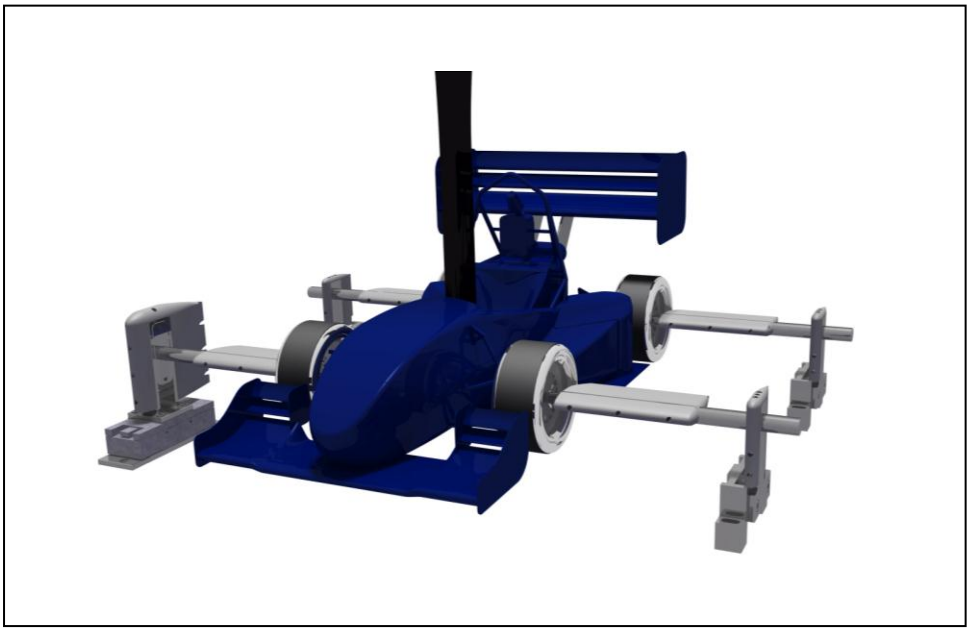

Adjustable wind tunnel model for an open wheeled vehicle

Kandidatarbete inom civilingenjörsprogrammet Maskinteknik

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Abstract

Wind tunnel models are used when designing race cars both as an effective way to test new ideas and a method to validate the calculations. Chalmers Formula Student (CFS) want a wind tunnel model to use in their design work and testing but making a new model for each year is restricted in time and cost. In 2011 CFS made their first wind tunnel model which was static and due to the absence of rotating wheels, had limited correlation with the real car. It could not be used by any other team since it was specific to that year's car design. It was desirable to obtain an adjustable model with standardized interfaces to easily change the exterior design without having to remake the model. To be able to maximize the usefulness it was also important to receive numerical data from measurements to compare with calculations.

This report describes the making of a reusable wind tunnel, which will decrease the time spent developing it each year and provide means of acquiring credible and desirable data. It describes the benchmarking of existing technology and what can be implemented in the project. It will also explain the design and manufacturing of the model, which problems arose and what to consider when using the resulting model or making an additional model.

The goal of this project was to create a platform for CFS to use in their wind tunnel testing. This was to be done by designing and building a frame to which changeable body features would be attached. To get as realistic modelling as possible a system for having rolling wheels was designed and ways of measuring was developed. The frame and the wheels were manufactured but the body features although designed, were not manufactured and testing in the wind tunnel was outside the scope of this project. Finally some recommendations are made around the model and guidelines how to use it are drawn.

This project was completed as a part of Chalmers Formula Students Advanced Research Programme to improve the aerodynamics of the car and to increase the analysis toolbox at hand. It will hopefully contribute to an increased ranking in the Formula Student contest and a gain in the international respect for Chalmers as a professional institute for education.

Table of contents

List of figures

List of tables

Abbreviations

CFS – Chalmers Formula Student

CFD – Computational Fluid Dynamics

CNC – Computer Numerically Controlled

FEA – Finite Element Analysis

FEM– Finite Element Method

FSAE – Formula - Society of Automobile Engineers

SLS – Selective Laser Sintering (here using plastic)

NACA-profile – (National Advisory Committee for Aeronautics) a symmetrical shape that minimizes drag

1 Introduction

The Chalmers Formula Student

The Chalmers Formula Student-team (CFS) is a group of Chalmers students that will design, build and compete with a small Formula - Society of Automobile Engineers (FSAE)-race car. The competitive part of this project is mostly related to engineering solutions and making well motivated design choices. There is some competitive driving at certain occasions as well. The dimensions of a car like this are approximately 1.5 meters wide and 3 meters long, and it seats one driver at a time. A scaled model of a car like this will be 1:3 scale of its original size, to fit the purposes as a wind tunnel model

Figure 1.1 CFS10 in action

Wind tunnel model thesis

Wind tunnels are used to blow air at objects in a controlled manor. The object of interest is placed in the wind tunnel and equipped with different measuring equipment. In the tunnel the air then flows around the object and for example pressures are measured to obtain readings of how the object behaves. The challenge with wind tunnel modelling is to obtain a representative model. Often the model has to be attached to the tunnel with features that the real product does not have which in turn creates a flow disturbance that does not exists on the real product. Other problems are that it is hard to predict the real world conditions and often impossible to know the conditions in for example a race. One can approximate the air to blow head on to the car but it is most likely not the true case. There are almost certainly all kinds of disturbances from the wind or another car, making it difficult to correlate the tests to reality.

The problem that the project is based upon is that CFS-team does not have a fast and easy way to test different body-ideas at an early stage in the design process and validation of Computational Fluid Dynamics (CFD) analysis. The current way of deciding whether a body panel or wing has the desired properties is to perform a CFD-analysis on the car. This makes it difficult to test multiple concepts as these calculations are time consuming. An analysis of this kind is done using a computer, the results of which could easily be corrupted if the boundary conditions are not applied in the correct manner. An additional way to test the aerodynamic properties of the car is to build a static model, using a 3D printer, and fit it in the Chalmers wind tunnel. This is also a good way to confirm that the CFD has produced a correct solution by running tests with real air flowing around a scaled model of the car.

However this method has faults. The availability of the 3D printer that has been used is limited, which does not make this method suitable for repeating tests with every new design. Using the printer that is located at Chalmers is expensive and its work space of it is smaller than desired.

This thesis therefore aims at making a wind tunnel model that is easily fitted to different designs. This will reduce costs, save time and give more realistic results than making a completely new model every time the design changes.

Wind tunnel setup

There are two different ways to test cars in wind tunnels. The first is a static model of the complete car standing on the floor of the wind tunnel. This is the traditional way to perform a wind tunnel test due to the simplicity of manufacturing the scale model. The second way consists of having the body of the car static and the wheels rotating, and the ground also moving, both in the correlating speed of the air flow. Using the second method gives a result that resembles the reality of a car moving along the road, in a better way than the traditional method [7] [3]. This improvement in accuracy are further enhanced by the fact that the wheels of a FSAE-car do not have wheel houses but are open which means that estimated 40% of the total drag of the car comes from the wheels [4] and therefore having a great impact on the result. Having this as a starting point for the project states the importance of having the features of moving ground and rotating wheels on the model.

In reality the moving ground system can either be a conveyor belt construction that is located at the same level as the floor of the wind tunnel. Either a construction of one roller for each wheel and a smaller conveyor belt in the middle to approximately simulate the moving ground underneath the car. The latter is mostly used for testing full scale models where a conveyor belt cannot take the weight of the car at the desired speed, whereas the first is used for smaller scale testing. As a 1:3 scale model in utilized in this thesis, the version with a larger conveyor belt will be used, this is also because of the availability of the equipment of those at Chalmers wind tunnel laboratory.

When mounting the model in the wind tunnel there have to be some kind of feature holding the model in place, this feature is often referred to as a “Sting”. The sting is a device which is designed to minimize the disturbance to the flow, as it is unnatural to the model, while it is stable enough to support the model without too much deflection. The Chalmers sting is shaped like a symmetrical NACA airfoil (Figure 1.2) and made out of carbon fibre. Stings can also be used when mounting model features in the tunnel that are not attached to the main body of the model itself. It is still used for the same reasons, to mount features in the wind tunnel at a way that disturbs the flow the least. In figure 1.3 the Chalmers main sting can be seen coming from the ceiling of the wind tunnel while smaller stings can be seen on the side, holding the wheels of the model.

Figure 1.2 Symmetrical NACA airfoil

Figure 1.3 Stings holding a model

When making tests in the wind tunnel it is desirable to have as much control and knowledge about the flow as possible. One aspect of the testing is that the tunnel is a closed volume with a certain cross-section area. This leads to an alteration of the flow around the wind tunnel model due to that the model has a certain cross-section area which reduces the volume available to the air flow. Since the mass flow never changes but the volume does, the speed and pressure around the model will change due to this blocking of the tunnel cross-section. This leads to different flow properties then the wanted and is a source of error in the tests. There is a rule of thumb of no more blockage than 10% of the tunnel cross-section to make sure that the flow properties stay within an acceptable error limit. The Chalmers wind tunnel has a cross-section of 2.08 m^2 which lead to a maximum cross-section area of the car of 0.208 m^2. This in turn leads to the decision to make the model in 1:3 scale, since it does not create too much blockage, around 7% for the CFS12 edition, in the tunnel while still being an even number easy to calculate with.

Thesis goal

“We will by efficient engineering and methodical work, design and manufacture an adjustable Wind Tunnel model before 18th May 2012, which will assist future CFS-teams.”

To write the thesis, perform the design and complete the manufacturing is an ambitious goal, but it is not considered to be impossible.

Technical background

The thesis work will be limited by the need to use the existing wind tunnel material that is currently possessed by Chalmers. This is a limitation regarding the costs of equipment used in wind tunnels as the budget is beyond that of this work. This results in technical limitations which forms a starting point for the thesis. They will hereby briefly be discussed.

- The size of the cross section of the test section of the wind tunnel is limited. This makes the cross section blockage, and in extension the size of the projected area of the model body, limited. This means that a specific scale of the car had to be used for the model body.
- The moving ground system has a limited top speed of 35 m/s. This has to be taken into account as the most interesting testing speed according to the CFS-team is 56 kph or 50 m/s scaled to fit the model. This is because of that the Reynolds number has to be constant to

have the same flow conditions. During the project 50 m/s will be the dimensioning speed to account for potential future updates of the wind tunnel facility at Chalmers.

- The force measuring equipment called a balance could not be specifically purchased for this thesis. The existing balance was limited to withstand a certain force in the vertical direction. The estimated down force and the weight of the model and body could therefore under no circumstance exceed 1200 N in vertical Z-direction.

2 Method

Time disposition

The way that the time will be disposed in this project is the same as the CFS-project. This means that the project first of all will be divided into four phases. But for this thesis only the first three were used, there is not enough time for the fourth phase, test phase. Each phase is finished by a report that concludes the result and motivates the choices that have been made. To know when each phase must be ended a planning schedule has to be made as a beginning of the project.

The first phase is the pre-study phase which aims at gathering knowledge concerning the subject at hand. This is done by researching databases, reading books and interviewing people. Other ways of gathering knowledge during this phase could be to send out surveys or making real life testing. Those methods were not used because the amount of people with knowledge of wind tunnels at the institution for applied mechanics was small. Therefore interviews were less time consuming. As for the testing of different solutions that option was not available due to the limited access to the Chalmers wind tunnel.

The work on the thesis started with the drawing of a functional model. The functional model describes which subsystems there are (see the Departments of responsibility) and how they interact with each other. This is a way to split the whole system, being the wind tunnel model, into its functional elements and their interactions. This is important work as the project becomes divided into smaller systems and the comprehension of the whole project is more visible. At the end of this phase the performance of the complete system of parts or single parts was stated and formulated into so called Design-targets. Design-targets consist of quantifiable units of measure, relevant to the function of the system being considered. It is preferable that the design targets can be approximated during the design phase to make sure that the design work is running in the right direction. The design targets will be evaluated at the end of the project by real life testing to display to which degree the design work is successful. Having design goals as a base for the design phase consisting of many parts is also a good way to make sure that no part becomes forgotten or neglected.

Phase two is the design phase. During this phase the actual parts are designed and final dimensions decided and made into material that enables it to be manufactured. This phase was completely carried out on the computers, using the 3D-modeling software Catia v5 and the FEA software ANSYS 13. Catia was chosen because of its good capability of handling systems of many assembled parts. ANSYS was chosen since it is used by the CFS-team and there is in house knowledge. The last phase of the project is the manufacturing of the parts that are concerned in the project, and putting them together, making the model complete. As much of the manufacturing as possible will take place in the Prototype-workshop at Chalmers. What limits which parts cannot be manufactured there is the range of machines available.

This three stage method for time planning was used for this thesis because the thesis goals are to deliver a physical adjustable wind tunnel model, which this method is supposed to result in. By using this method the project will be structured by deadlines that ensure that every phase will receive its planned amount of time, and the design choices will be well motivated.

Source criticism

The subject of wind tunnel testing makes craftsmanship and theoretically derived connections come together. Also there is no wind tunnel setup that resembles the other, as the purposes of using wind tunnels are almost always different. These factors give the possibility that conclusions of each study may vary. Therefore the sources must be critically studied.

The main sources used for this thesis are technical papers about different kinds of work concerning wind tunnels. The way these papers are brought to attention is partly through key-word searches in a large database. This database is purposed to house different types of automobile engineering depictions and is called the SAE-database, or Society of Automobile Engineers' database. Other sources that might be used will be suggested by the supervisor, examiner or otherwise qualified members of the institution.

If other sources than the ones chosen had been used, the result of the thesis might have varied. This could be because that real life testing not was possible, which made the conclusions from other studies unable to be verified for the purpose of this thesis. As interviews also were made, the answers might have been influenced by the persons own preferences.

Areas of responsibility

As the thesis work is cantered at making well engineered parts, and that the complete system will most likely contain a large amount of parts, all group members will be responsible for specific parts. Having someone responsible for a certain share of the project is favourable because otherwise it will be hard to make sure every part is realised. The initial conditions (see Technical background) of the project made these departments of responsibility natural to define, as the different systems of a wind tunnel model have different aspects that require consideration. These departments of responsibility will hereby be referred to as subsystems, which is the term used in this working method. Each subsystem shall have a correlating subgroup that will take care of the work. There were four subsystems which meant each of the group members received responsibly for one of the departments. This also meant that there was only one member of each subgroup. Being the responsible does not mean that all the work concerning the subsystem should be done singlehanded by this person. Being responsible means to organize the work needed to be done and distributing the workload to a suitable member of the subgroup, or in this case the suitable project group member.

3 Pre Study phase

To make sure that the result of the project, the physical wind tunnel model, fulfils the requested demands it is crucial to clarify all demands and needs of the product. It is also important to gather the required knowledge to be able to manage the task. This work was done during the pre-study phase where the main problem was broken down into smaller and more manageable problems that could be investigated deeply. All the knowledge was gathered through literature studies, interviews and reading technical papers. When designing a product there is no need to reinvent the wheel, so it was of considerable interest of doing research on earlier wind tunnel models to see what is done and what is working. All this information was analysed and evaluated during the pre-study phase to make sure that the design was to be as good as possible. Several tools were used to carry out the work for example “the functional model”- a structured way of braking up a large system into smaller subsystems and see how they really interact with each other. The results and conclusions from that work can be found in this chapter.

3.1 Functional model

The functional model is presented in Figure 3.1.

Explanation of the functional model

The problem has been divided into the following four subgroups. The first is to create a structure with a standardized system for making the changing of a body feature easy and quick. This subgroup is called Frame, as it will develop a backbone of the wind tunnel model. The second subgroup will design the scale body panels of the CFS12-car, not altering the current design but making them ready for manufacturing and easy mounting on the frame. The third one is rotating wheels and moving ground system. Having rotating wheels and moving ground will provide a model that simulates the reality in a way that is not possible with a static model. The last subgroup will provide sensor equipment required to be able to back up visual observations and confirm the CFD results with real life data.

The subsystems explained are bounded by the red dashed lines. This will also define the areas of responsibility of the project. The functional elements, represented by the boxes, are divided into two categories. Green ones are internal to the system of concern, and therefore belong to one of the four subgroups. The red ones are external to the wind tunnel model, and therefore also outside the system boundary. The red functional elements will not be included in this thesis.

The arrows represent the functions, or interactions between the functional elements. The ones that are green represent the main functions. These functions are the ones that are demanded of the wind tunnel model. The blue ones are support functions, which are not demanded but still might contribute to the satisfaction of using the wind tunnel model. The red arrows display the undesired functions. These are functions that the user has to deal with in order to maintain the product running, or functions that otherwise affecting the product in a negative manner.

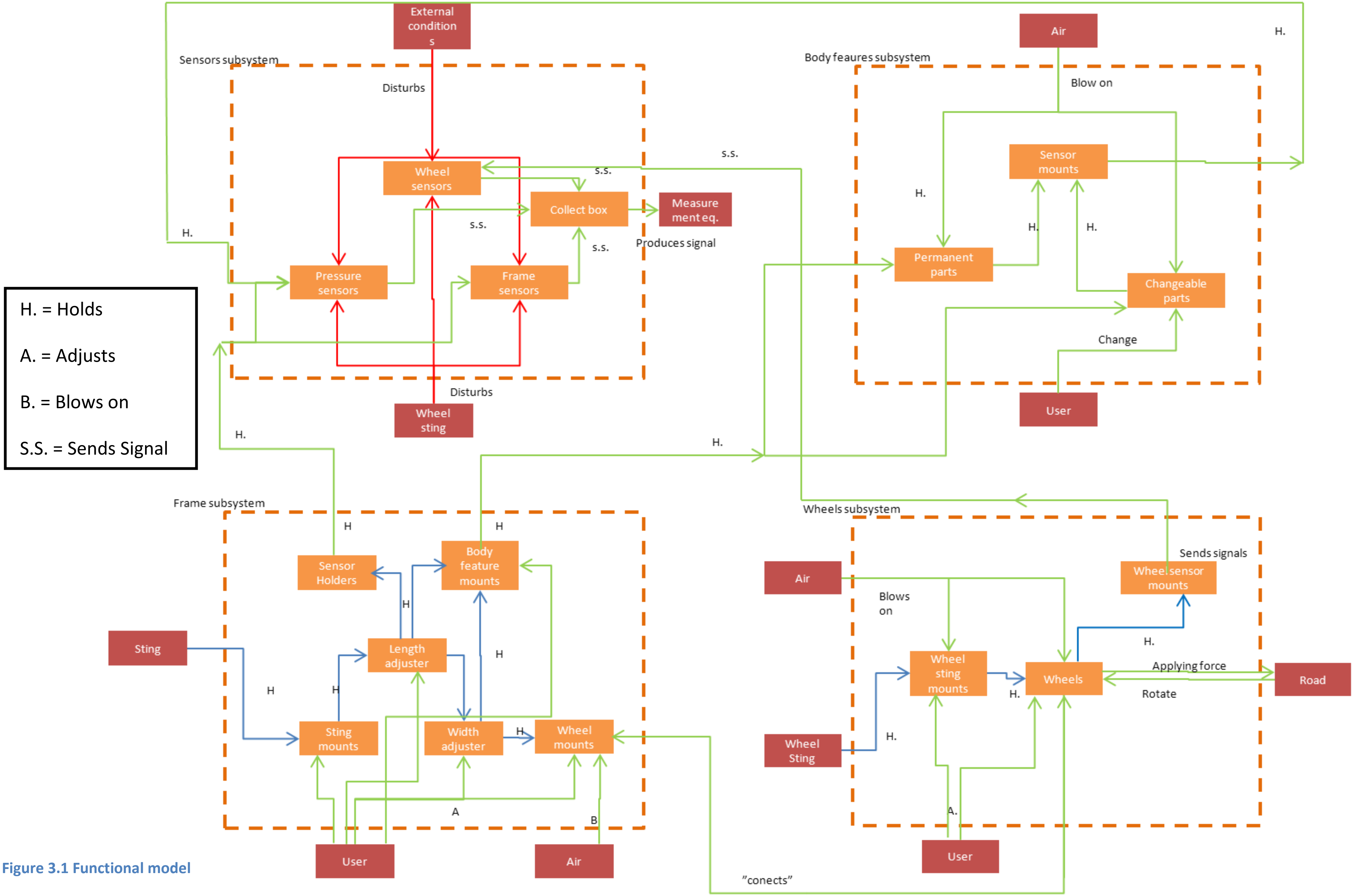

Figure 3.1 Functional model

3.2 Benchmarking

Benchmarking is a method used to ensure that the time spent during the project is not misused by developing subsystems that already exist. To ensure that this was not the case, papers from the SAE database were read and specially selected chapters in books and PhD-theses were studied. What was concluded will be presented in this chapter.

