating the use of pultrusions as a replacement to the original steel frame, bolted connections have been chosen as the most suitable means of connecting the original hood structures to the new composite wing design. This system will utilize u-bolts which will clamp the hoods in position. This was chosen over drilling holes into the section as research clearly indicated that this would affect the composites ability to transfer load throughout the fibres and in turn reduce the capacity of member. It was also identified that the clamping action of this joint may also affect the capacity of the section and if practical tests showed the need for support at these location a strengthening member could be inserted into the inside of the pultrusion to add the required strength. Such inserts could be made of steel but to avoid corrosion inside the composite, moulded recycled plastics could be used. This would be both economically and environmentally sustainable.

6.4 Cost analysis

For a composite wing design to be considered a viable alternative it is vital that the cost of proposed design is similar to that of the current design. Or if the costs are higher, then the advantages of the new design need to significantly outweigh the cost disadvantage. As previously mentioned, to analyse both the original and new composite design will require a lot of time, specialized skill and experience. Therefore the costing analysis has been conducted purely on material costing. This is definitely not a comprehensive analysis however it showed that the initial material costs of a composite wing will be approximately $1170 greater than those of the original steel design. Now when compared to the estimated cost of the original design ($40-$50 000) this is a relatively small amount. It is therefore very important that further analysis is conducted into the costing of a fibre composite wing so as a more accurate comparison can be made.

As there is some doubt about a relative difference this apparent cost disadvantage needs significant investigation against several factors:

1. The affect on the total cost of the machine,
2. Any design changes which reduce the material required,
3. Any saving that may be recouped through a reduction in manufacturing costs, and
4. The possibility of reduced lifetime maintenance costs.

Once these factors are investigated it would then be possible to better compare the designs and produce an accurate cost comparison. However through the research conducted it has been shown in other projects that by the use of fibre composites certain manufacturing processes have been reduced. For example the current proposed design utilizes adhesive bonded joints to hold the structures together, this requires less time than welding and therefore savings in labor costs would be produced.

6.5 Improvements

Due to the time constraints of the project many components of the current design were maintained to ensure the project was able to be completed within the specified time scale. These areas include the wheels and their connections along with the hood structures. With further investigation improvements could be made to both of these areas to further reduce their weight and the resulting load upon the wing structure.

The research conducted in Chapter 3 discovered that there are a number of determining factors which influence the magnitude of rolling resistance created by the wheel. Some of these variables cannot be altered for example the soil conditions in which the machine operates while the others such as wheel size can be changed. Through this research it was found that increasing the diameter of the wheel decreased the rolling resistance of the wheel. This is also the case for larger width tyres however increasing the pressure in the tyres will increase the resistance. The current wheel is quite small at 520mm diameter. If a larger diameter wheels were used then the effect of the rolling resistance will be significantly reduced.

This is just one of the options that could be used to reduce the effect of rolling resistance on the structure. Instead of using 2 smaller wheels a single larger wheel could be used which may reduce the cost of the machine as extra parts will be no longer necessary. For example one set of hubs and bearings will be eliminated which intern reduces weight and maintenance costs.

The other region that would need to be addressed is the hood design. The current design is made of 25x25x3mm SHS while the angle is made of 25x25x3mm. Once welded together these hood structures add an extra 15kg/m or 240kg over the length of the 8m wing. The purpose of these hoods is to carry a relatively lightweight black plastic which prevents significant amount of light from penetrating into the cameras vision.

These 15kg/m frames are extremely heavy when compared to the load they are carrying which would be approximately 1kg/m maximum of 3mm thick plastic. Research should be conducted into suitable lightweight materials which can both filter light and provide adequate strength to form the hoods. A suitable lightweight design can significantly reduce the load upon the wing structure.

As mentioned due to the time constraints of this project the two issues outlined above have not been thoroughly investigated as a means to reduce the load applied to the spray rig wing. Reducing the loads applied to the wing may reduce the size of the composite sections that are required and thereby reduce the overall cost of the project. This may also lead to wider spans being able to be used with the same sized sections. If these two issues can be addressed in further development, the use of a composite sprayer would be an even more viable option.

6.6 Implementation

As discovered during the literature review in Chapter 3, education plays a large role in the uptake of any new technology and fibre composites are no different. This would be especially true with the use of fibre composites being used in the agricultural industry as a replacement for the conventional material, steel. There are a number of solutions that aid in this process of educating both manufacturers and consumers.

It was found through research that to overcome this problem, sound engineering solutions need to be found. Engineers need to be aware of the advantages of fibre composites over conventional materials and use these advantages as a means of providing solutions that are superior to the competition. This will include a great deal of field testing to ensure the design can perform the required task. The intended consumers; farmers and contractors, want a machine that is strong, lightweight and requires minimal maintenance, all of which are properties of fibre composites. A sound engineering solution alone will not overcome the issue of converting manufacturers to use and more importantly consumers to purchase equipment made from the new material.

Along with a sound design a lot of education is required to ensure the uptake of any new design system. It is believed that one of the best methods of conducting such education in the agricultural industry is through field days. This would involve taking the machine to many different areas. This will ensure that the many interested parties will be able to view the machine working in the way in which it was designed. Some of these people would otherwise not consider driving long distances to simply see the spray rig sitting idle. These on-site field days would play a vital role in the education process of consumers showing that the design is capable of producing the same results as a similar product made of steel.

Through these efforts it will be possible to better educate end users of the benefits of fibre composites over conventional materials and in turn increase the number of units sold.

6.7 Self changes

Through experience, farmers are usually people who like to make modifications to their machinery if the need arises. It is for this reason that they may see a fibre composite SprayCam Spray Rig as a disadvantage over one made of steel. For example if the farmer decides to make an alteration to their machine it will be much more difficult for them to do so with a machine made of fibre composites than a steel one where basic tools such as a welder and other metal working tools could be used to make alterations. It would not be recommended that the same modifications be made to a composite machine without the supervision of an expert in the field of composite manufacturing.