3.2.1 Frame

The frame of the model can be seen as a spine that holds the model together. All the mechanical measuring equipment is mounted in the frame so the stiffness has to be considered. The model will be a 1:3 scale so all deflections on the model will be multiplied with three on the real car [9]. While this is an adjustable model it is important that the main dimensions of the frame can be easily adjusted to each new design. The weight of the whole model is limited to 30 kg do to the limit of the balance and that put a demand on the frame to not be beyond this weight. The demand of the fastening system is to make the change of body parts easy. The different options for each subsystem will be discussed below.

Carbon fibre spine

A spine made out of carbon fibre has advantages of light weight and high stiffness to weight ratio. There is the possibility to achieve complicated geometries with carbon fibre and the surface finish can be good when removed from the mould. The disadvantage is that it is time-consuming to make the moulds and casting the carbon fibre. If the body features will be screwed to the carbon fibre spine there is problem of how to get threads in the carbon fibre, as there must be some form of insert nut. Carbon fibre cannot be manufactured at Chalmers so that must be done at an external manufacturer.

Computer Numerically Controlled (CNC) machined aluminium spine

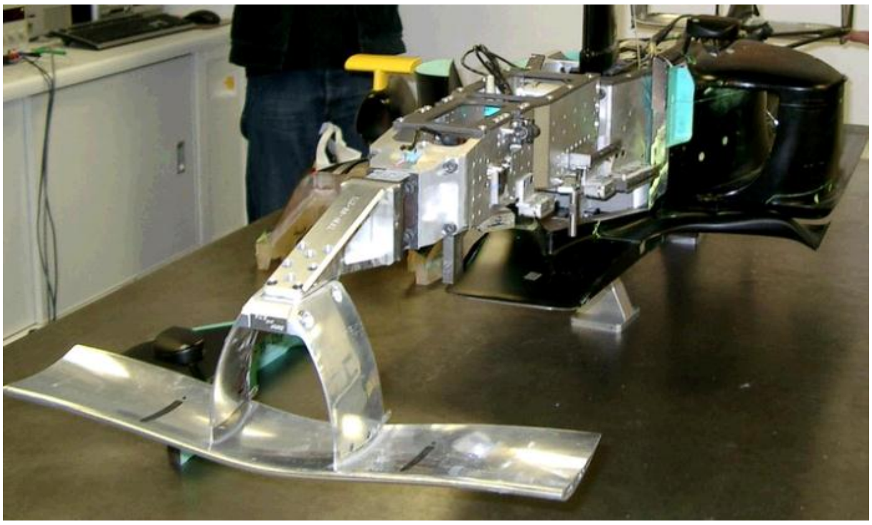

Figure 3.2 Example of a wind tunnel model spine made of CNC-machined parts

CNC machined aluminium has a high stiffness and it is easy to thread holes that can be used to fasten both body features and wings. The surface finish is rougher than the carbon fibre, so surfaces that are exposed to the main air flow will require a higher quality surface finish. The CNC work can be completed in the workshop at Chalmers and there is significant knowledge of working with metals at

Chalmers that is not the case for carbon fibre. The model can easily be divided into parts and sections that will ease the adjusting of wheel base and track width.

Aluminium profile spine

Profiles have the same advantages of the CNC aluminium spine except the disadvantages earlier mentioned. A significant disadvantage with profiles is that it is difficult to achieve more complex shapes and it could be necessary to machine the parts. If it is a straight shape and there is a standard profile that fits the model it can save material.

Discussion and final solution

The main function of the model is adjustability. It includes both changing different body features and adjusting the dimensions of the car. Carbon fibre has disadvantages on these points, it is necessary to have some fasteners in the carbon fibre to be able to fasten parts to it and it is harder to adjust the dimensions. The machined aluminium can be threaded and split up into sections that ease the adjustment of the dimensions. Both the machined aluminium and the carbon fibre can be manufactured into advanced geometries but the carbon fibre work requires more time and knowledge of how to achieve a high degree of accuracy. There is no need to build a mould when working in aluminium and for the carbon fibre it is necessary to have a mould that must be machined, which adds additional work hours. The stiffness of the model will be achieved with both carbon fibre and aluminium. The disadvantage of undertaking complex shapes with the profile is a significant drawback for this solution but it may be interesting to combine the profiles with the machined aluminium. The solution that is preferred is the machined aluminium in combination with profiles because it is much easier to manufacture and mount features on.

3.2.2 Wheels

The wheels of the model will be rotating, in contact with the moving ground. The most important requirements of the wheels are that they replicate the real wheels and tires, in terms of size and shape [3]. There are existing wheels at Chalmers but they did not fit the dimensions required by this project. That is why the ideas of using the existing wheels were not considered and work to make a new design was initiated.

The options

The benchmarking showed that the type of wheels used on a rolling road was only wheels machined out of solid aluminium. If the scale of the model was too big for the wheels to be solid, they were still made of aluminium but instead an assembly of high precision machined parts. Otherwise they were a scale replica of the actual wheel, with inflatable tire and rim. In all cases the wheels were mounted on an axis with ball bearings.

One feature of the wheels that was different when using aluminium wheels was the coating, or the surface treatment of the contact surface. Some examples had only the texture of the turned periphery, while others had a thin plastic coating, forming a sticky layer at the contact surface of the wheel.

Discussion and solution

The wheels of the model will have ball bearings that will withstand speeds spanning from 4200 up to 6000 rpm. These bearings will be supplied by SKF, because they supply all the data needed for basic calculations of life time and friction.

At the specified 1:3 scale of the actual dimensions of the car, the wheels can be turned from a solid bar of aluminium. The contact surface will have the vulcanized plastic tube attached. Doing so will substantially decrease the force required between the wheel and the moving ground to achieve a rotating wheel. Why this is desirable is because a greater force on the moving road, the belt, will generate more heat, and therefore shorten the testing sessions significantly. This solution makes the wheels more complex and therefore more expensive to manufacture, but this choice is still preferable despite the extra effort.

Side mounted wheel stings

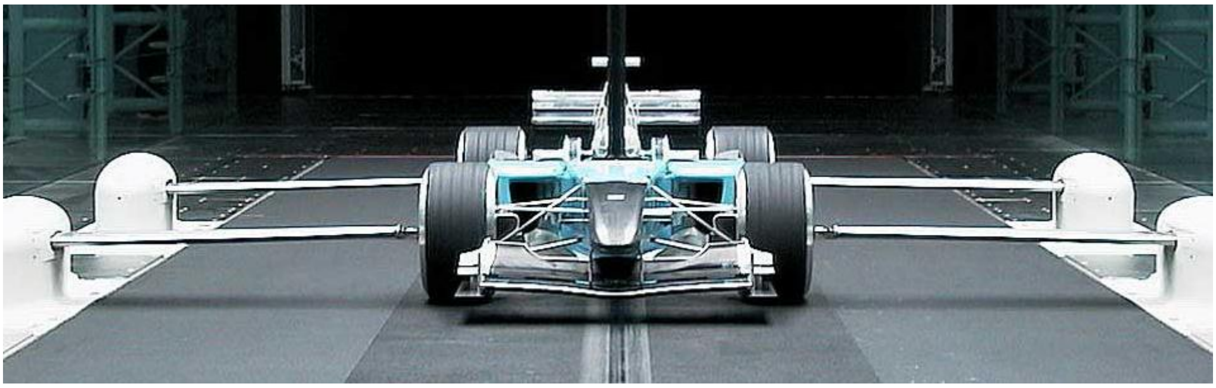

Figure 3.3 Example of a wind tunnel setup using side mounted stings

The wheels have to be fixed at a certain position in relation to the model body, in contact with the moving ground. Good attributes of a sting is low disturbance of the airflow and low deflection or change in position. This type of mounting means having one sting for each wheel stretching from the side of the moving ground, perpendicular to its rotating direction, to the outside of the wheel. This means that the model body, and therefore the balance, is not connected to the wheels. This is a drawback because then the probable lift and drag generated from the wheels will not influence the readout of lift and drag from the balance. The track and wheelbase can quickly be changed by moving the stings with the wheels, on the slides next to the moving ground. The stings will have an effect on the flow of air around them.

Spine mounted wheels

This solution intends the wheels to be mounted on the spine of the model. This will make the lift and drag produced by the wheels added to the balance. Another positive aspect of having the wheels mounted to the spine is that no stings on the side of the vehicle are present, as in reality. A downside with the spine mounted stings is that any vibrations in the wheels caused by the moving ground will disturb all the readouts from the balance.

Conclusion and solution

Due to the need to change body parts quickly, and the layout of these parts changing from each year, the easiest way to mount the wheels is with the side mounted stings. If the wheels are mounted on the spine the mountings would have to be durable to support the loads without deflecting. This type of mount has to be complex as well to be able to fit each new car design and will therefore disturb the air flow more than necessary.

3.2.3 Sensors

Sensors are put into the model for a number of reasons. Firstly they assist in the teams' process in evaluating their design decisions. The team will have design targets for every part and this need to be verified. The sensors also provide a helpful tool when using the wind tunnel to design a part. The model can be used quickly and easily to try out small setting changes e.g. attack angle of the wings. When doing this the sensors provide a means for objectivity in the evaluation. Lastly the sensors can be used to verify and complement the CFD calculations.

There are a number of considerations to take into account when using sensors. One important aspect is the disturbances from the stings. This is a problem that has to be addressed when designing the stings but will have to be taken into consideration when analysing the data collected. The amount of data that can be collected is also something that is limited. In this model that will be limited by the time it takes to rig the sensors rather than the capacity of the wind tunnel.

Load measurement

The ability to measure load is of great significance when testing a wind tunnel model. It is the way of determining the properties of the car as a whole. Mainly the drag and lift of the car but also the distribution of force on the front and rear wheels. Chalmers has a balance that can measure load and torque in x-, y-, z-direction and this is the balance that will be used. There exists a program in the wind tunnel lab to collect and process the data and this will be used. The balance has large dimensions but this will not pose a problem in the design. It also acts as an interface between the frame and the sting.

Pressure measurement

The purpose of measuring pressure can differ between different models. This model will be used mostly as a way to quickly test and compare different aerodynamic concepts. To do this it is important that measurements do not take a long time to complete. There are a number of alternative ways of measuring pressure [2].

Pitot tubes

At Chalmers pitot tubes are the most common way of measuring pressure. It is easy to adjust to the amount of data that are sought. The user can determine whether the pressure should be measured at a single point or what resolution that is desired. The strength is that if a user wishes to evaluate e.g. a pressure drop over a certain component, then pitot tubes are quick and easy to use. If the user wants to evaluate the pressure distribution over an entire body and get good resolution of results then pitot tubes is a more strenuous method. At the Chalmers wind tunnel there exists equipment to use pitot tubes.

Pressure sensitive paint

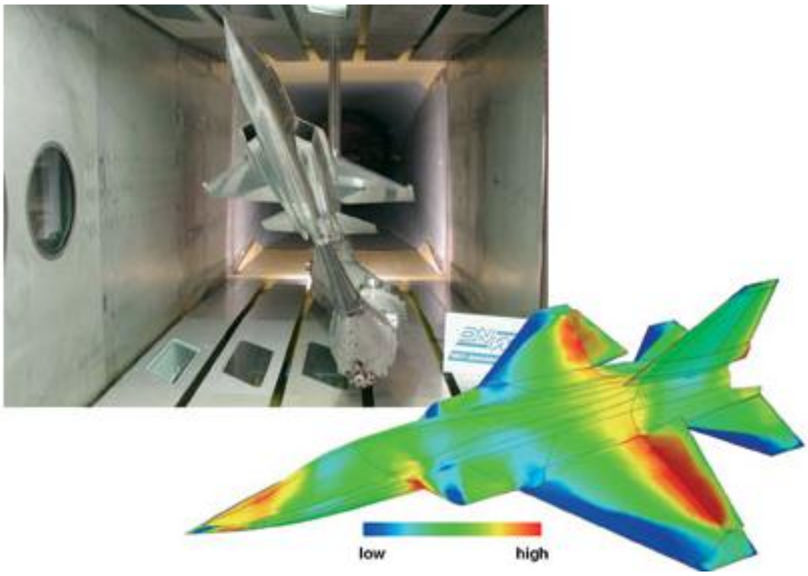

Figure 3.4 Example of a model prepared with pressure sensitive paint and its corresponding scanned readout

There exists paint that is pressure sensitive which can in a certain light and with certain equipment be used to measure pressure. The strength of this is that it is relatively easy to get an idea of the pressure distribution over the model. The downside is that it requires equipment that Chalmers does not have. Therefore it is not considered furthermore.

Taped on pressure sensors

Taped on pressure sensors function are similar to that of the pitot tubes. They measure pressure at a single point but differ from the pitot tubes in that these are not integrated in the body of the model but instead taped directly to the body. The big from pitot tubes is that they are mounted to the surface of the model. This makes for a lot of tubes and equipment in the flow and unnecessary disturbances.

Conclusion and solution

Based on how the team will utilize the model, the pitot tubes will be the way of measuring pressure. The team is mostly interested in investigating how alternative designs affect the pressure over a specifically selected areas of the vehicle e.g. how the flow through the cooler changes inside the side pods, as this is a vital for the function of the engine. The pitot tubes will make the least disturbances to the flow while still being sufficiently easy to handle.

3.2.5 Body features

This part of the solution model concerns the production method of the body features, which will go on the spine, more than the selection of parts itself as the parts will change each year. What is desired from the body parts is that all of them should be replaceable within a specified amount of time, and that they will resemble the geometry and surface of the actual car. What is here considered to be body features is: body panels, wings, wing attachments, visible frame sections and visible suspension parts.

Since there are a number of solutions that are suitable for a wind tunnel model, the advantages and disadvantages of these solutions will be discussed.

Moulded carbon fibre body features

Figure 3.5 Example of a body made of carbon fibre panels

The process of making a part in carbon fibre starts by making a mould in the shape of the final product. The carbon fibre reinforced epoxy is then put inside the mould and fixed using a vacuum bag, to reduce air bubbles that will weaken the part. This method will give an incredibly strong and light body panel that has a very smooth surface. The drawback of this method is that the mould is time consuming to produce, and a new one needs to be made every time the design changes.

SLS-printed body features (Selective Laser Sintering)

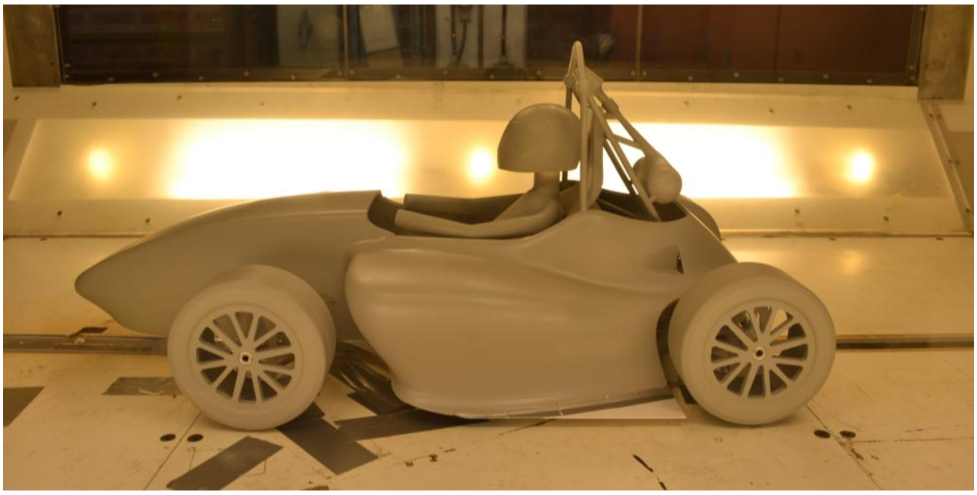

Figure 3.6 CFS11 car printed in a 3D printer

This is a production method that can be described as 3D-printing of plastic parts. The best aspect about this method is that it requires a CAD model and time measured in hours for the machine to print a finished part. What may be of concern is that the mechanical properties of the material, therefore limiting the variety of designs that could be tested. The surface of these parts is almost certainly in need of sanding and painting to obtain the same surface properties as the real painted panel of the car.

Conclusion and solution

As the time in a wind tunnel is limited the quality of fast readjustments is crucial. Therefore the SLS-machining is most suitable in this aspect. Also desired by the CFS-team is a mock up model engine to make the simulation more realistic, which will be manufactured easily using SLS-printing. However wing supports or struts, that will carry loads on the model, might have to be made by other methods because of the lack of load bearing strength of the sintered plastic. Aluminium tubes will be sufficient to this purpose.

If some part is more favourable to manufacture using an alternative process, they will be compatible if the surface finishes are alike.

3.3 Solution model

The pre study phase started with a functional model and resulted in a solutions model through benchmarking and research.

Description solutions model

The solutions model resembles the functional model, but its functional elements are also filled with a stated solution for the function.

A difference from the functional model is the wheel sting box. This solution was added to the system as the result of the benchmarking was not anticipated. In addition, rather than using an existing solution the wheels needed to be designed as the existing wheels did not fit the scale of the vehicle. This was not anticipated to be within the scope of the project.

The result of the pre study is that the wind tunnel model will consist of a CNC-machined aluminium frame with SLS-printed plastic body features bolted to it. It will have wheels made out of aluminium that are attached to the wind tunnel by separate stings, mounted beside the moving ground system. There will be a balance that measures forces on the model and pitot tubes to measure pressure at desired locations.

The solution model is shown in Figure 3.7.

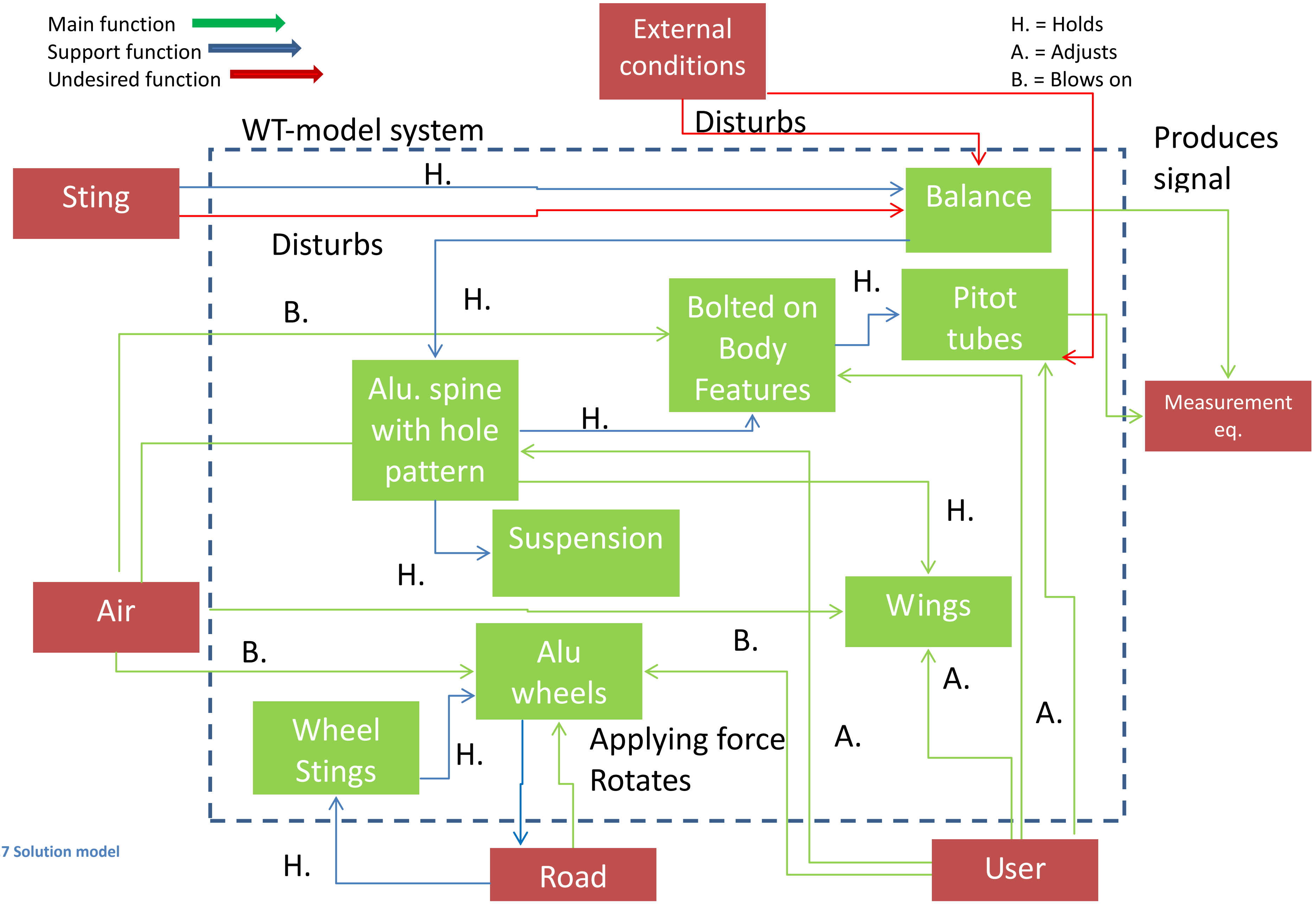

Figure 3.7 Solution model

Each member of the group was assigned with an area of responsibility. This was not an assignment to do all the work associated to the subsystem but to have an overview. All areas of responsible and who is assigned to that subsystem as well as the priority can be seen below.

Subsystem	Responsible	Priority
Aluminium spine with hole pattern	Lars Wallin	Needed
Suspension	Lars Wallin	Optional
Bolted on body features	Mathias Bergfjord	Needed
Wings	Mathias Bergfjord	Needed
Aluminium wheels	Rickard Lindstrand	Needed
Wheel stings	Rickard Lindstrand	Needed
Balance	Adam Jareteg	Needed
Pitot tubes	Adam Jareteg	Optional

4 Design phase

During the design phase each subsystem from the solution model was to be completely designed. The work consisted of deciding how every part should look and how they would be assembled together to form the subsystem. In this work the solution model was very helpful to see how different subsystems should interact with each other. In the following chapter all parts will be presented with the chosen design, justification for and how the chosen design has developed throughout the design phase. The contents of this chapter vary between the different subgroups which is due to the fact that it was only the frame and the wheels with wheel stings that were completely designed. The body feature was already designed by the CFS12 team and instead needed to be adapted and scaled down for the model, and the sensors had to be decided how to use them in a most efficient way and make them as adjustable as possible. All drawings can be seen in appendix B.

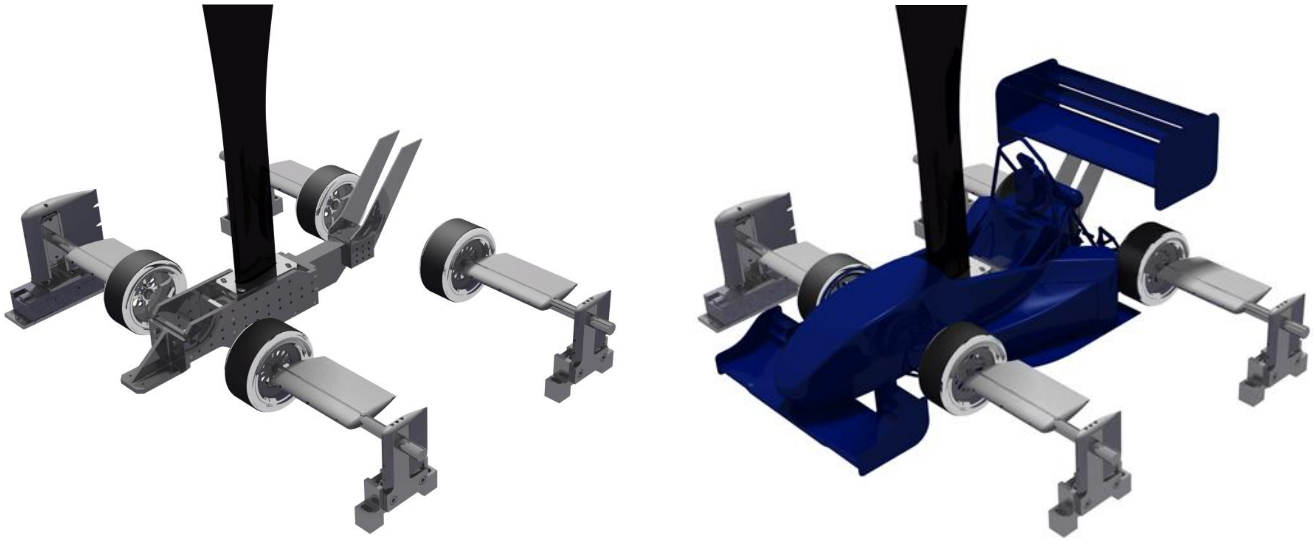

Figure 4.1 Complete model with and without the body mounted

4.1 Frame

4.1.1 Design selection

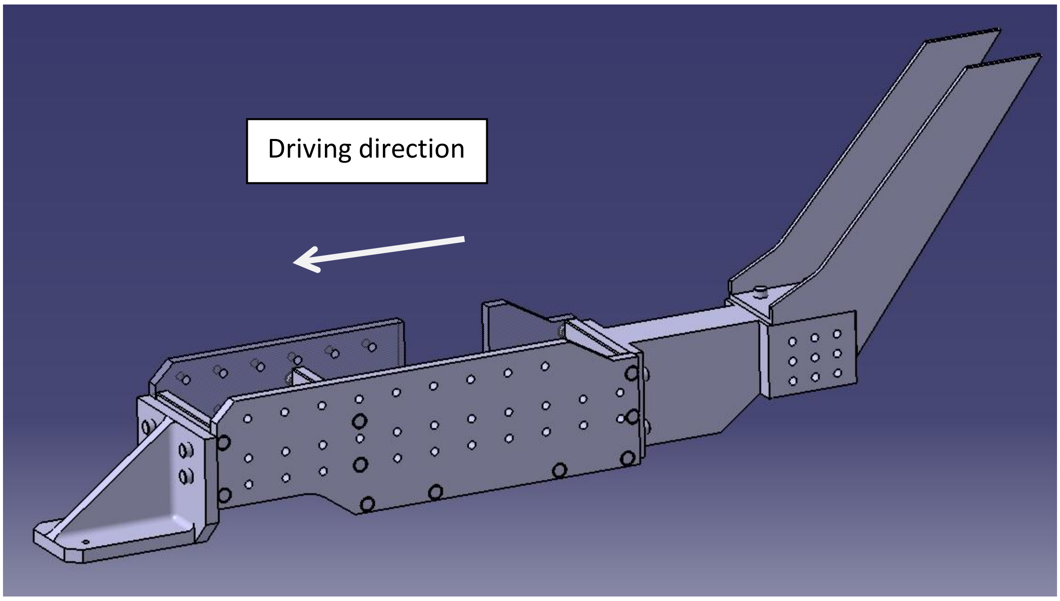

Figure 4.2 Complete frame design

From the pre-study it was decided that the frame would be made from machined aluminium. This is due to ease of manufacturing and mounting body features to the frame. When designing the frame the first and foremost design challenge to address was the space it could take so as not to restrict future vehicle designs. This space was given by the FSAE rules [8] as these state a minimum size for the vehicle. That size was set as the maximum size that the frame was allowed to be. The minimum size of the frame was given by the dimensions of the balance which was in the pre study phase decided to be the existing balance at the institution. The balance also made certain requirements on the stiffness of the frame where it was mounted. To obtain accurate results and to not risk damaging the equipment it was necessary to have a strong mounting for the balance to ensure it has small deflections [10]. Since it was decided to have threaded holes in the frame to mount the body features, it was discussed how durable the threads in aluminium would be. The body features will be changed each year and the mounting points will therefore be exposed to wear and fatigue. The main advantage of having the frame in aluminium is that it is lightweight but the disadvantage is that the threads may be weak. Therefore it was decided to prioritize a frame that would withstand the wear and fatigue. To achieve this, the main frame was to be designed in steel, which is heavier than aluminium but alternatively the threads are stronger and will last longer.

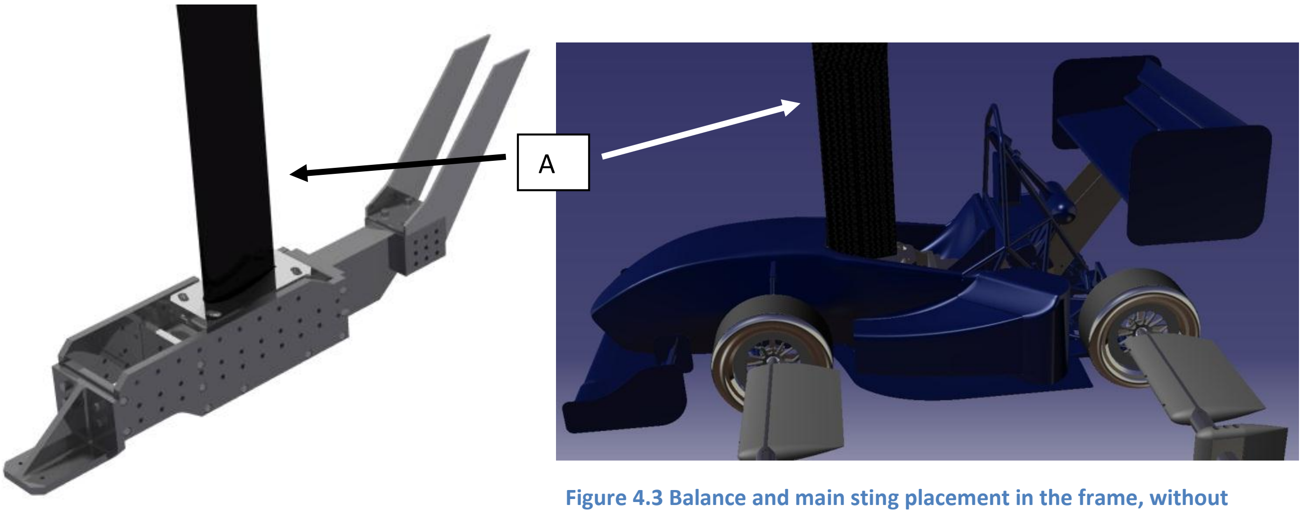

Figure 4.3 Balance and main sting placement in the frame, without and with body panels

The balance placement

The placement of the balance relative the body features was the deciding parameter to where the frame would be located in the model. The balance is attached to the main sting (Part A in Figure 4.3) which will have an impact on the flow around the car and the placement of this sting was made to minimize this impact. The limitations of the placement of the sting were mainly three different criterions. The first was the tunnel design that limits the sting to only be mountable from above the model and not from the back of the model. The second limitation was that the balance cannot withstand more than 120 Nm of torque around the Y-axel and with this figure including the down force in the actual test which means that the initial torque can be 30Nm. The most preferable was to place the balance in the centre of gravity of the model to obtain as low an initial torque on the balance as possible. The third criterion was the goal not to alter the design of the car. These limitations combined resulted in the sting being placed in the cockpit of the car. The main sting has the shape of a symmetric NACA airfoil to minimize the drag and the distortion of the flow around the sting. The main feature in that region that distorts the flow is the roll bar and the drivers head and to minimize the disturbances to the flow the sting was placed as far to the front of the cockpit area. The placing of the sting was chosen so that the disturbances created by the drivers head and the main roll bar would be as realistic as possible. It was known that the main sting was causing effects on the flow wherever it was placed since it do not exists at the real car. The goal was to design the frame and the model so it had as little a negative impact on the results as possible.

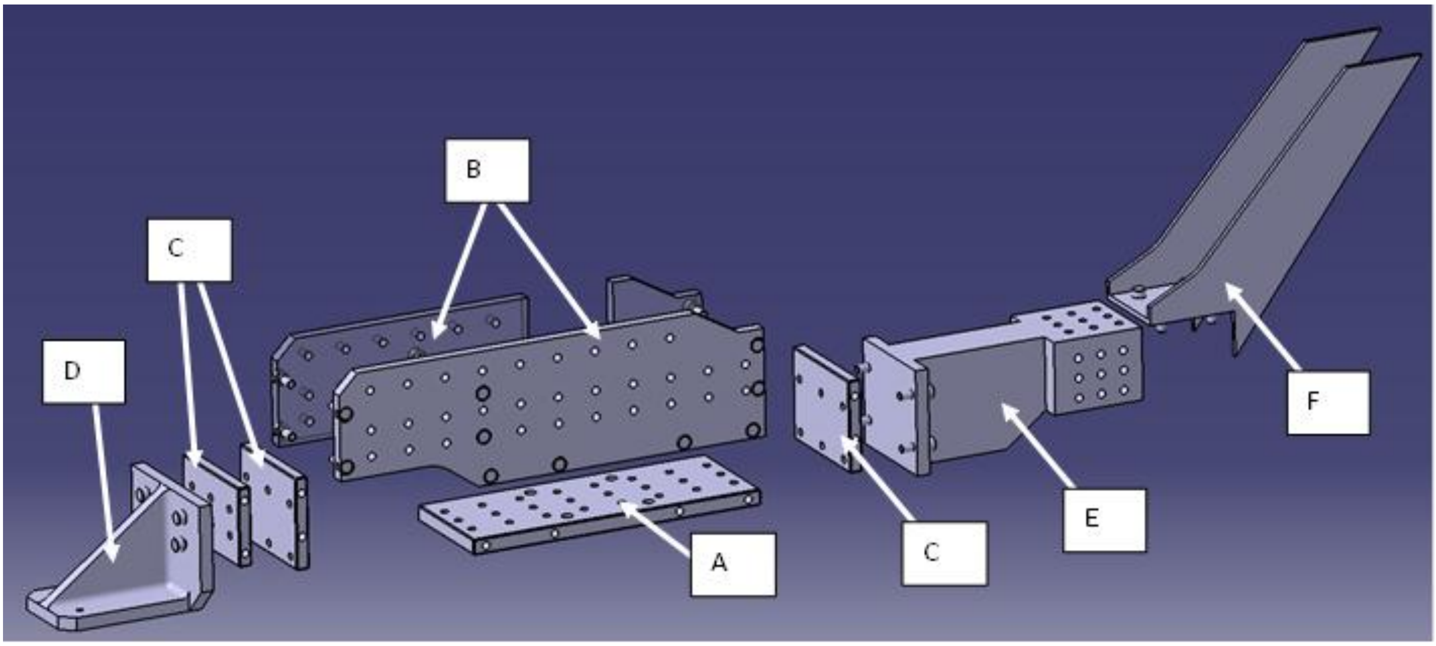

Figure 4.4 Complete frame in an exploded view

Main frame structure

The most important property of the model was adjustability so that the model can be used for multiple years without the need to change the main frame every year. The main frame consist of a bottom plate (A in Figure 4.4), two side plates (B in Figure 4.4) and spacer plates (C in Figure 4.4). The frame had to be rigid since all the aerodynamic forces had to be transferred from the body features through the frame into the balance to obtain the measurements. The balance had mounting points underneath and was attached to the frame with screws.

The frame was designed out of steel plates that were screwed together to form a box around the balance. The bottom consists of one plate to which the balance attaches. To this there is one plate on each side. Between the side plates there are three short spacer plates to form the rigid box. On all plates there are threaded holes in a pattern to mount the body features to.