One of the most common changes they may wish to do to a sprayer would be to change the width to accommodate changes in their farming practice. This main change would be to the use of a larger 24m sprayer. With the way the current machine has been design the addition of extra sections are relatively simple. This is due to original design being shortened to its current 18m state. To increase its size the addition of a 3m section is required as well as an additional wheel system. While this alteration has not been undertaken in this task, the analysis would be relatively simple to determine the additional forces that act upon the extended section. The only additional force acting on the original section would be the rolling resistance of the extra set of wheels since the loading acting downwards due to the mass of the extra section and hoods would be taken by the wheels. It is therefore recommended that this is investigated as it would attract many more potential buyers to the product and create a well rounded product.

6.8 Transportation

With a machine of such a size there are several issues of transportation from one site to another that need to be addressed to ensure there are no possible unforeseen issues that would need to be considered in the design of the spray rig.

The first issue is of moving the machine from the construction site to the farm location. The main construction will be undertaken in a workshop to ensure the highest possible standard of workmanship is undertaken. Generally the construction site will be in an urban area potentially many kilometres and even hundreds of kilometres away from the farm location. Therefore transportation by the use of a tractor driving the machine along the road is not a viable option. A more suitable option, is transportation via a truck and trailer. However this also creates problems of its own.

When moving such a large piece of equipment there are two options available for transportation, either move it fully assembled or in parts which can be assembled on site. The former method is used to move the current sprayer long distances. A prime mover semi trailer is used which has a crane situated at the front, enabling the entire machine to be lifted and placed onto the trailer with ease. However each has its advantages and disadvantages which will be outlined below to ensure the best possible outcome is found.

Fully assembled transportation

- **Pros**

  - Little time required for preparation

  - Can be done with a single competent person, decreasing labour cost

  - Increased quality control over final product

- **Cons**

  - Large trailer required to transport equipment

  - Specialist lifting equipment required to ensure safe lift (Crane/large HiAB)

Dismantled transportation

- **Pros**

  - Smaller truck required

  - Less specialist equipment required as a forklift would be suitable.

- **Cons**

  - More hours required to assemble on site
  - Tools need to be taken to site of construction
  - Harder to ensure quality control on site when compared to workshop

Once the issue of transport from the place of manufacturing to the farm is determined the issue of moving short distances, from one farm to another, becomes important.

Queensland Transport (2010) defines an oversize vehicle or combination that is wider than 2.5m must have:

- one warning sign at its front;

- one warning sign at the rear, or if it is carrying a rear projecting load, at the rear of the load; and
- four warning flags, with one flag fitted to each side of the front and rear of the vehicle, or if there is any projecting load at each side of both the front and rear of the projecting load.

It also mentions that if the vehicle is wider than 3m, a warning light should also be used during the movement of vehicle.

The SprayCam System is designed to fold during transportation. Each wing will fold behind the machine to a width of approximately 2.9m and is therefore under the legal requirement for a pilot escort as well as a warning light. However warning flags and warning signs should be used to ensure safety when traveling along public roads. It should also be mentioned that most tractors that will be operating this sprayer will already have a warning light installed and therefore should be used to ensure maximum safety during road travel.

It should be noted that the above information is in regards to wide vehicles in the state of Queensland and should not be used in any other State or Territory. Therefore correct information should be obtained in these areas before transportation of the machine occurs.

6.9 Chapter conclusions

The analysis of both the original wing and the new composite have both produced successful results. The original design has confirmed the original hypothesis that it is over engineered for the purpose of an agricultural sprayer and therefore makes inefficient use of materials. The analysis of a composite wing design showed that such a wing would be comparable to a design made of steel and therefore further research and testing should be conducted so that an optimal solution is produced.

Chapter 7 – Conclusions

7.1 Introduction

This chapter aims to summarise the findings of the report. The original objectives will be reflected upon and the achievement of these objectives discussed. Any future work will also be discussed so others have a clear direction for any continued research with the product.

7.2 Project Summary

Essentially this project consisted of two main facets: the first of which was to investigate and analyse the current SprayCam sprayer to determine whether its design is suitable for use of a selective weed spot sprayer. This aim related directly to the first two objectives of the project:

- Convert the current 2D CAD Drawings into a 3D modeller
- Conduct an initial finite element analysis (FEA) on the current wing design of the Rees Spray Rig. This includes detailed load calculation that acts upon the machine during operation. This will also validate the claim that the original structure is over designed

In order to conduct the FEA it was first necessary to complete a detailed 3D model of the wing design. Independent of the scope of this project, a model of the complete spray rig was required by Rees. The position of wing connection points was driven by the centre section. This extended the total project time as the only drawings currently available were basic 2D drawings. Significant time and effort was required to ensure that all components assembled in the correct locations without any interferences occurring. With the model assembled in SolidWorks, this first objective was successfully completed which then allowed the FEA to be completed.

The finite element analysis of the current steel design was conducted with the use of the software package ANSYS. In order to conduct this analysis it was first necessary to determine all the appropriate load cases which the wing is subjected to during operation. This required a great deal of research to determine the most suitable method of calculating the wing load.

The results of the finite elements showed that the current sprayer is over designed as the original hypothesis predicted. This design shows a maximum safety factor of four which when compared to other agricultural sprayers is over designed. Many other agricultural equipment uses large factors of safety within their design, which on consultation with the chief engineer of Rees is not warranted in this situation. Therefore when looking at the size and weight of the wing design it shows an inefficient use of materials. For the SprayCam Spray Rig to be successfully sold and marketed as an alternative to the current selective spot sprayers on the market which can work at both day and night, it is vital that a more refined design is produced. This should lead to higher sales and in turn a higher income for the company.