The height of the side plates (B in Figure 4.4) were designed to be as small as possible to fit future designs of the front of the car that might vary from the one used in 2012 which can be favourable to obtain better aerodynamics of the car. The height of the plate is also a compromise between making it as small as possible to allow bigger changes of the front design and obtaining enough frame-surface to support body features. The biggest force that the frame will be exposed to during a test is the down force caused by the aerodynamic package on the car. Since the wind tunnel model is suspended in the middle of the frame by the main sting, the frame wants to deflect downwards in the front and in the rear. To prevent this deflection the side plates are positioned in a way so that the surface moment of inertia is as high as possible, hence the width of the plates. At the right side plate in the driving direction there is a cut out to fit the adapter between the balance and the main sting. This adapter, which comes with the sting, has a passage to route the pitot tubes from the frame and the body features into the main sting. It was known that this cut out would give stress concentrations but it was necessary for it to be there. To minimize the stress concentrations the corner was given a larger radius. The frame ends rather suddenly after the balance as there are no limitations in the FSAE rules [8] that limit the size of that area.

Frame extensions

As the main frame dimensions are inside the minimum dimensions stated in the rules of FSAE the frame required extensions that could easily be changed to fit the design of future cars [8]. In the front the main frame reaches longer into the nose of the car than it does in the rear. Therefore the extension in the front (D in Figure 4.4) had to be smaller than the one in the rear (E in Figure 4.4). The main function of the front extension is to hold the front wing in place and transfer the force from the wing into the main frame. The design for the front extension was chosen to be as light as possible to not increase the initial torque on the balance. Since this part may be changed every year the design also had to be simple and easy to manufacture. The part consists of a 90 degree angled plate of aluminium with a welded reinforcing plate in the middle. The FEA showed that due to the high forces from the wing reinforcements were needed otherwise the deflection of the extension would be 10 times larger than 0.03 mm whit the reinforcement. The wing will be held in place with two screws at the front of the extension and the whole part is screwed to the main frame in the front.

At the rear of the main frame the rear extension (E in Figure 4.4) is attached with screws to the fame. Forces from the rear wing and the diffusor (209,6 N) are much larger than the forces from the front wing (148 N) and for that reason the rear extension had to more rigid than the one in the front (Appendix F). It could also be of interest to mount more body features to the rear extension which requires more surface area to support the body features on the model. Similar to the front extension, the rear extension had to be as light as possible to not add extra torque on the balance and also be easy to manufacture. Under the rear extension the diffuser is mounted so the shape of the part had to be designed so it did not obstruct the diffusor outlet, which is located higher than the rest of the floor. The part itself is manufactured from aluminium, milled to the correct size and has threaded holes to mount the body features to the extension.

On the actual CFS12 car the rear wing is mounted to the back of the frame using six carbon fibre tubes with a diameter of 20 mm. If the same mounting method would be used in the wind tunnel model the tubes had to be scaled down to a third of the real size. The tubes then became so small and it would be hard to get the wing to be stable during tests as these tubes had to transfer large (186 N) loads into the frame (Appendix F). Therefore it was decided to add an additional support (F in Figure 4.4) for the wing. This support will transfer all the forces from the wing and provide it stability. Since this support does not exists on the real car the placing and the shape of it had to be carefully selected to not create large disturbances the flow around the rear of the car and the rear wing. The shape that was chosen was two narrow plates reaching from the rear frame extension up to the rear wing with the narrow sides of the plates facing in the driving direction of the car (F in Figure 4.4) For the placing of the support is was of significant interest to locate an area at the rear of the car that already had turbulent flow caused by the shape of the car and the driver. The CFS12 team had undertaken CFD-analysis of the car and that showed that the area behind the driver and the main roll bar had a high rate of turbulent flow which made it a suitable place to put the support in. The material of the support was chosen by completing FEA to simulate the load case that the support would experience during a test. It was shown that the support had to be made out of steel due to the higher Young’s module to minimize the deflection of the part.

4.1.2 Discussion of design selection

At first it was investigated if the main frame could be made out of a standard square profile that could be purchased as a standard part to minimize the work that had to be completed on each piece. But it was not feasible to find a suitable profile with the correct dimensions that were required for the frame. Instead steel plates were machined to the correct dimensions and bolted together. An advantage of the chosen solution was that if in case that the sides of the frame have to be changed in shape and size, there is a limited amount of components (two maximum) parts that need to be remanufactured and the plate underneath the balance can be kept as it is.

4.1.3 Simulations

Due to the complex shapes of the frame and that it contains multiple components, all calculations were completed in ANSYS with Finite Element Method (FEM). The frame geometry was imported from Catia into ANSYS where the boundary conditions such as forces and supports were applied. The frame was set to have fixed supports in the holes that the balance should be attached to the frame and all the other surfaces were free to move. The load case that was used was the simulated loads from the CFD-analysis that the CFS12 team had made on the car. That load case includes down force from the front wing, rear wing and the diffusor and were applied on the geometry as if all body features where mounted on the frame as it should be during a test in the wind tunnel. It was chosen to use the downforce as the load case because this was a factor of three larger (Appendix F) than the drag force and it was hard to state exactly where the drag force acts on the frame. To compensate for using the downforce on its own, a safety factor of two was applied to all forces that were applied. The real load case during a test in the wind tunnel will never be as high as the simulated load case because that will exceed the limit of the balance.

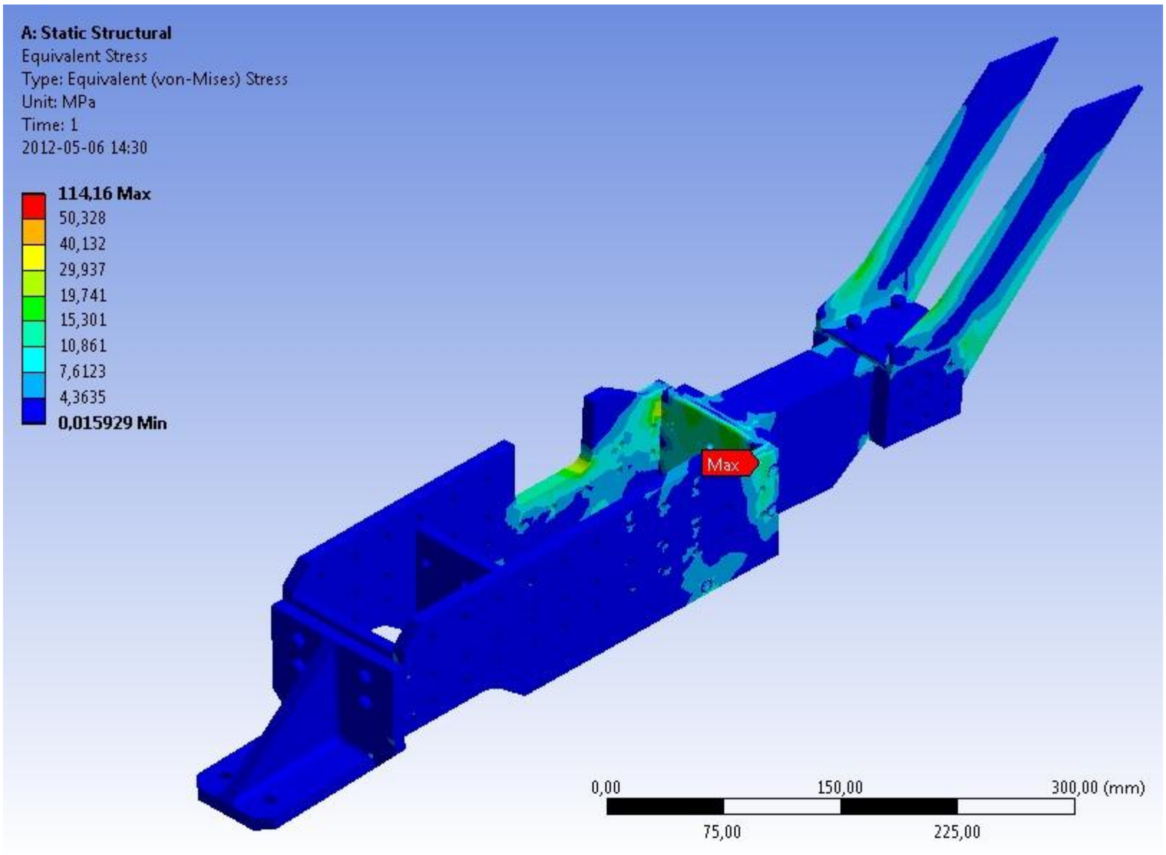

Figure 4.5 FEA on the frame with von-Mises stresses shown

The result from the FEA shows that the maximum stress level in the frame was 114 MPa , which is below the yield strength of both ordinary tool steel (SS1650) and aluminium (6082T6) , 310MPa [5]and 250MPa respectively [11]. That result was not unexpected when the material thickness is large compared to the forces acting on the model. Instead the deflections of the frame were more interesting to analyse since all deflections will alter the angles of the wings and aerodynamic features of the body. As expected the largest deflection was in the rear of the frame, on the extension and the wing support. This was due to the large forces that the rear wing produces and for that reason it was the most critical area that had to be designed to handle these forces. The largest deflection was 0.3 mm at the top of the rear wing support and it was acceptable. This deflection was the reason that the wing support had to be made in steel instead of aluminium which gave twice the deflection.

4.2 Wheels

Background

The wheels of a real car will rotate as the car is driving, therefore they should do this in the wind tunnel model as well. The main difference from the real car is that the wheels of the model will be rotated by the belt, the moving ground system, instead of a driveshaft. The rotating wheels on a wind tunnel model serve the main purpose of simulating the flow of air caused by the real car at speed. As there are synergy effects between the body and the wheels when they are in motion this is an issue that cannot be properly studied on one piece of the car, at a time [3].

To make this possible the wheels had to be held in place at their given location in relation to the car. To make the wheels stay in the given position to the car a set of wheel stings had to be designed, with the purpose to make them fit alternative wheel diameters, wheelbases and track widths. A wheel sting is a device that locates the wheel in the direction of the moving ground, without causing disturbance in the air flow. The sting should also be able to maintain the wheels position during the whole test session. A wheel sting that disturbs the air flow will affect the readouts of the measuring equipment as all bodies inside the wind tunnel will interact.

The wheels themselves had to be able to represent the flow of a real rim. As concluded in [3], a change of rim pattern has greater effect of the flow around the wheel when it is rotating, than when it is static. On top of this, the orientation of the rim pattern will affect the result noticeably in the static case. As concluded in [4] 40% of the drag of an open wheeled car comes only from the wheels, this area of wind tunnel testing is very important. In short the rim pattern had to be made alterable to represent different designs not to neglect these potential differences.

The overall goal of the design phase was to make all the components of the wind tunnel model to be adjustable and yet withstand the targeted loads. This section will therefore discuss that.

4.2.1 Design choices

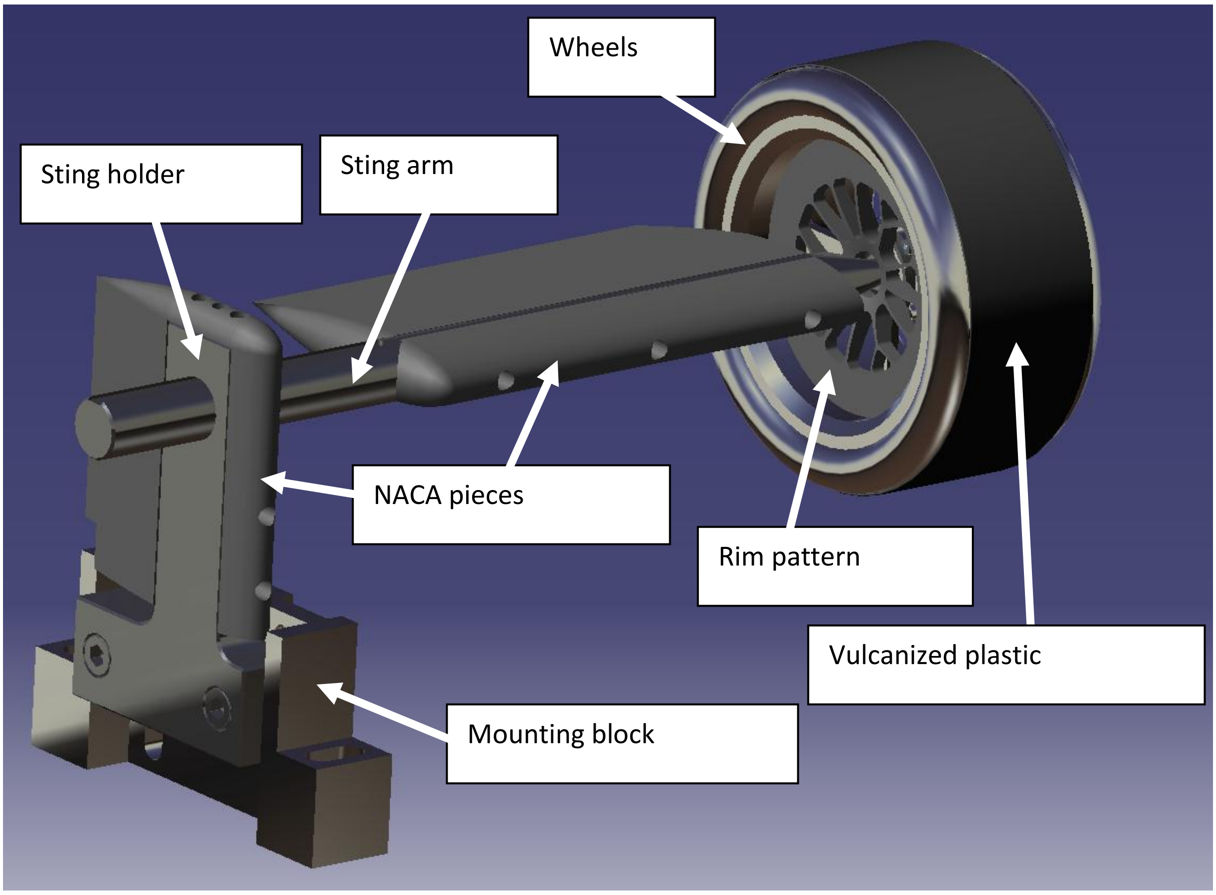

Figure 4.6 Complete wheel assembly

Wheel dimensions

The outer dimensions of the wheel are representing the tyre and these dimensions, outer diameter and width, were crucial for the accuracy of the force measurements on the wheel because they define the projected area towards the air flow. The choice of dimensions was based on an average of the Hoosier FSAE tire range, spanning the tires fitting the 10 to 13 inches rims [12]. These are the tyre diameter range that the CFS-team will choose from and should there be a change in the outer diameter of the tyre, a new scaled wheel has to be manufactured. Therefore the average diameter was used.

Wheel spoke pattern

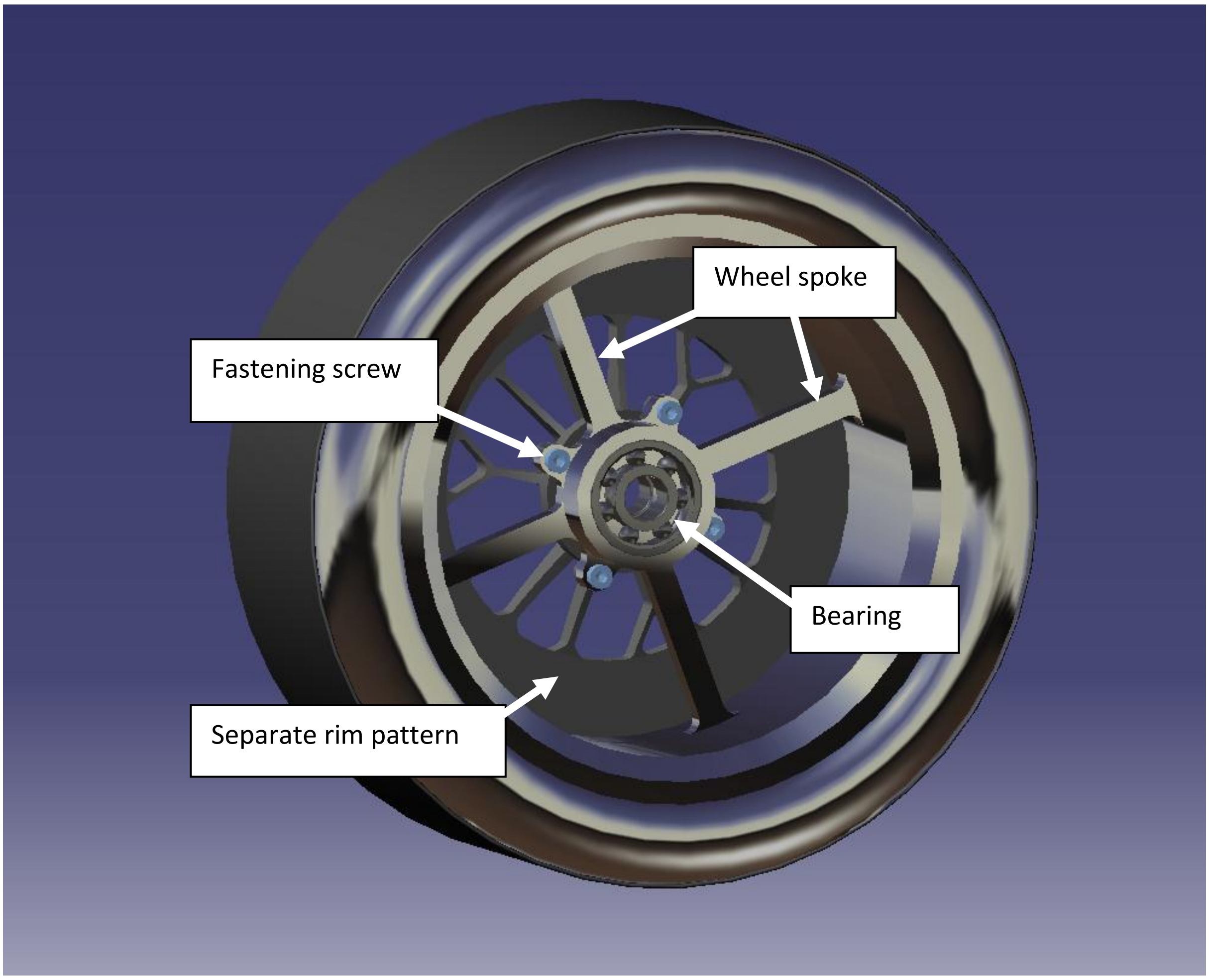

Figure 4.7 Wheel design close-up

The spoke pattern of the wheels was an issue that lead to the design going through multiple revisions. The first thoughts were to design an arbitrary rim pattern that was to be milled out of the solid aluminium rim. This however made it impossible to change the design, but it would still let air flow pass through. As concluded in [3] the rim pattern has great importance in this matter, which is why this first idea was rejected. The design effort was then focused on making the rim of the aluminium wheel a blank canvas to mount separate rim patterns to. This resulted in a thin four spoke rim pattern that would disturb the flow minimally. The position of the spokes on the rim is not centred to enable the separate rim pattern to be mounted in the middle of the rim, if that would be desired in the future. The rim is otherwise symmetrical so it could be mounted on the sting arm in both directions. The mounts for the separate rim pattern are four small screw holes on the hub of the wheel, the threads will be in the material of the separate rim pattern itself.