Since the current design of the spray rig is "over-designed" for its intended purpose a more suitable design should be investigated. This directly leads onto the third and fourth of objectives of the project:

- Investigate and analyse the wing structure with the use of fibre composite sections as the main wing frame as an option to significantly reduce the weight without sacrificing the operation of the machine, and
- Investigate different methods of joining each composite together and also other accessories currently attached to the wing of the spray rig.

Fibre composite pultrusions were identified as an alternative material for the redesign of the SprayCam Spray Rig. The reason for choosing pultrusions is that although there has been a lot of research into the properties of fibre composite, the industry is still in its infancy with the technology yet to really begin to consider a real alternative to convention engineering materials. It was therefore identified that a great learning opportunity would be gained by investigating the properties of fibre composites and then applying it to an engineering design situation.

For a new composite design to be considered a viable alternative to the current spray rig, it must satisfy the design specifications as outlined in Chapter 4, Methodology.

- Be able to be used in the same way as it was originally designed without sacrificing any functionality.
- Must be able to support current accessories such as hoods, camera holders and wheel structures. The initial investigation into redesigning the sprayer will maintain the current hood and wheel structure as a means of time saving for this project. In future work these should be looked at as there are several obvious changes that could be made
- Must be able to maintain structural integrity during operation so that stresses do not exceed acceptable levels
- Deflections are to be kept to a minimum so that optics are not affected by the change in focal length.
- The cost must be of an acceptable level when compared to original design and also the competitor's products. Ultimately the sprayer is a tool of which the owner wishes to make money from by selling each unit and therefore the redesigned machine needs to be economically viable

The design has been evaluated and analysed on its ability to meet these design requirements and constraints. Since this is only a conceptual design, the ability of the design to meet this requirements have been analysed to an appropriate stage.

The chosen design of the new spray rig inherent a similar design to that of the original sprayer. It utilizes a large rectangular truss system which enables the existing accessories to be simply added to the design. This ensures the first two objectives are suitably obtained.

To investigate the third and fourth requirements a finite element analysis was conducted which resulted in the achievement of these requirements. The results showed that the stress and deflection would be suitable for the design. The level of stress is acceptable when compared to fatigue models produced in previous research. It was also found that the deflection which occurred during the analysis was acceptable so that cameras remained in focus during operation. However it was found that for a design to be put into production it would be necessary that full scale testing be conducted to ensure the integrity of the design.

The final requirement of cost is a major issue with fibre composite materials. This was also the verified within the literature review as a major issue associated with the material. The analysis conducted on the wing design was only a relatively basic analysis which looked at the costing of the materials associated with the wing design. The difference in price for this analysis was approximately $1170/wing. As has been mentioned some of this difference may be made up with when including the cost of labour and also maintenance cost e.g. painting. Therefore this price difference is an acceptable amount when comparing the original design to the new composite design.

Since only a basic cost analysis has been conducted it is very difficult to determine the comparison in costing of the product when compared to other products within the market. This should be completed in future work to determine a total economic viability of the product.

7.3 Future Work

Although the preliminary design and evaluation has been conducted into the use of a pultrused fibre composites it is important that following work be completed to ensure that a composite sprayer is a viable alternative to that of the original steel machine. This future work that needs to be completed is as follows

- Conduct testing on the joining methods which hold the composites together
- Conduct full scale test on the composite design
- Produce a detailed costing analysis of the composite wing design and also analyse the products viability in the current market.

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Appendix A

University of Southern Queensland

ENG 4111/4112 Research Project

PROJECT SPECIFICATION

For: Benjamin Rackemann

Topic: THE ANALYSIS AND REDESIGN OF THE SPRAYCAM SPRAYER TO INCORPORATE FIBRE COMPOSITE PULTRUSIONS

Supervisors Jayantha Epaarachchi, University of Southern Queensland
Luke Hogan, Chindoz Pharming Pty Ltd

Project Aim This projects seeks to investigate the use of fibre composites in the agricultural equipment to reduce the weight of a weed detecting sprayer.

Programme Issue A, 22 March 2011

Conduct an initial FEA on the current wing design of the Rees Sprayer. This will include determining all the forces that act upon the machine during operation. Investigate and analyse the structure with the use of pultrusion fibre composite sections as the main frame as an option to significantly reduce the weight. These sections must satisfy the following criteria so that the machine operates in the way in which it was originally designed:

- Must be able to maintain structural integrity during operation so as stresses do not exceed acceptable levels
- Deflection is to be kept to a minimum so that optics are not affected by the change in focal length.
- Cost must not be acceptable to be competitive in the current market.
- Investigate different methods of joining and manufacturing original sub structure to the composite main frame.

APPROVED

......................(Student) .... , ...(Supervisors)

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Appendix B

FEA Report

Job Name: SprayCam Rig
(Current analysis)
Job Number: 2
Analyst: Ben Rackemann

Related Drawings:

Problem Description

It has been identified by the current engineer at Rees Equipment Pty Ltd that the current SprayCam Rig is overdesigned for its intended role as an agricultural sprayer. It is therefore the purpose of this report to analyse this statement to determine its validity.

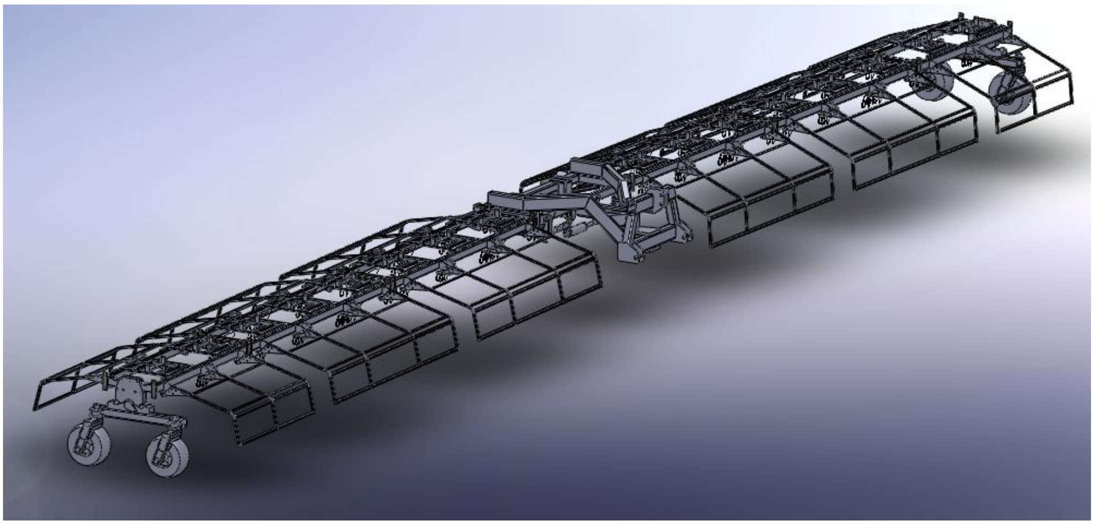


Figure 1 Solid Model of the SprayCam Rig

Approach to Analysis

Analysis Type: Static Structural

Package Used: ANSYS

Elements Used: Triangles with a maximum element size of 5cm

Modelling Assumptions:

It was assumed

- That a loading case of 2G is applied to the wing
- That the forces acting are representative of the loading conditions.
- That the welds and bolts are adequate to hold the structure together.

Basic Model

It is the purpose of this analysis to determine the properties of the wing structure and therefore this will be analysed separately from the other sections of the rig. The hoods and other accessories will be added to the analysis by the use of the appropriate loading cases.

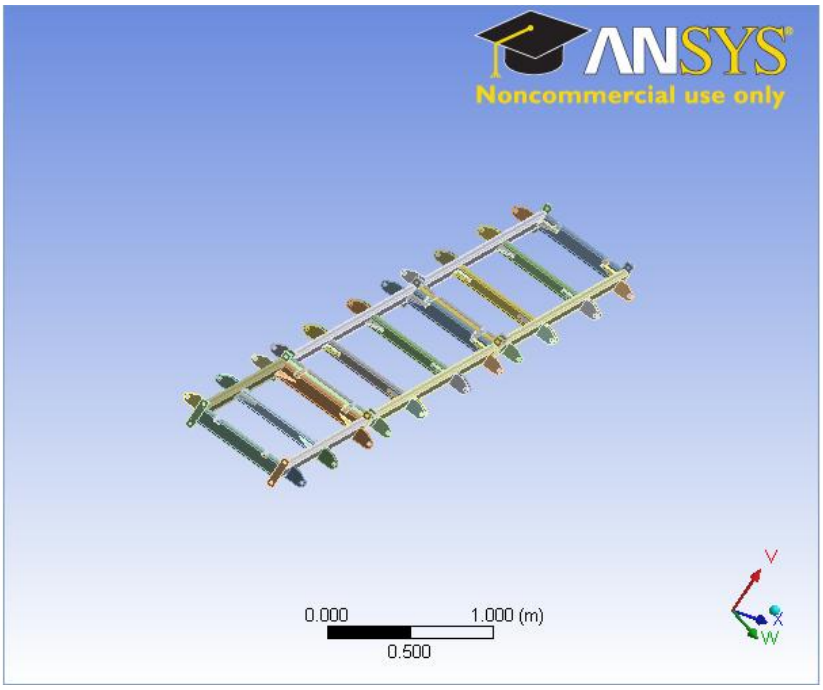


Figure 2: Model which was analysed

Mesh Generation

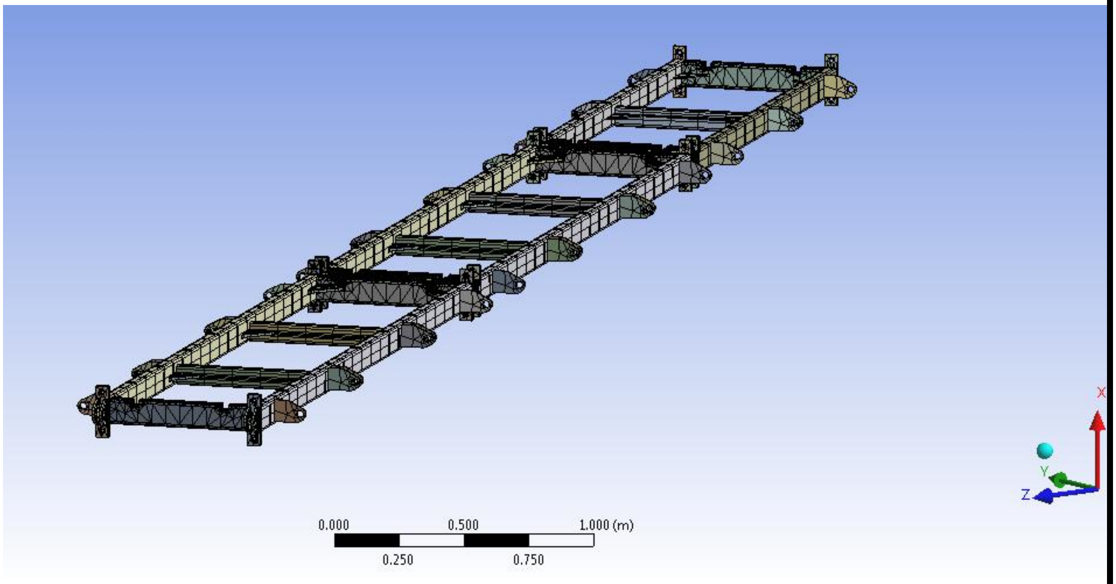


Figure 3: Generated Mesh

Material Selection

Material data for structural steel

Yield Strength: 200MPa

Ultimate Tensile Strength: 460MPa

Supports

See section 5.2.6 of report

Loading Cases

See section 5.2.4 of report. This analysis is of the loading case 2

Default Freedom Conditions: UX UY UZ ROTX ROTY ROTZ

Model Summary
Number of Nodes: 101942
Number of Elements: 23854
Number of DOF: 6
Maximum Half-Bandwidth (or Wavefront):
RAM Required: 92 Mb
Disk Required: 500 Mb
Solution Time (CPU seconds): 318 seconds