The separate spoke pattern will be designed by the user of the wind tunnel model. The offset of the rim pattern will be defined by the design of the scaled rim pattern part. A preferable way to manufacture the rim pattern is SLS, because it will only carry the load caused by the air flow through it. The time it takes to SLS-print is also relatively small.

Sting arm

The sting arm is the horizontal part that the wheel mounts on to. The sting arm also defines the length from the side of the moving ground system to the location of the wheel. In reality this will represent the track width of the car. The track width measurement has to be adjustable as the FSAE rule does not state a maximum width. [8] This is achieved by letting the sting arm slide back and forth through its mounting devise. To fix the sting arm in the specified position, a locking screw is used. The design of the profile of the sting arm went through a number of revisions, after realizing that the desired NACA-profile was too costly to manufacture. The profile was then decided to be round, a shape that can easily be manufactured. The sting arm is 420 mm long and has a 25 mm diameter profile (used in the calculations in 4.2.1). The length of the sting arm enables the span of the scaled car to span from 420 to 600 mm of track width, in full scale this represents 1260 to 1800 mm. However the round profile is notorious for creating a von Karman vortex-street when it is exposed to a laminar flow of fluid [9]. To deal with this phenomenon the desired NACA-profile will be manufactured as two pieces, using SLS plastic, and then fastened on to the front and back side of the sting arm. Consequently the round steel bar will carry the loads caused by the wheel and the plastic profile will smooth out the vortex-street and therefore minimize the impact the stings have on the flow round the body of the car. As the NACA-profile parts stick on to the round bar the locking screw also need to line up with a grove to make sure that the orientation is correct.

Sting holder

The fastening device for the sting arm is called the sting holder. This part was designed in the same way as the sting arm, it contains a steel core with NACA-profiles at the front and rear. This design is motivated by the same arguments as for the sting arm. To enable future changes of wheels or wheel contact surface that will alter the outer diameter, this sting holder needed to be adjustable in the vertical direction. This is achieved by mounting the sting holder on to the existing mounting blocks, which allow a certain difference in vertical mounting position. The vertical span of 140 to 190 mm of wheel diameter was considered to be enough. The mounting blocks are then mounted on to the rail at the side of the moving ground system. To be able to measure the lift and drag caused by the wheel itself, the existing balance will be used. For this application the balance will be mounted to a special sting holder. The balance sting holder has to be bigger than the standard ones to still support the vertical span and maintain the rigidity of the standard ones. This is because there is a lack of space between the side of the moving ground system and the side wall of the wind tunnel. In other words, the mounting blocks cannot be used. There will be one balance sting mount manufactured that will then be moved to the front or rear wheel pair. The balance sting holder is symmetrical enough to be used at both sides of the model but testing at one side will be enough as the car is symmetrical along its centre.

Forces acting on the wheels

There are several forces acting on the wheel when it is situated in the wind tunnel, first of which is the drag of the wheel. The numerical value for this force was taken from the data sheet supplied by the CFS12, containing results from CFD-runs on a single wheel. The highest of these values was chosen, 24 N. The second force acting in the same direction as the moving ground system is the friction inside the bearings. When using the SKF online catalogue a friction torque is calculated, this had to be converted into a force by dividing it by the radius of the wheel. The drag force caused by the friction was 8.8 N.

There are forces acting vertically on the sting arm as well. The CFD analysis shows that the wheel generates lift when it is rolling on the ground. The lift force was also taken from the datasheet, 15.6 N. In the same direction as the lift is the pretention against the moving ground acting on the sting arm. This force is necessary to stop the wheel from slipping and making the rotation speed improper to the moving ground. This value was estimated to be small, because of the vulcanized plastic was added to increase the friction and therefore reducing the pretention needed. The pretention was set to 15 N.

As these two sets of forces are acting perpendicular to each other the resultant is calculated using Pythagoras theorem, then a scaling factor of 2 is multiplied to make sure that these forces are high enough. The force F in the calculations is 89 N.

An axial pretention on the bearings is also present to fix them properly at the sting arm. This is set to 10 N.

Input data			
Forces			
fa	Axial pretention on the bearing, estimated	10	N
frlift	Lift caused by the wheel, from CFD made by CFS12	15.6	N
frfs	Pretention towards the moving ground system, estimated	15	N
frz	Sum of forces in z-direction	30.6	N
frdrag	Drag caused by the wheel, from CFD made by CFS12	24	N
frfriction	Force caused by friction in bearing, from SKF engineer.cat.	8.8	N
frx	Sum of forces in x-direction	32.8	N
fr	Resultant of the radial forces, Pythagoras theorem, a safety factor of 2 is multiplied	89.7	N

Table 4.1 Forces acting on the wheel

Measuring the forces on the wheels

Due to the limitations of only having one balance to measure all of the desired forces, the one at disposal has to be used for different measurements at different mounting positions. As stated in Table 4.1, the approximated values for the calculations are based on CFD analyses, which is why it is desired to verify these values by testing. Therefore a targeted function of the wind tunnel model is to measure the actual drag and lift forces of the wheels.

It was therefore relevant for the wheel sting design to produce a device that would fit beside the moving ground system that holds the balance in place for measuring the forces caused only by the wheel. This device would still have to make sure that the track width and wheel diameter was adjustable.

As there is only one balance available it would only be necessary to manufacture one of these balance holding sting mounts. During testing it has to be switched from the front to the rear wheel position and measurements on the wheels made separately one at a time. A balance mockup has to be manufactured to take its place in the main frame of the model when the balance is mounted at the sting, and vice versa.

4.2.2 Mechanical calculations

Loading the wheel sting

The majority of the force acting on the wheel sting is caused by the wheels, which is mounted at the end of the sting arm. This makes the maximum shifting of the wheel position similar to an elementary case of a point loaded beam with round cross section. The sting holder is considered to be fixed. Then the deflection of the beam can be analytically calculated using the following equations according to [5], table 31.1 & 32.3:

$$I = \frac{\pi d^4}{4 * 2^4}$$

$$d = \frac{FL^3}{3EI}$$

The deflection then will be 0.206mm if the track width of the model car is 400mm.

Reflections on the calculation

Due to the design of the sting arm these calculations is not completely accurate. There are small holes in the sting arm and a groove at the top of it, therefore the whole assembly was evaluated using an ANSYS FE analysis. The results from this simulation run showed that the maximum deflection was 0.430mm. This is still an acceptable value and why no further changes were made to the sting arm. This also showed that the sting holder was in fact fixed and did not deflect.

This calculation and the FE-analysis were done using steel as the construction material. In addition to sufficient mechanical properties for this calculation, steel is also a good choice because of its wear resistance on threads and grooves. Which is important as the wind tunnel model will be used for many years.

Life time of the bearings

The selection of the bearings to be used was limited to SKF's range as they are partners of the CFS team, who would provide the bearings for this project.

One type of bearing that was suitable for the dimensions of the wheel was the 6000*. To be sure that this bearing would withstand the dimensioning load (calculated above) for a representative time a life time calculation was required. The goal for the bearing life was 365 days of 8h of testing in the wind tunnel.

Input data			
Wind tunnel			
v	Speed of the moving ground	50	m/s
d_h	Diameter of wheel	0.165	m
n	Rotating speed, $60v/(\pi d_h)$	5788	rpm
Bearings: SKF 6000*			
c	Load rating	4.75	kN
C_0	Basic dynamic load rating	1.96	kN
p_u	Fatigue load limit	0.083	kN
F_0	Factor for calculating buoyancy	12	-
η_c	Cleanness of the oil factor	0.7	-
a_{skf}	SKF life modification factor	0.3	-
a_1	Reliability adjustment factor	1	-

Table 4.2 Bearing life time calculation data

The formula used to calculate the life time of the bearings was the following, according to [6], where p is the force F, calculated above, in kN. L_{nm8h} is the life time expressed in a number of days of 8 hours of constant running in the wind tunnel.

(To calculate the a_{skf} and the a_1 needed for the formula, several calculations have to be done according to the calculation procedure in [6]. The complete calculation is displayed in appendix E.

$$L_{nm8h} = \frac{a_1 a_{SKF} \left({}^{C}/_{p}\right)^3 10^6}{60n} * \frac{1}{8}$$

The result is 16’000 days.

Frictional torque in the bearing

The loss in power caused by the friction in the bearing itself is used in both of these previous calculations, and approximated above to be 8.8 N per wheel as each wheel have two bearings. The fact that the two bearings also split the load of one wheel is also taken into account in this calculation. The input data to calculate this number is depending on the output data which means this is an approximation. The calculation itself is undertaken using SKF’s “Engineering Catalogue” at their homepage, as recommended in [6].

The calculated life of the bearings is much longer than what was targeted. However this life time could be shortened if the working temperature in the ball bearing increases unexpectedly. If for example the pretention of the wheel toward the moving ground has to be increased, this could be the case.

4.2.3 Results of the wheel design phase

The result of the design phase was a design that met the mechanical requirements and could span the targeted change of dimensions. The disturbance of the air flow could have been decreased, which of course would have been desirable, but the project budget was a limiting factor. Where the biggest gains could have been made, concerning low disturbance, are probably in the sting arms. Even with the NACA-profile add-ons there will still be some sections of the round bar that is exposed to the air flow. The balance sting could be smaller if another balance that was smaller than the existing one could be used. This would also most likely decrease disturbance as the projected frontal area of the balance sting is three times larger than the original sting.

4.3 Sensors

During the pre-study phase it was decided that the measuring equipment which were to be used would be a balance (Figure 4.8) from Chalmers and pitot tubes. When implementing these sensors in the model it was mostly a matter of making sure there was space allocated for the equipment. The balance was used as a minimum size for the frame and a starting block for designing the frame (See chapter 4.1). Since pressure measuring will be different between the different years the location will change as well. The idea for the 2012 years edition of the model was to measure pressure difference in the diffusers and the cooler. The reason of measuring in the diffusers was mostly to compare the measurements to the results from the CFDs and try to validate the calculation. The tubes are drawn from the transducer lying in the model under the frame, laying on the undertray, backwards to the diffusers. There they are attached to the diffusers. The transducer is connected to a computer via cables in the sting. To obtain as accurate results as possible it is desirable that the tubes are of the same length. Most of the design work in the sensors subgroup was made designing a model cooler to replicate the race cars cooler. This was earlier decided to be one of the more interesting things to measure when measuring pressure.

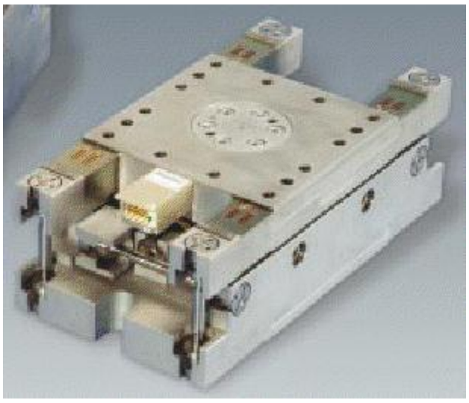

Figure 4.8 Balance

The balance

As stated Chalmers has a balance, a Ruag Waage 196-6H, they use in the wind tunnel lab and this is the one also used in this project. It is 200x80x50 mm and has a weight of around 3.8 kg. The loading limitations of the balance have been a restricting factor when designing the model mostly because the two largest forces, the weight of the model and the downforce generated, loads the balance in the same direction. The maximum load limits of the balance can be seen in table 2 and the corresponding coordinate system in appendix D.

	X	Y	Z
Max Force [N]	350	250	1200
Max Torque [Nm]	100	120	130

Table 4.3 Load limits on the balance

The cooler mock-up

The coolers task in the model car is to generate a flow resistance similar to that of the real cooler in the race car. This enables the measuring of a pressure drop to make sure that the cooler obtains the correct amount of air. The cooler consists of a frame that holds metal meshes that acts as the flow resistance. Depending on the properties of the racing cars cooler different amounts and sizes of meshes will have to be used. This has to be adjusted for each cooler and tested to verify the correct behaviour. Testing can be done in the wind tunnel or some smaller test rig, the goal is to make sure that the cooler at a certain wind speed provides a pressure drop corresponding to that of the racing cars cooler. When then mounted in the model car, measuring the pressure drop over the cooler will give the air flow through it which then can be compared to desired values. The 2012 year's cooler can be seen in figure 4.9 and was made out of two pieces. The metal meshes are placed between these pieces and squeezed together to stay in place. In between the frame pieces is also an aluminium honey comb that supports the metal mesh and straightens the flow. The frame is screwed together with four screws and the whole package is screwed to the side pod.

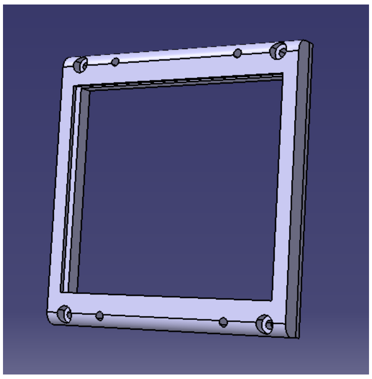
Figure 4.9 CAD model of the cooler

When making the model cooler the real cooler was used as a starting point. Since the side pod on the model will have an outer appearance similar to the race car the cooler can also look something like the reality. The side pods interior does not have to look like the race cars pods. This meant that it was possible to add some material to the side pod to support screwing the cooler directly to the pod. When designing the cooler it was considered to make a model that could be altered in the airs angle of attack against the cooler. This was ruled out because it was not possible to motivate the increased complexity with the desired function. The 2012 team already designed their cooler and did not have an interest the angle of attack. Since the cooler is a feature that changes a lot through the years it was not justifiable to make a more complex and general model than this.

The cooler is assumed to generate a pressure drop similar to that of the race cars cooler even when tested in other wind speeds than that it was calibrated after [1]. This is assumed to be legitimate in wind speeds around the calibration speed and the assumption makes it possible to predict the behaviour of the race cars cooler when measuring on the model cooler.

4.4 Body features

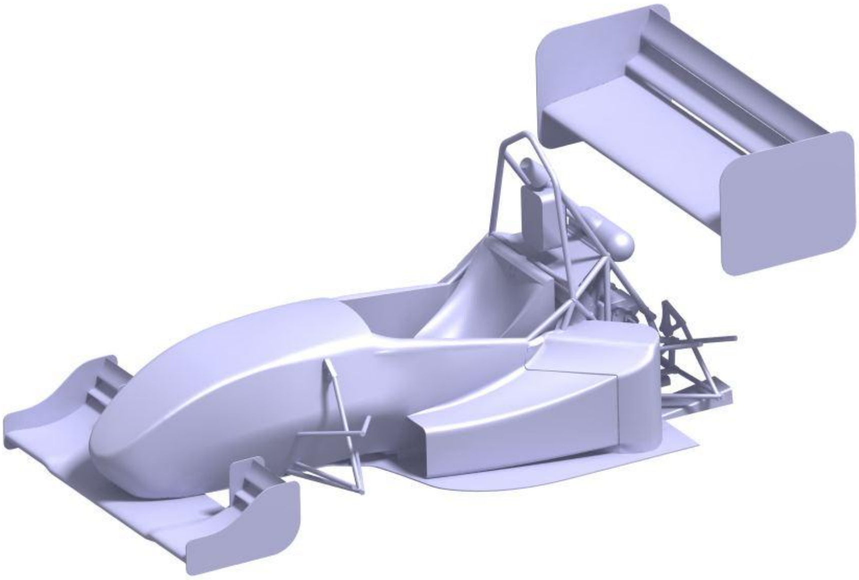

Figure 4.10 Entire body package

4.4.1 Design selection

To gain the most adjustability without losing stiffness and strength and keep down the weight of the body, it was decided to divide it into sections that could be changed individually without being forced to change the whole body. In this way the testing will be simplified with the ability to test many different concepts of body parts in areas of the body that are the most interesting to study. This will also be a benefit in the budget due to the lower manufacturing cost when changing single parts. The most critical design choice is the decision of having rear and front wings. These will be placed on the outermost parts of the frame and will give large forces relatively to the remaining body. This requires a stiff and strong material that will be able to withstand the stresses and support the body parts. The most efficient compromise that could be used for the construction of the body is a combination of complex and supportive parts made by SLS and thin and simple parts made of aluminium. With these processes an acceptable complexity, surface texture and strength [13] will be met and the model will be a good resemblance of the car and give correct results in the wind tunnel. To be able to visualize the wind flow around the car smoke is pumped inside a long tube and held in front of the car. The plastic that is used in SLS is white in colour and will cause the smoke to blend in and become hard to see, therefore will the body be painted matte black to be able to show the light grey smoke clearly.

These different sections will be mounted on the frame with bolts and the holes for the bolts will be covered with thin tape. The large amount of fixation points will add to the adjustability factor and give a greater degree of freedom in placement of future body parts. Dimensions and priority for SLS of the sections is estimated and can be seen below.

Split along x-axis	PARTS	Δx	Δy	Δz	Priority	Comments
X	Front wing main	160	460	50	High	The small wings can be made at Chalmers
	Nose cone	375	210	200	Small	
	Middle section 1 (2x)	200	230	185	Medium	
	Middle section 2 (2x)	190	230	160	Medium	
X	Engine	220	355	350	High	Can be reduced a lot if small beams is made out of steel tubes
X	Rear wing main	130	460	35	High	Manu. in two parts so that a mounting can be placed within
X	Rear wing small (2x)	40	460	15	High	
	Seat and driver	200	160	300	High	
	Diffuser	300	300	25	Medium	

Table 4.4 Approximate dimensions for SLS manufacturing of body features

Wings

Both the front wing and rear wing are divided into *main* and *secondary* wings due to these will be made with SLS separately and then connected with aluminium side plates to gain the needed stiffness when exposed to air with high velocity. The rear wing will be manufactured in two parts divided along its span and a metal plate will be placed within the two parts. This metal base will be the bracket for the rear wing support that is mounted on the frame. To be able to mount the aluminium side plates to the wings, cavities for brackets will be designed in the sides. These will then hold the bolts that are attached to the side plates and stabilize the wing structure.

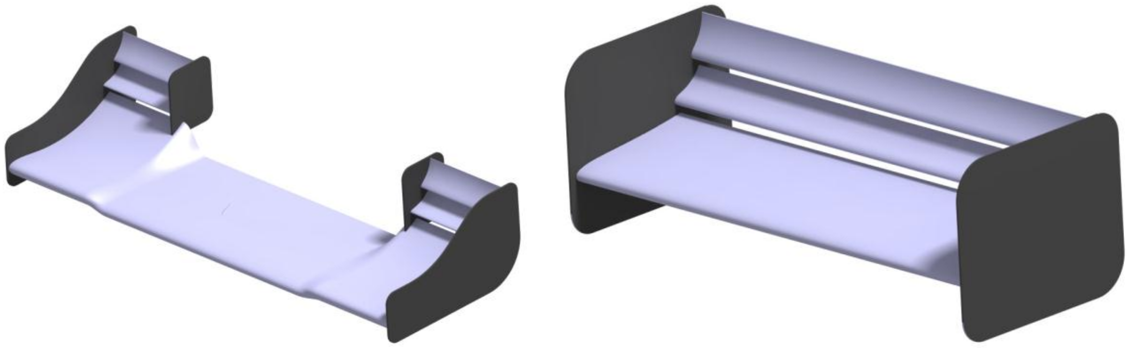

Figure 4.11 Front and rear wing sections

Main body

The most efficient way of partitioning the main body is into three sections due to dimension restrictions of the SLS machine. The boundaries for the first section will be at the end of the nose cone and will include the foremost part of the diffuser. The second and third segment will be from the end of the nose cone back to the side pods and divided symmetrically along their mirror axis. These body panels will have a thickness that is based on the material properties of the SLS plastic and the limitations of the SLS printer. In the part that has the side pods there will be mounting points for the cooler test rig so that the mass flow can be calculated properly. To be able to attach the panels to the frame, spacers will be constructed on the body part itself or be made out of metal where bolts are put through and secured in the frame. In seams that are not glued, tape is used to minimize the aerodynamic disturbances and the same is done with bolt holes. If the main body is uncomplicated a CNC machine can be used to mill out the body from a block of plastic.

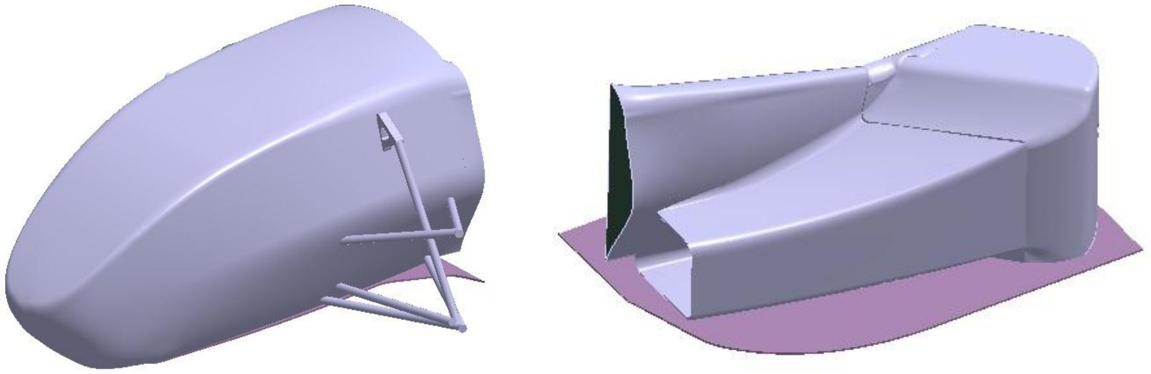

Figure 4.12 Main body sections

Seat and Driver

Only a part of the seat and driver will be made due to the balance and sting position in the driver cabin and because of the complex form these will be made with SLS.

Engine

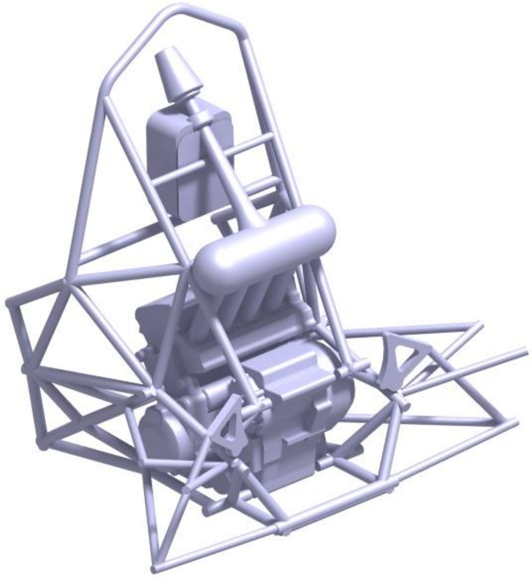

Figure 4.13 Engine section

This part will be attached over the Rear wing support and on the rear frame extension with bolts. The frame will be visible in the rear and therefore affect the wind. The engine and rear is the most complex part in the assembly and therefore is needed to be manufactured with SLS. Due to the driver and seat disturbing the wind flow rearwards, the design of the engine and components in the rear under the wing can be simplified and the variance in aerodynamic properties and disturbances will be negligible. Therefore small aluminium or steel tubes can be used to mimic the frame tubes in the rear.

Diffuser

To be able to test different diffusers this will be a standalone part that will be mounted on the frame’s rear extension beneath the engine with bolts. This part can be made with both SLS or out of aluminium, it is important that it has the correct resembling shape as the car to give realistic measurements.

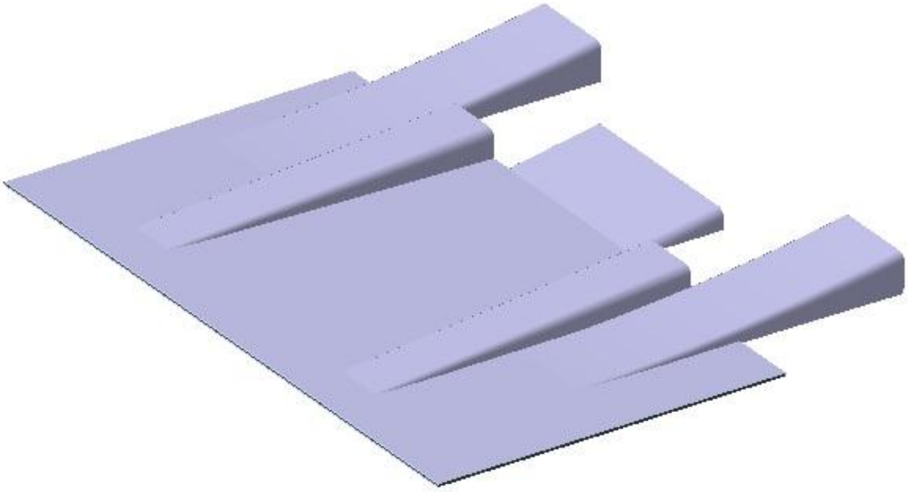

Figure 4.14 Diffuser section

4.4.2 Discussion of design selection

In comparison to the SLS process there are a number of alternative ways of manufacturing the body. One not found in the pre-study phase is making a soft core of a type of polystyrene – commonly called Styrofoam. This core is divided into cross sections of the body with a set thickness and then ground down to a smooth surface texture. This core can be used as a mould for carbon fibre, as a structure that can be covered with modelling clay – this particular approach is used in industry for full scale models, though smaller and complex parts are made with SLS – or if it is a dense enough foam it can be used in standard form with a top coating to obtain the necessary surface finish. This polystyrene can also be processed with a CNC to obtain more exact correspondence with the original body surface.

The most positive aspect with this process is the cost as the foam and clay cost less than carbon fibre and SLS plastics. The negative part is the difficulty to obtain the surface to match the real body if the cross section method is used. If a CNC machine is used, this error in surface texture will be negligible but this also more expensive and harder to manufacture and therefore will need to be outsourced to a manufacturer. The same issues occur when using carbon fibre and SLS, the body will be stiff and have a good finish but the outsourcing or knowledge from an external manufacturer is critical.

4.4.3 Simulations

In collaboration with the CFS's body subgroup, data from CFD analysis on the whole car and on individual parts has been used to evaluate the strength of the frame and see where there will be crucial areas that is important to focus on.

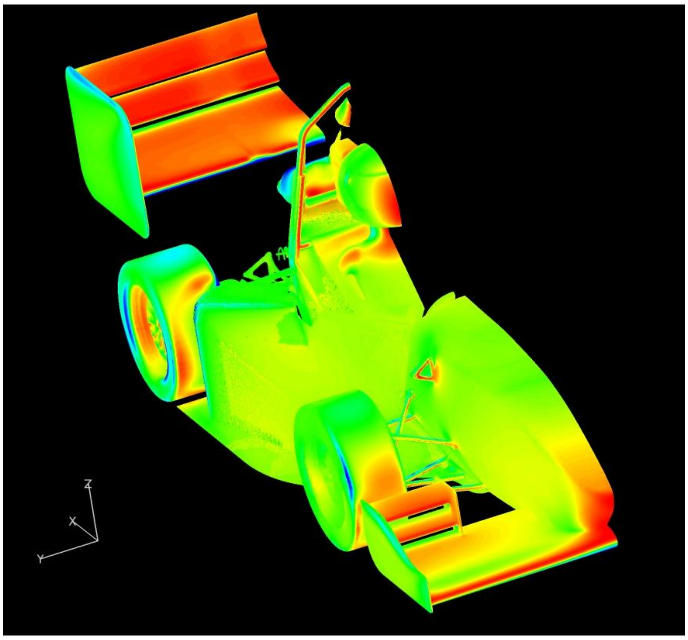

Figure 4.15 Total pressure distribution on CFS12 car in CFD

A concern when using SLS plastics was that the plastic is built up with layers in a specific way with a specific fibre direction. This may be a problem when analysing the wind flow in the wind tunnel when it comes to aerodynamic disturbances so it may have to be ground before testing. A test piece of the front wing was printed in the Chalmers SLS machine and the surface texture, if using the right fibre direction, will not have to be ground.

4.4.4 Designing guide

Modelling of the body parts is completed in CAD using CATIA V5R19. There are a number of ways of creating parts that will be manufacturing with SLS. The easiest way is using "Surfaces" in CATIA. There are some steps the designer should go through and if one method does not work, go to the next one, and unfortunately the time will increase depending on how far down the list you end up before it works.

1. Use *Thick Surface* tool in *Part design*.

   This tool will generate a solid with a user decided thickness from only one surface. Errors are often obtained by using this tool because if there are gaps between surfaces, or if only an edge is highlighted, a solid can't be generated. If this occurs, identify the conflicting element and use one of the following methods for that part.

2. Split the surface into all its sub-faces.

   The tool *Disassemble* can be used to break apart all joined or healed surfaces to its sub-surfaces again. This will often solve problems with surfaces not being able to become solids. Use "*Thick Surface*" tool on these sub-faces to get separate solids. Make sure that these solids are joined together properly.

3. Create surfaces and "fill" the created volume with a solid

   Make an offset of the original surface in the direction you want to add the thickness. Merge the edges with new surfaces constructed with the tools from the *Surface* toolbar. After a volume of surfaces are made use the *Join* tool to close any gap between the surfaces. Then use the *Close Surface* tool to fill the body up as a solid. This method requires everything to be free from gaps in the same way as *Thick Surface* does but it will manage edges and strange shapes in a much better way. Use *Healing* tool the see where there are gaps.

4. If none of the above works, redo the part with solid in mind and use the original surfaces as base.

When using *Join* and *Healing* it will highlight all edges, including gaps, with green lines. This could be very useful when trying to find where the problems are. When scaling down the model, scale the surface. It is very easily achieved in three steps – one for each x-, y- and z-axis – with a tool called *Scaling* under *Operations* toolbar in *Generative Surface Design*. There exists a tutorial that describes how this is done on the Chalmers Formula Student internal drive located in [formula > 2011 > CAD > CAD_Assembly > The_Whole_Car > Body_a1000 > Rapid > Important].

When preparing for manufacturing of the SLS parts the designer will have to make sections corresponding to the machine restrictions at the manufacturer. These sections can be decided in different ways; if the whole model is to be printed the model can be divided into cubes with dimensions decided by the manufacturer and then glued together. If some sections have complicated geometry or some details is "hanging" in the air the dimensions may be changed to get the seams in the optimum place. If small tubes or similar shapes are intersecting each other these section may have to be smoothed in order to prevent disturbances in the airflow and issues when manufacturing with SLS. Depending on the SLS machine used, a support structure may be necessary to obtain the desired strength. Certain machines have built in software that generates this automatically in the SLS process. The last step before manufacturing is converting the CAD files to the desired format used in the SLS machine. The most common tools are *.cat*, *.step*, and *.igs*. When doing this the CAD assembly model will be merged into one body and locked for editing. If *Assembly* mode is used to assemble a lot of solid parts the tool *Generate CATPart from Product* can be used to merge all parts to one, which then can be saved in the correct format.

5 Analysis

5.1 Software tools

The analysis completed on the model has been solely of the calculating sort. For this the programs Matlab and ANSYS have been used. Matlab has been used for the manual calculations on the wheel bearings and ANSYS for all FEA. ANSYS is a frequently used software for FEA with a wide variety of options, from almost all program controlled settings to very user specified settings. For this project the ANSYS manuals provided by CFS were used and are recommended as a starting guide for the software.

5.2 Simulation steps and parameters

In all FEA analyses the CAD model was imported from CATIA and the parts were assigned their respective material. A part made of steel was assigned the “Structural Steel” material, a part made of aluminium was assigned the “Aluminium Alloy” material and a plastic detail (cooler) was assigned “Polyethylene”. None of the materials are the exact materials that they are manufactured from but the metals have their important properties, such as Youngs modulus, therefore the differences are negligible. Regarding the plastic material it will create a difference between the real product and the FEA material. The reason for this is that it was at the time not known exactly what material was going to be used and a normal, comparably weak, material was used in the calculation to ensure an adequate safety margin.

Frame analysis

When imported and with the right material assigned the connections were set. Connections are the way the different parts of a product interact and in ANSYS there are five alternative ways of parts to interact. Of these five two are linear and three are non-linear. Having non-linear connections significantly increases the solving time but are closer to the reality. Choosing the correct compromise between these options is not always obvious since having linear and quick connections can often be sufficient while it is not certain that having non-linear connections require that much time. If the time required to solve the non-linear problem is below 1 minute, it is acceptable.

When analysing the frame the goal was to obtain an indication of deflections, where the stresses would be and how the different parts interacted with each other. The calculations served as an aid in the designing of the model to understand where improvements could be made and where there was unnecessary material. This had to be an efficient process and not require significant effort. As the model had approximately 80 individual contacts it was decided to only utilize the simpler linear connections and to generalize some. The different contacts which were used were “Bonded” and “No Separation”. “Bonded” means that the parts cannot move in relation to each other and the “No Separation” condition means that the parts can move in the plane the interface makes up but not normal to this plane. The model consisted of 9 parts and approximately 30 screws. All of the screws contacts with parts they would in the real model have been bolted so were set to “Bonded”. This was because in the reality they will be bonded to each other. Interfaces between the screws and parts that would only be in contact with but not bolted to each other were set to “No Separation”. This is because in reality they would only experience limited friction between them but since it was decided that only linear conditions were to be used the “No Separation” was the most similar contact. The parts interfaces with each other were all set to “No Separation” and for the same reasons as with the interfaces between the screws and the parts. Meshes is another main aspect of FEA and as with the connections often a compromise between accuracy and time consumption. As with the contacts, time spent was in focus and the mesh was set to “Medium” size and the rest was all automated.

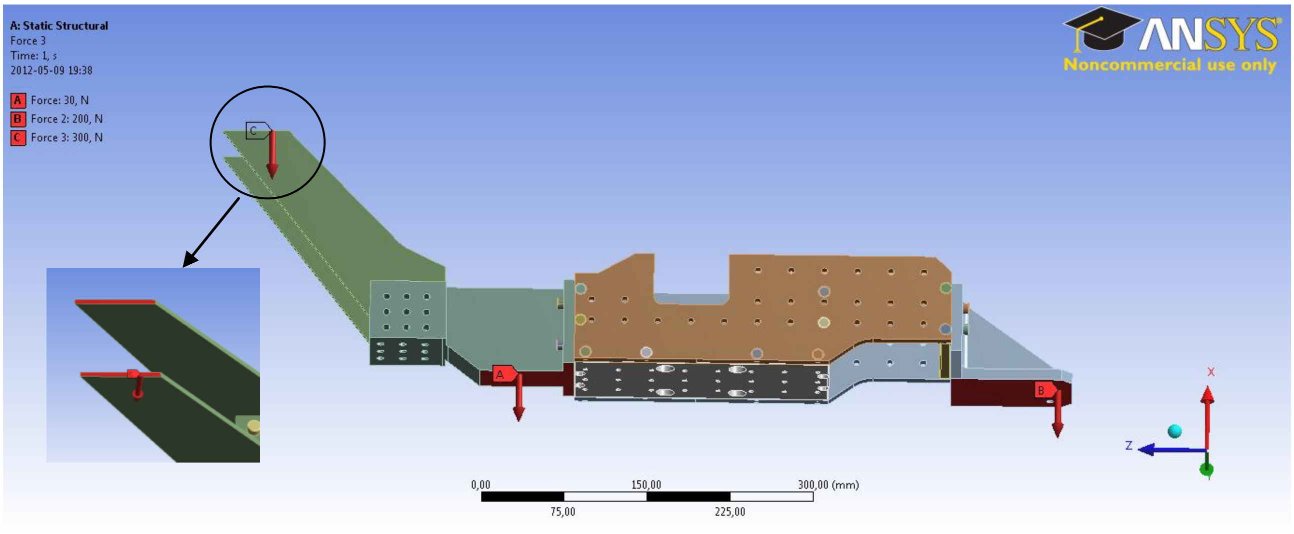

Figure 5.1 Applied forces on the frame in ANSYS

The loads on the model were taken from CFD studies undertake by the CFS12 team. They calculated loads on the diffusers, front and rear wing. These were added to the FEM model at locations as similar to that of the real model as possible. As seen in figure 5.1 the front wing load of 400 N was added to the surface B, the rear wing load of 600 N to the surface C and the diffuser load of 60 N to the surface A. Supports were inserted where the frame is attached to the balance to resemble the real conditions as accurately as possible. These were set on surface in contact with the screws as “Fixed Support” thus locking the model in all directions.