STRESS

After applying all required data the following results were obtained by ANSYS.

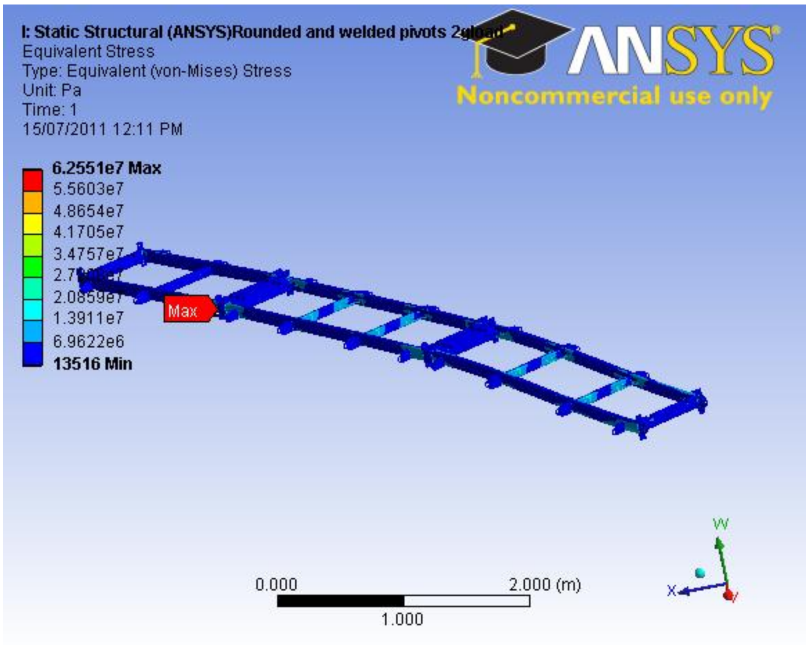


Figure 4: Stress within the wing

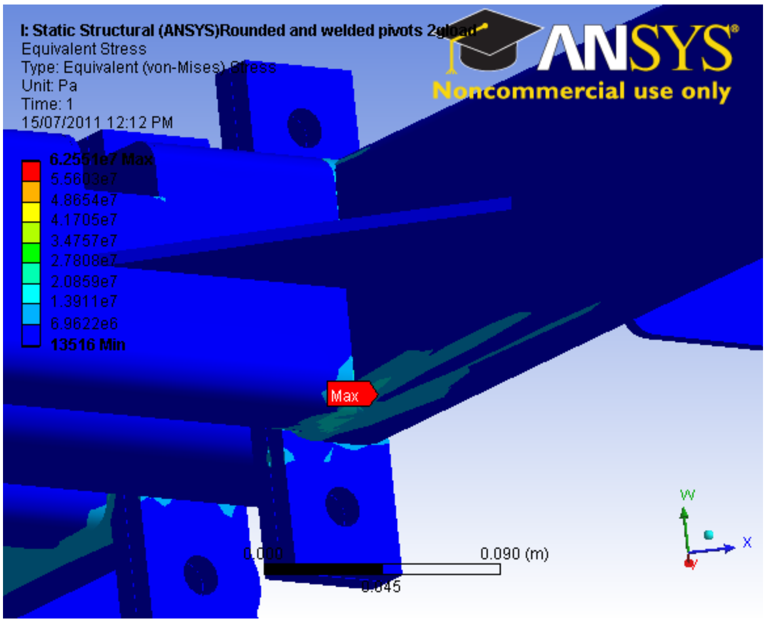


Figure 5: Maximum Stress

The location of the maximum stress areas are in the location which would be expected. There is a large stress occurring at the middle of the structure due to the large loads created by self weight. This combined with the stress located at the inside of the wing created by the rolling resistance at the outside combines to produce a high stress level located where the FEA has depicted.

The maximum stress is shown to be 62.5 MPa giving a safety of factor of approximately 4 using a yield strength of 250 MPa. Since all the loading cases have been shown to be almost a worst case scenario this shows the design is over engineered for the purpose of an agricultural sprayer.

Deformation

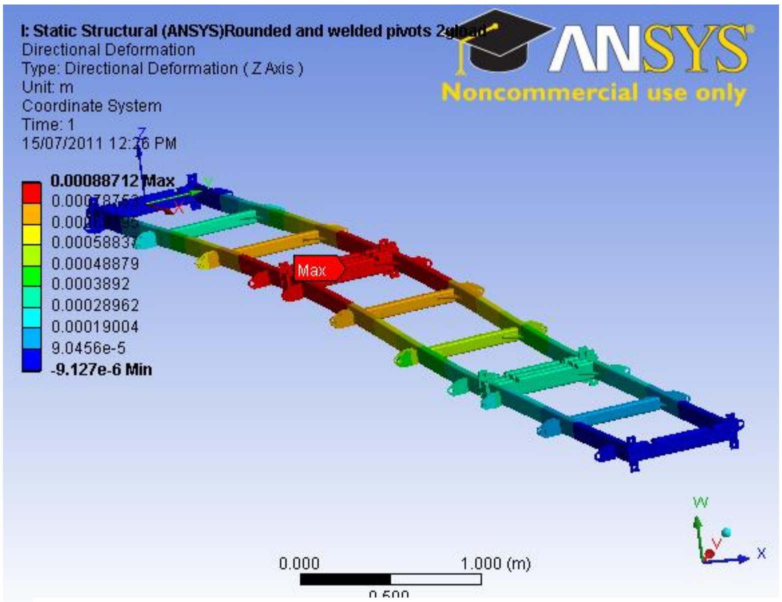


Figure 6: Maximum Deflection in the Z-direction

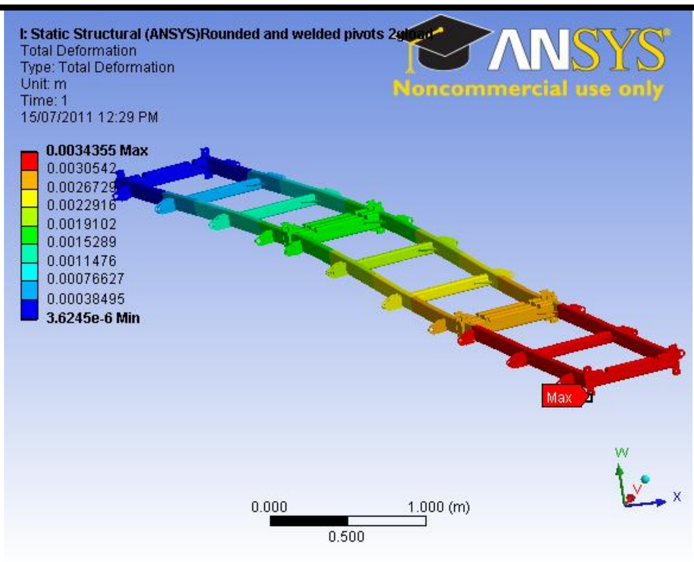


Figure 7: Total deformation

On investigation of the deformation of the system it is quite obvious that little deformation occurs when the loads are applied and therefore is not an issue for the cameras maintaining the required focal length

Action to be taken:

From the answers provided by ANSYS it can be assumed that the frame is over designed to an extent. The yield strength of the material is 250MPa and the maximum stress is 62.5MPa. This is a safety factor of approximately 4. It would be recommended that further analyses be done on simulating the scenario with greater attention to the loading cases of the wings. However I believe this will not make a dramatic difference to the overall result of the analysis.

Since the design is very heavy for its size I recommended investigations into other alternative designs in order to reduce the size and cost of the current machine

Date: 25/8/2011 Signed: Benjamin Rackemann

FEA Report

Job Name: SprayCam Rig (Composite)
Job Number: 4
Analyst: Ben Rackemann

Problem Description

Related Drawings:

The FEA conducted on the current SprayCam Rig showed the design is over-engineered for its role as an agricultural sprayer. As a means of redesigning the current wing frame composite pultrusions have been investigated with the aid of FEA to determine their suitability for the task. This report outlines the analysis conducted on the 6mm thickness 100x100mm wing design.

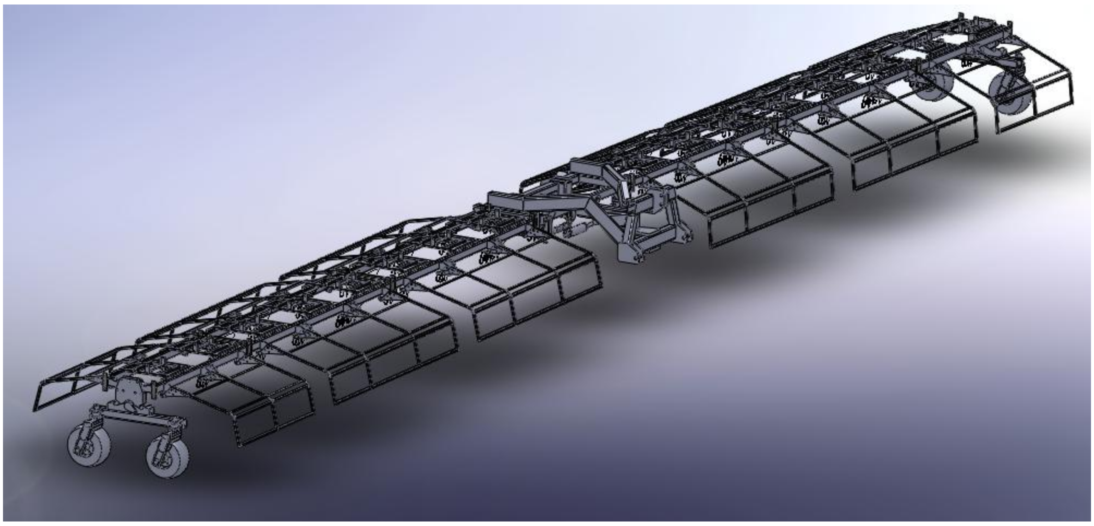


Figure 1 Solid Model of the SprayCam Rig

Approach to Analysis

Analysis Type: Linear Static

Package Used: Strand 7

Elements Used: Squares with a maximum size of 10mm

Modelling Assumptions:

It was assumed

- That a loading case of 2G is applied to the wing
- That the forces acting are representative of the loading conditions.
- That the joins adequate to hold the structure together.