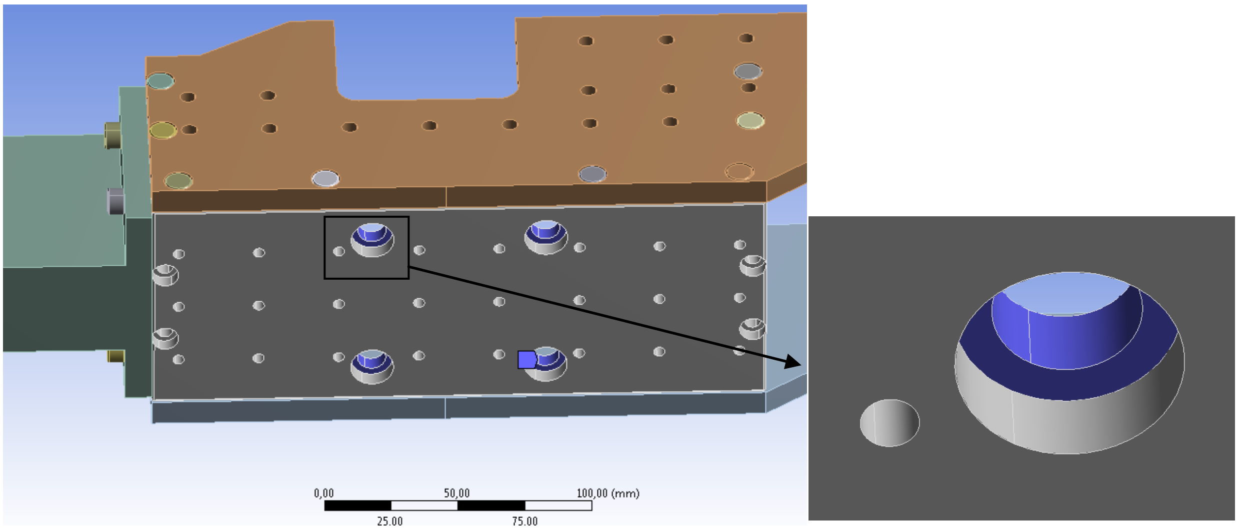

Figure 5.2 Support placement

Wheels

When analysing the wheels it was undertaken with similar goals as with the frame. It was undertaken to obtain an indication of the sizes of stresses and deflections to understand if the dimensions were correct. As with the frame the FEA model consisted of several parts and since the goal was to obtain a basic understanding of the product quickly, the contacts between the parts were set to “Bonded” with the exception of the NACA profile contacts with the parts (not screws) and the interface between the wheel sting arm and its holder. These were set to “No Separation” so that they did not relieve the sting arm from the loads of the wheel. Supports were added in a similar way to those in the frame model, inserted where the screws would have been attached to the wind tunnel and set as “Frictionless Supports”. This locked the model in all directions with as realistic boundary conditions as possible without using up computational time. The wheel was loaded with a “Bearing load” with the components used for calculations on the wheel (see Table 4.1).

5.3 Results

The results of the frame analysis have been previously shown in chapter X and will not be dealt with further. The result of the wheels shows in figure 5.3. The maximal stress occurs at sharp edges which is expected but the actual values are almost certainly not the correct value due to numerical errors in the discontinuities. The stresses in the continuous material are accurate and give a maximum of about 30 MPa which is of no concern. Alternatively the deflection exceeded 1 mm, which should be taken into consideration. It was initially larger and was reason for a change in the design where the sting was thickened to reduce the deflection to the acceptable 1 mm.

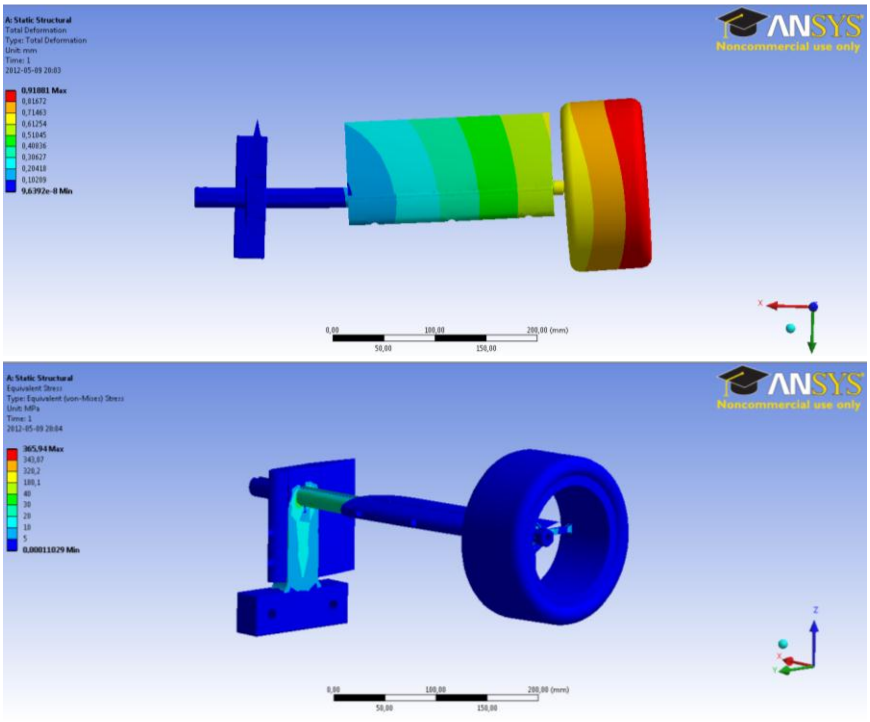

Figure 5.3 FEA on wheel sting assembly

5.4 Recommendation

When making analysis on CAD assemblies with screws it is easier to use screws that make a “perfect” fit in the holes. That means that screws with threads should not be used since there will be many small pockets between the threads and ANSYS does not have a good way of dealing with this. It will take more time to solve the model. If CATIAs standard library screws are used then ensure the holes are the same sizes. Changing the holes according to CATIAs standard screws might be viable but that most likely creates problems with drawings since the holes are in obscure dimensions. The best way is to make the holes in nominal size (i.e. 6 mm wide for a M6 hole) and create the screws yourself in the CAD program with the correct dimensions. To have screws with the exact size of the holes makes ANSYS understand the contact in a smooth way and not trigger a lot of “fixing” scripts to understand gaps and clashes.

If it is possible to use the original assembly format in ANSYS then this should be utilized. It means that the parts can be updated individually if the CAD changes and it saves time when not having to re-mesh everything every time something changes. It also helps to use sensible part names in the CAD model since the names can easily be imported to the FEA model and help with understanding the different contacts existing.

6 Manufacturing

6.1 Frame

The majority of the parts for the frame and the wheels are manufactured in-house in the workshop at Chalmers. The steel components except the rear wing support are manufactured out of pre ground SS1650 steel plates. As the plates have a large side area compared to the thickness skewness may occur when the plates are machined a lot and therefore heated. The simplest way of avoiding this phenomenon is to not complete unnecessary machining on the pieces. That is why the plates are bought pre ground in sizes as close to the desired dimensions so that the amount of machining of each plate is kept to a minimum.

Components made of aluminium are manufactured using aluminium that is offered at Chalmers. This aluminium can vary in alloy number but the most frequent used are 6000-series and 7075. Common to all these alloys are that they are hardened in so they are sufficiently strong to manage the mechanical stress and strain of the wind tunnel model.

Main frame plates

All steel plates in the frame had the same manufacturing methodology even if the parts have different shapes and sizes. The raw material was cut larger than desired by saw and milled to the right dimensions. All holes were drilled in the mill and then threaded by hand since it is difficult to thread in a manual mill. Threading by hand was time consuming work but in order to get the holes correct and minimizing the risk of breaking the thread taps it was the best way to achieve this. As several parts in the frame are the same, the time of manufacturing could have been reduced by using a CNC-mill instead of a manual mill. The advantage of the CNC is that when one part is complete the rest are much quicker to complete when the program is completed and debugged. The disadvantage is the time it takes to write the program but when there are several parts that are the same it will reduce overall time.

There were no design changes on the frame during the manufacturing. This was because of the simple design of the plates and that the manufacturability was taken in account during the design phase.

Rear frame extension

The rear frame extension was manufactured in the same fashion as that of the frame plates. The raw material of aluminium was cut out to a cuboid by a saw and then milled to the correct dimensions. As for the plates the holes were drilled and threaded. Since the extension has a more complex shape it had to be roughly cut to a shape near that desired and then reclamped in the mill several times to mill down the sides to the right size and shape. The designed shape gives increased material waste but it was more important to obtain a light and strong structure.

The wing support was manufactured differently from the other parts. The part was divided in three sheet metal parts that was cut out and the mounting holes were drilled. All three sheet metal parts were welded together to form the final part. A jig had to been built so that it was ensured that the sides were straight when it was welded together. The jig also serves the purpose to stop skewness due to the heating from the welding.

There were no design changes during the manufacturing.

Front frame extension

Manufacturing

The front extension was also split up into three separate plates (the two mounting plates and the reinforcement plate) that were welded together. Every plate was cut to the desired size with a saw and then all the holes were made. The two mounting plates where first welded together to form the 90 degree angle then the reinforcement triangle was welded in place. Last, the welds were ground so the surfaces were flat.

There were no design changes during the manufacturing.

6.2 Wheels

Sting arms

The sting arms were manufactured in house. The bar that was used was a round bar ground to the dimension of 25 mm in diameter. It was then cut in house to the correct length using the band saw. Having a bar with nice finish like this one saves the time of turning the diameter all over the sting arm. The geometry on the end of the sting arm consists of a cone and a diameter which has a fine tolerance to make the bearing fix properly. This tolerance was 10mm -0.01mm. The end of this tap was threaded with a M10 thread. At the other end of the sting arm there is a groove that was milled with an endmill. This groove was then used to line up the round bar to drill the steering holes for the NACA-pieces at a perpendicular angle. The ability to manufacture was thought of all throughout the design process.

Adjustment block

The adjustment block was manufactured in house. A rectangular bar was sawn off to the specified length of the part. All of the remaining machining was performed in the manually operated milling machine. The hole in which the sting arm will fit was first predrilled with an 8 mm drill and then drilled a second time using a 24.5 mm drill which enabled the last holing operation to be performed correctly. The last holing operation is called reaming and what the reamer does is to make the sides of the hole smooth and the dimension of 25 mm fit the h7 tolerance. The other holes were not finished with this precise process. As the part was meant to be machined using a NC machine the round corners could not be completed by hand in an effective way. The corners were therefore chamfered 10x10 mm. This change will not compromise the function of the part.

Sting holders

The sting holders were manufactured in house. The challenge which was presented by the sting holders were their size in combination with the hardness of steel. The outer dimensions were first face milled out of a solid steel block. The T-shape of the sting holder was then sawn out of the solid block. This shape could have been milled as well but that would have taken an unacceptable amount of time. The sawing was done in a way that left material on the part to be milled away to get a better surface and better control of the actual dimension. The hole in which the sting arm will fit was first predrilled with an 8 mm drill and then drilled a second time using a 24.5 mm drill which enabled the last holing operation to be done correctly. The last holing was reaming which makes the surface of the hole smooth and the dimension of 25 mm fit the h7 tolerance. The other holes were performed using the drill bit of the correct dimension. The whole part was manufactured as planned. The sting holders are unique to each side of the car simply by mirroring. There are therefore no differences in manufacturing.

Wheels

The wheels are at the time of the writing of this report not manufactured. The reason for that is that no suitable way of manufacturing the wheels in the Prototype-workshop was found. The preferred way of manufacturing would be turning because of the necessity to have the periphery completely coincident with the hub for the ball bearing, this is to prevent vibrations when the wheel is rotating at high speed. The limiting dimension is the outer diameter of the wheel which is too big for the CNC-turning machine. The spokes could then be milled in the same clamping in the turning machine to ensure good balance. The wheels could also have been manufactured in the three axis NC-milling machine using fine stepping to get the surface smooth. Using this method would mean pinpointing the centre of the wheel using very sensitive measurement clocks, and staring the coordinate system from there. The result of this is not accurate enough due to the natural rotational symmetry of a turning machine. The manufacturing of the wheels could have been made by a contractor, but the price would exceed the thesis budget.

Balance sting holder

The balance sting holder will be manufactured in the same way as the regular sting holders. A difference will be that the U-shape of the balance sting holder has to be milled. The fixing of the sting arm will be done by the adjustment block, but grooves that enable the adjustment block to slide up and down must also be milled. The counter boring of the four screws that attaches the balance sting holder to the balance itself cannot be done. This is because of the lack of space for the drill tool between the U-shaped section of the sting holder and the holes. The screw heads do not however need the counter boring because the screw heads will be shielded underneath the aluminium sheet that covers the gap between the moving ground system and the wall of the wind tunnel. The holes that accommodate the threads for the vertical NACA-pieces have to be drilled before the inside of the U-shape is milled, otherwise the drill bit will break as it comes through the first wall of the U-shape. Manufacturing this part took a longer time than was planned for.

NACA-pieces

The NACA-pieces were printed in the SLS-machine. The holes in the nose and tail will then be covered by aluminium tape, or completely filled over with some a putty or filler. This is done to make the sting arm and sting holders as streamlined as possible.

6.3 Bought parts

- 8 Ball bearings. SKF 6000*.

7 Conclusions and recommendations

In this project three stages were completed; a pre-study was made, a designing of the model was made and lastly the model was manufactured. The pre-study showed that the most preferable concept of a wind tunnel model was with a stiff and ridged backbone or frame. To this frame edition specific body features, printed in SLS plastic would be attached. The model aluminium wheels would be attached to the tunnel itself via separate wheels stings and all measuring would be undertaken with a balance and pitot tubes from Chalmers. When the design phase began, these rough outlines were refined to the finished model. It resulted in a steel core with CFS12-edition specific aluminium features as the frame of the model. The body features are to be made out of SLS plastic and to fit the machine the CAD model of the body is split into smaller pieces. The wheels are made out of aluminium with separate stings. These consist of a steel foundation with round bars of steel that insert into the air flow and hold the wheels in place. To the bars, plastic details are added to minimize the flow disturbance and it is also possible to change the rim pattern via changing the SLSed rims. A special mount for the wheels is made to allow for measuring forces on the wheels by enabling attachment of the balance equipment. The measuring, both on the main body of the model and the wheels, are made with the Chalmers balance and pitot tubes. The tubes are placed in a model cooler and in the diffusers.

The manufacturing of these parts then began and the frame, wheels and wheel stings were manufactured. The majority of the parts were made in house at the prototype workshop and only a small number were made by external manufacturers. It was during this phase the project ran into its first issue. The body parts were too expensive to manufacture the way it was first planed. This is a problem still not overcome and the source to why the project did not fully complete its goal statement. Some ways of getting around this problem are suggested in the discussion of the body features chapter (Chapter 4.4.2).

The goal statement of this project was:

"We will by efficient engineering and methodical work, design and manufacture an adjustable Wind Tunnel model before 18th May 2012, which will assist future CFS-teams."

It was known from the beginning of the project that this was an ambitious goal and it would be hard to complete. When now summarizing the project, the conclusion is that most of the projects goals are completed but not all. The work has been completed methodical and through efficient engineering, although this might be a subjective dimension. The goal to design a complete model is also fully completed but the part of manufacturing it has not been reached fully. There were some complications concerning the manufacturing of the body. This due to both an underestimation of the price of printing the entire body in SLS and misunderstandings made finding other solutions The goal of completing it before the 18th of May will therefore not be completely fulfilled but having in mind the scope of the project it is still considered a success.

A new car is built every year and new forces and stresses are implemented as the body changes with the car. These forces will give new torques on the frame and the weight ratio front/back may change. This will be problematic when using delicate measuring equipment such as the Balance. To prevent exceeding the maximum forces and torques and thus damage the equipment, each new project must analyse the aerodynamic drag and lift on car with CFD. These calculations can then also be used in a FEA analysis to control that the frame will withstand the forces. It is therefore crucial to have knowledge in the softwares for these calculations. When testing the model in the wind tunnel one has to have in mind that the equipment in use is expensive and delicate, so caution is crucial when assembling and installing the model in the wind tunnel. If a wing should be removed accidentally, the balance will break by the shifting weight distribution and the wing fragments will damage the whole tunnel when going through the fan. When starting the test it should be done in small steps and with close attention paid to the load outputs the balance measures when accelerating the wind flow. When the model is in place in the tunnel the test time is restricted and therefore easy exchange of body panels will be the key. Therefore all body modelling should be done with the rule that every part should be able to be exchanged fast and easy and without the need of changing other parts. This will also add to the possibility to evaluate different concepts by changing only one specific area of parts and keeping the remaining parts in place on the model. The fact that a new part on the old body may cause a different weight distribution or pressure over the car and this will in turn give an unknown load on the balance, keep in mind that analysis should always be performed beforehand with CFD.

It was concluded in the pre-study that manufacturing the body in Selective Laser Sintering would be the optimum way due to its ability to make complex and sturdy shapes from CAD-files in a short time period. Later in the project it was realized that the production of the whole body would be more expensive than realized. This was discussed with the SLS manufacturer and negotiations began. Due to the limitation in time for the bachelor thesis the decision of focusing on the frame, wheels and sensors was taken. If these complications would have been known at forehand more focus would have been put on an investigation in the benchmarking in the Pre-study phase for more options of manufacturing the body. If it is chosen to build the body out of SLS or CNC it is important that the designer is familiar with the construction software used. When building the body with surfaces one must be very thorough when merging the surfaces so no gaps are made. These gaps will create problems when trying to make solids in the later stages of design and will be very time consuming to find and repair.

The car will give both drag and down force when traveling. A large downforce will provide advantageous performance properties on the car and is often desired when construction and designing a race car. If the desired amount increases each year there will be an issue when using the wind tunnel model due to that the balance has restrictions in loads in each x-, y-, z-direction and exceeding this will cause a failure. There are ways of going around this problem and based on the design for each year this will have to be assessed after forces have been measured in CFD. By using a larger balance, obtaining a larger range of loads, the problem would be solved. Cost and increase in size are prohibitive due to the requirement of building a new frame. Another way is splitting the body into different rigs that will hold the most forces and test a specific part with the balance. By doing this the wind may be disturbed by the rigs holding the parts, but alternatively the test results will be relatively correct, compared to testing only selected parts in the tunnel. This is because the whole body will interact with the wind flow and will give the flow its natural path and pressure. This concept is used for measuring the forces on the wheels. When the balance is changed from the frame to the wheel mounts, a substitute spacer is used in the frame and the whole model is still placed in the wind tunnel to give the air flow its specific flow around the wheels to give realistic output values.

One thing to have in mind when testing the model in the wind tunnel is the amount of disturbance the wheel mountings will give. These have not been tested with CFD and may cause excessive disturbance in the wind flow around the wheel. Actions to prevent this may include redesigning the flaps on the wheel mount stings to redirect the flow in a realistic way. To fully understand the wheels influence on the air flow, each year can use SLS to manufacture new rim patterns to resemble that year's new wheel design.

The project itself will hopefully lead up to increased focus in the aerodynamic area in Formula Student. With increased knowledge and both equipment and facilities at the teams disposal, this may lead to the possibility to act as consultants to other Formula Student teams and provide the opportunity to use Chalmers wind tunnel for their on testing with our model frame. This would be the greatest achievement of the outcome of this Bachelor thesis.