Basic Model

The created model uses 100x100x6mm pulltrusions as the members which make up its frame

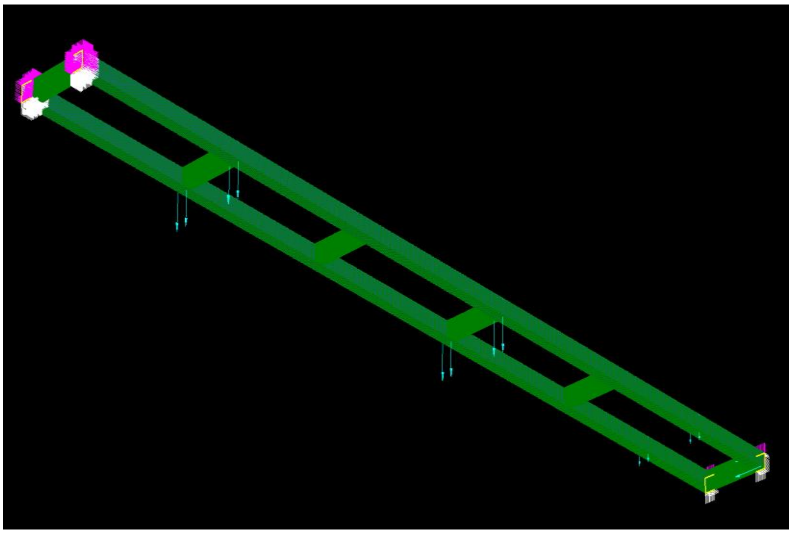


Figure 46: Wing model

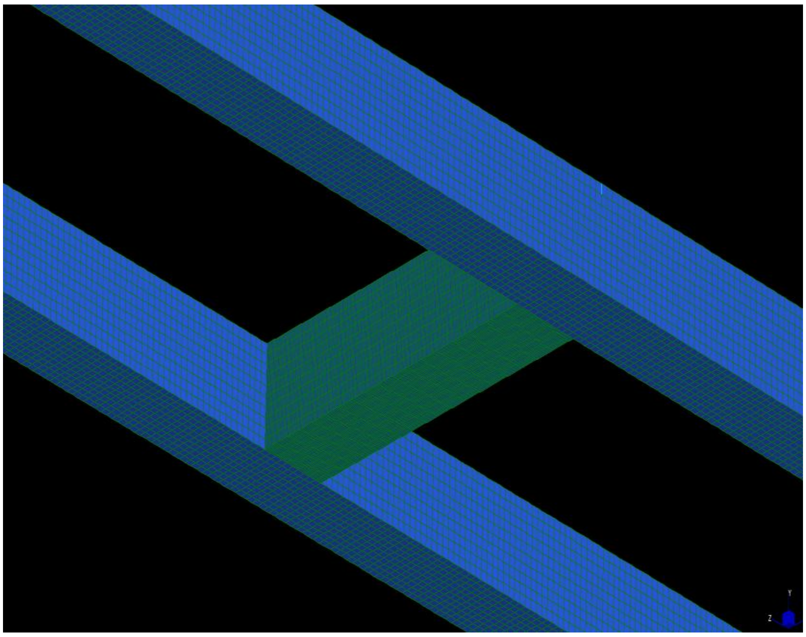


Figure 47: Generated mesh (Max 10mm)

Material Selection:

Material data for pultruded composite materials

Mechanical Property	Value
Youngs Modulus (E_1)	3.15 x 10^4 MPa
Youngs Modulus (E_2)	7.2 x 10^3 MPa
Shear Strength (G)	3.0 x 10^3 MPa
Poissons Ratio (*v*)	0.25
Density (*p*)	1.9 x 10^{-9} T/mm^3

Supports

See section 5.2.6 of report

Loading Cases

See section 5.2.4 of report

Model Summary
Number of Nodes: 101942
Number of Plates: 23854
Number of DOF: 6
Maximum Half-Bandwidth (or Wavefront):…
RAM Required: 81.9 Mb
Disk Required: 122.5 Mb
Solution Time (CPU seconds): 52 seconds

STRESS

After applying all required data the following results were obtained by ANSYS.

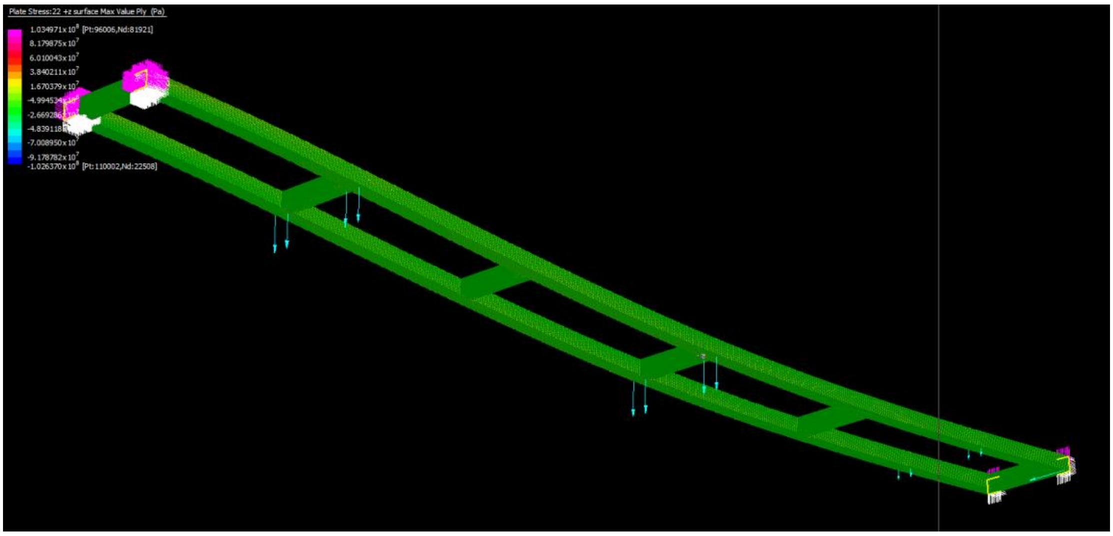
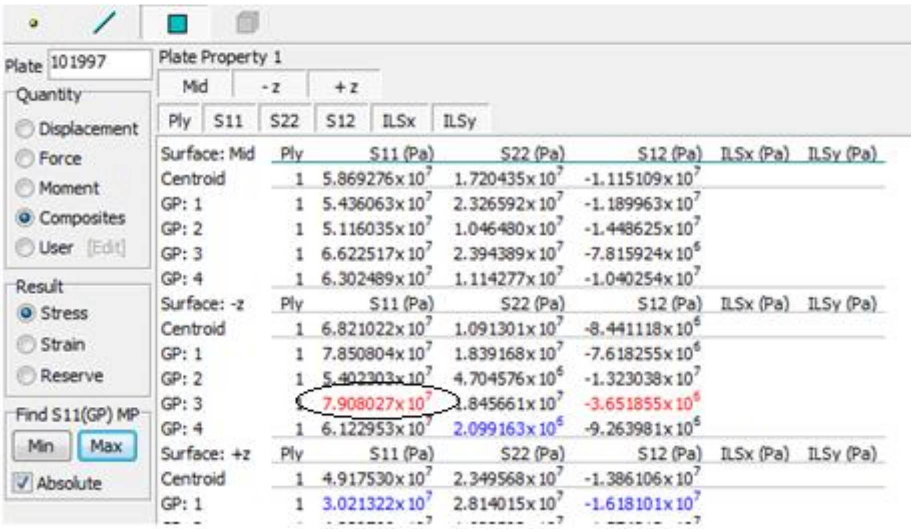


Figure 48: Stress within the structure



Surface: Mid	Ply	S11 (Pa)	S22 (Pa)	S12 (Pa)	ILSx (Pa)	ILSy (Pa)
Centroid	1	5.869276×10^7	1.720435×10^7	-1.115109×10^7		
GP: 1	1	5.436063×10^7	2.326592×10^7	-1.189963×10^7		
GP: 2	1	5.116035×10^7	1.046480×10^7	-1.448625×10^7		
GP: 3	1	6.622517×10^7	2.394389×10^7	-7.815924×10^6		
GP: 4	1	6.302489×10^7	1.114277×10^7	-1.040254×10^7		
Surface: -z	**Ply**	**S11 (Pa)**	**S22 (Pa)**	**S12 (Pa)**	**ILSx (Pa)**	**ILSy (Pa)**
Centroid	1	6.821022×10^7	1.091301×10^7	-8.441118×10^6		
GP: 1	1	7.850804×10^7	1.839168×10^7	-7.618255×10^6		
GP: 2	1	5.402303×10^7	4.704576×10^6	-1.323038×10^7		
GP: 3	1	7.908027×10^7	1.845661×10^7	-3.651855×10^6		
GP: 4	1	6.122953×10^7	2.099163×10^6	-9.263981×10^6		
Surface: +z	**Ply**	**S11 (Pa)**	**S22 (Pa)**	**S12 (Pa)**	**ILSx (Pa)**	**ILSy (Pa)**
Centroid	1	4.917530×10^7	2.349568×10^7	-1.386106×10^7		
GP: 1	1	3.021322×10^7	2.814015×10^7	-1.618101×10^7		

Figure 49: Maximum stress within the structure

From the above figures it can be seen that the maximum stress within the structure is 79 MPa which is an acceptable level when considering the fatigue strength of the material. However the maximum stress is only very localised at the joint of the two composite sections. When comparing this to the rest of the structure this stress concentration is very high and can be contributed to the rapid change in geometry. This rapid change would be reduced when joints are added and therefore would show smaller stress increases.

Deformation

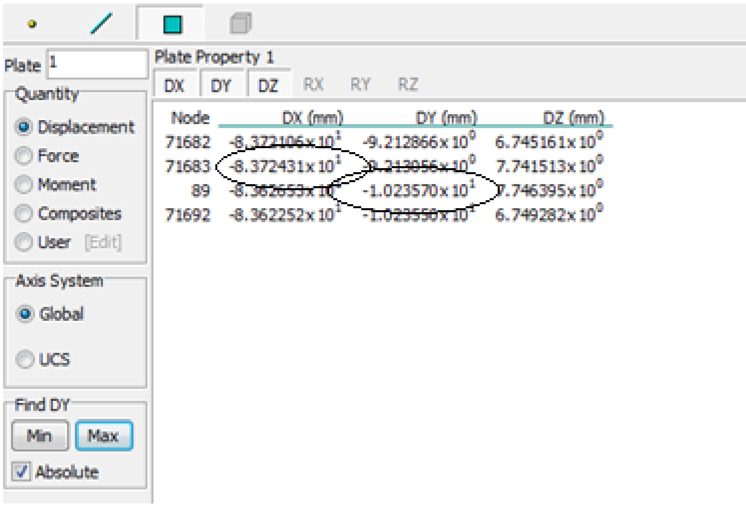


Figure 50: Maximum deflection within the wing

The maximum deflection which occurs is 83.6mm which end of the beam in the x-direction or backwards from the wing. This is due to the wing acting like a cantilever with the force of the rolling resistance acting on the end. The main deflection that affects the system is y direction as this would alter the focal length of the cameras making them less efficient. It can be seen that the maximum deflection in this direction is 10.2mm or 1cm. This is very small and would not affect the cameras operation.

Action to be taken:

From the analysis above it shows that a wing made of composites are a possibility as an alternative design for the SprayCam wing design. However these are only basic analysis and further work should be conducted on the producing more a more accurate FEA. Once this is complete real world testing should be conducted to validate the results obtained in the FEA.

Date: 12/8/2011 Signed: Benjamin Rackemann