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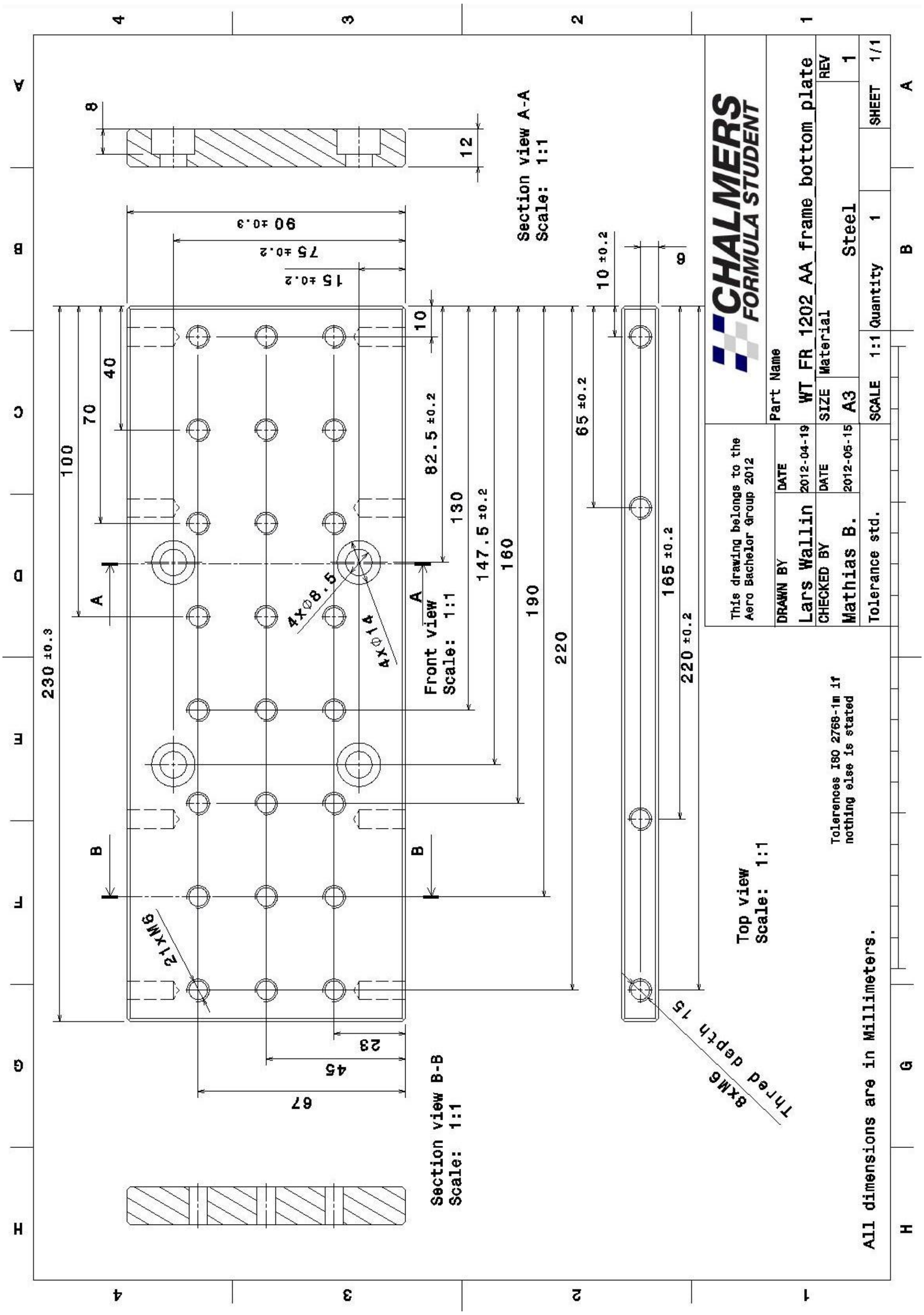
Appendices

A Material and Part list

Subassembly	Quantity	Part number
Frame	1	WT_FR_1201_AA_frame_side_plate
	1	WT_FR_1202_AA_frame_bottom_plate
	2	WT_FR_1204_AA_frame_forward_plate
	1	WT_FR_1205_AA_frame_forward_face
	1	WT_FR_1307_AA_back_frame
	1	Symmetry of WT_FR_1201_AA_frame_side_plate
	24	WT_FR_1002_AA_skruv_M6_16
	8	WT_FR_1001_AA_skruv_M6_20
	1	WT_BF_2204_AA_sting_wing
	1	WT_FR_1209_AA_front_wing_mount
Wheels	4	WT_WH_3103_AA_vulcanized_plastic
	8	WT_WH_3102_AA_bearing_6000_e
	16	WT_WH_3105_AA_m3_8
	4	WT_WH_3101_Aa_wheel
	4	WT_WH_3104_AA_rim_pattern_12
	4	WT_WH_3201_BA_small_sting
	4	WT_WH_3207_AA_sls_naca_tail
	4	WT_WH_3208_AA_sls_naca_nose
	1	WT_WH_3209_AA_sting_holder
	3	WT_WH_3210_AA_sh_tail
	3	WT_WH_3211_AA_sh_nose
	24	WT_WH_3212_AA_m3_30
	6	WT_WH_3212_AA_m3_50
	4	WT_WH_3205_AA_bushing
	4	WT_WH_3214_AA_m10_nut
	3	WT_WH_3219_AA_small_egg
	4	WT_WH_3215_AA_m8_lock_screw
	8	WT_WH_3218_AA_m4_12
	6	WT_WH_3216_AA_m10_37
	6	WT_WH_3217_AA_m10_nut
	2	Symmetry of WT_WH_3209_AA_sting_holder_1
	8	WT_WH_3303_AA_m8_20
	1	WT_WH_3304_AA_angle_plate
	1	WT_WH_3302_AA_sting_holder
	1	WT_WH_3307_AA_adjustment_block

Subassembly	Quantity	Part number
	1	WT_WH_3308_AA_sh_tail
	1	WT_WH_3309_AA_sh_nose
	3	WT_WH_3310_AA_m4_16
	3	WT_WH_3311_AA_m4_35
	2	WT_WH_3312_AA_m10_30
	1	WT_WH_3314_AA_big_egg
	1	WT_WH_3313_AA_balance_mock_up

B Drawings



This drawing belongs to the Aero Bachelor Group 2012

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DATE: 2012-04-19
CHECKED BY: Mathias B.
DATE: 2012-05-15
Part Name: WT FR 1202 AA frame bottom plate
SIZE: A3
Material: Steel
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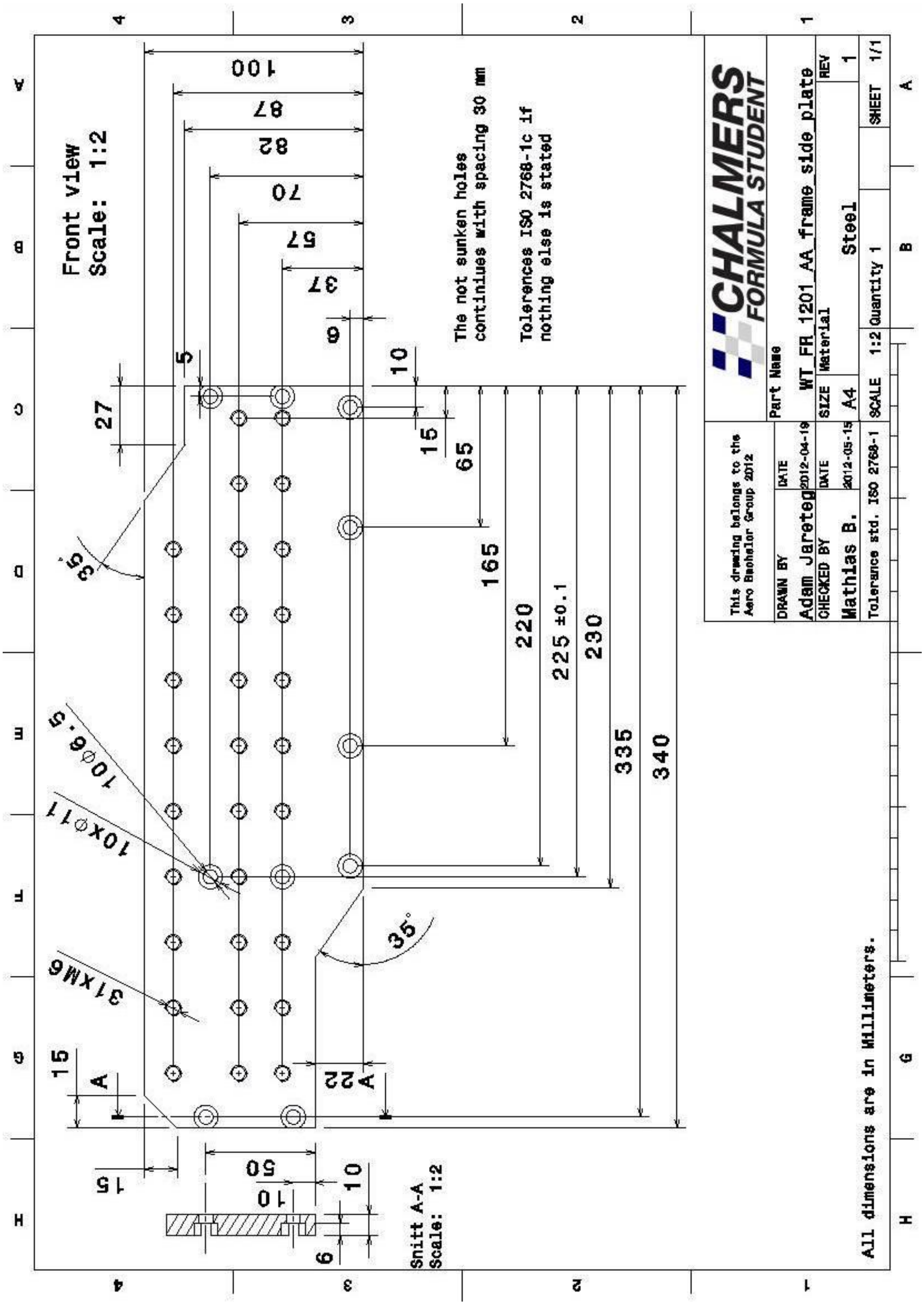
Quantity: 1
SHEET: 1/1
Tolerance std.

Tolerences ISO 2768-1m if nothing else is stated

All dimensions are in Millimeters.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87
82
70
57
37
6
5
27
10
15
65
165
220
225 ±0.1
230
335
340
35°
35°
10x⌀6.5
10x⌀11
31xM6
15
A
22
A
15
50
10
10
6
Snitt A-A
Scale: 1:2
The not sunken holes continues with spacing 30 mm
Tolerences ISO 2768-1c if nothing else is stated
All dimensions are in Millimeters.
This drawing belongs to the Aero Bachelor Group 2012
CHALMERS FORMULA STUDENT
Part Name
WT_FR_1201_AA_frame_side_plate
DRAWN BY
Adam Jareteg
DATE
2012-04-19
CHECKED BY
Mathias B.
DATE
2012-05-15
SIZE
A4
Material
Steel
REV
1
SCALE
1:2
Quantity 1
SHEET
1/1
Tolerance std. ISO 2768-1
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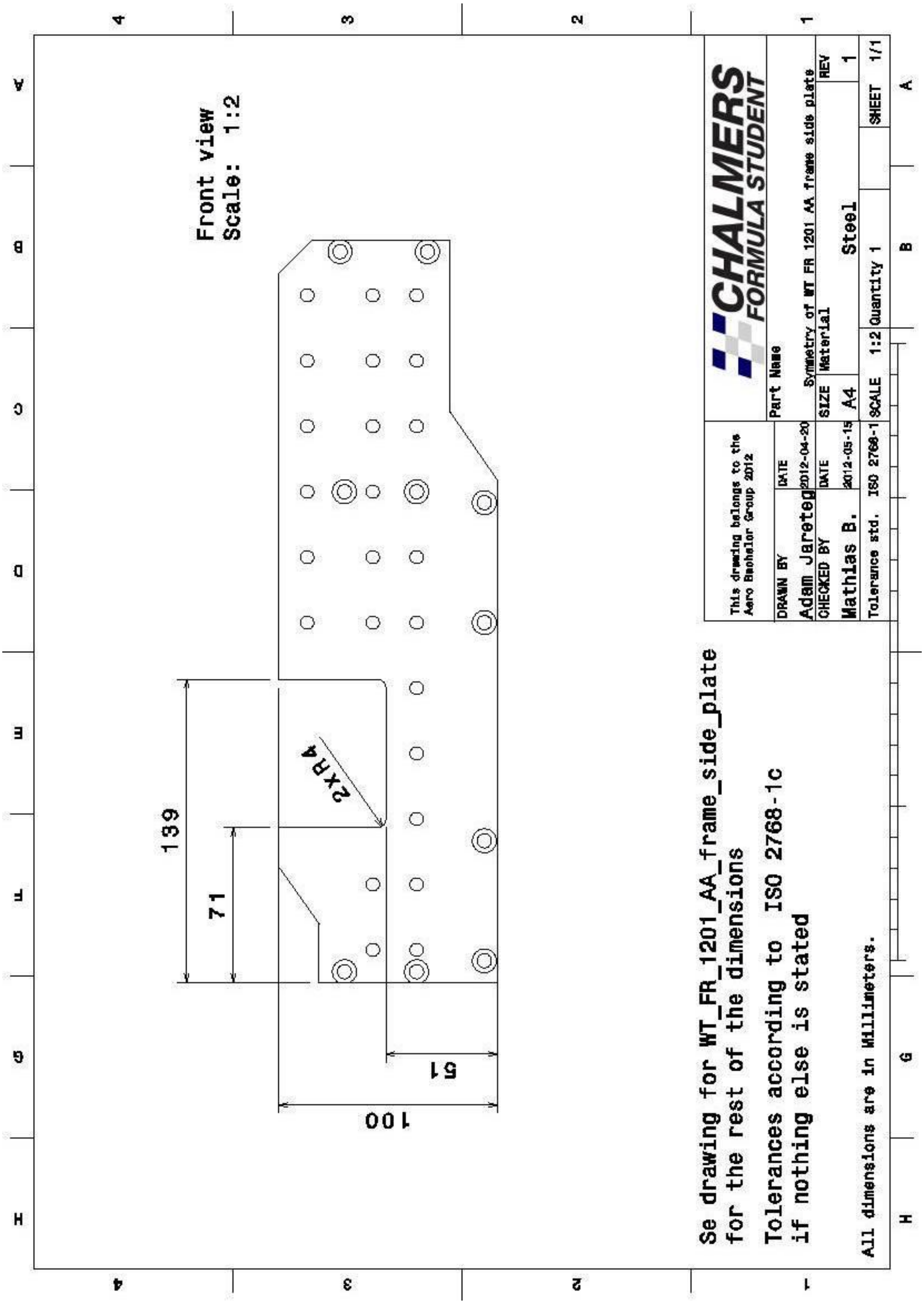
G
H
1
2
3
4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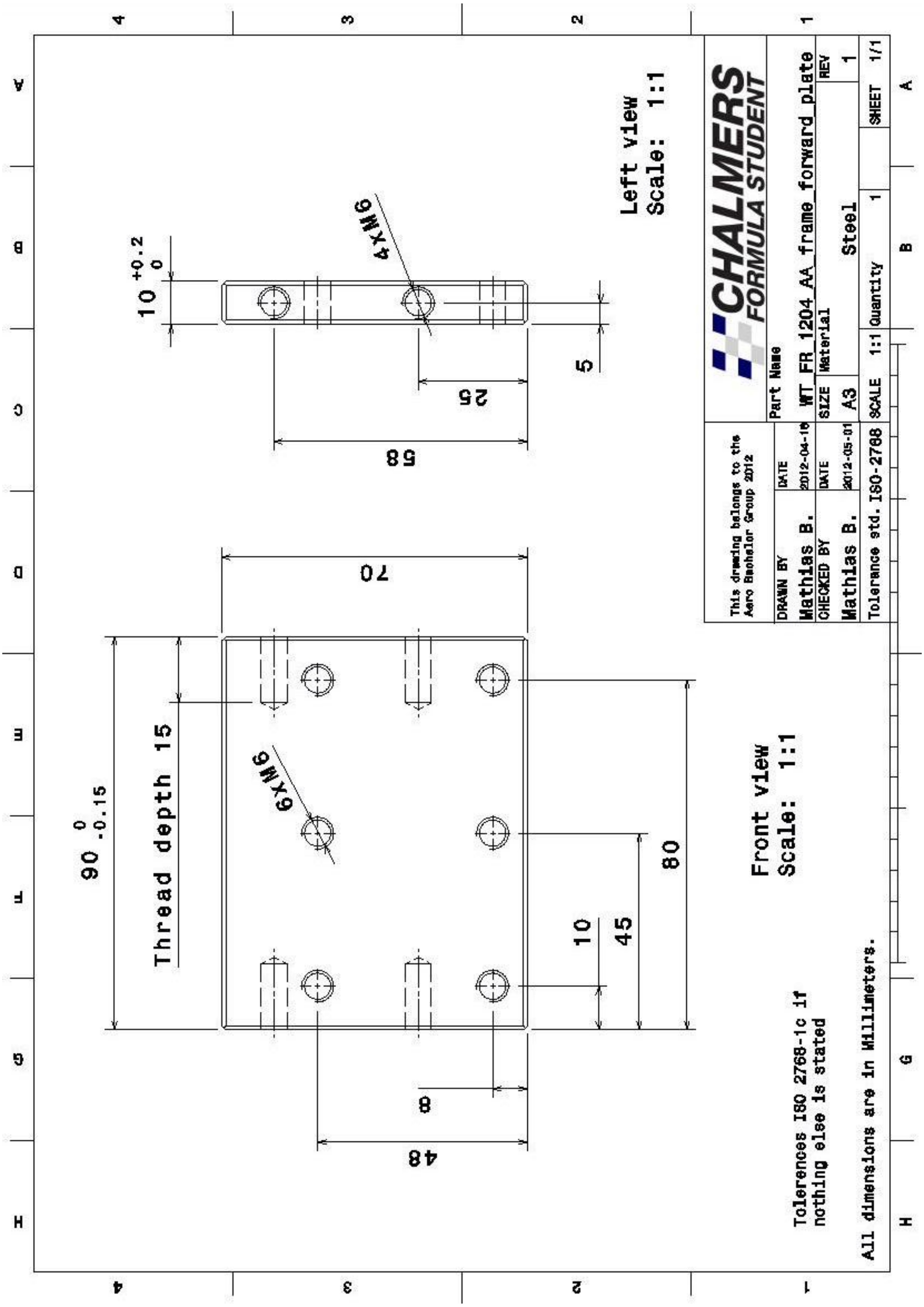
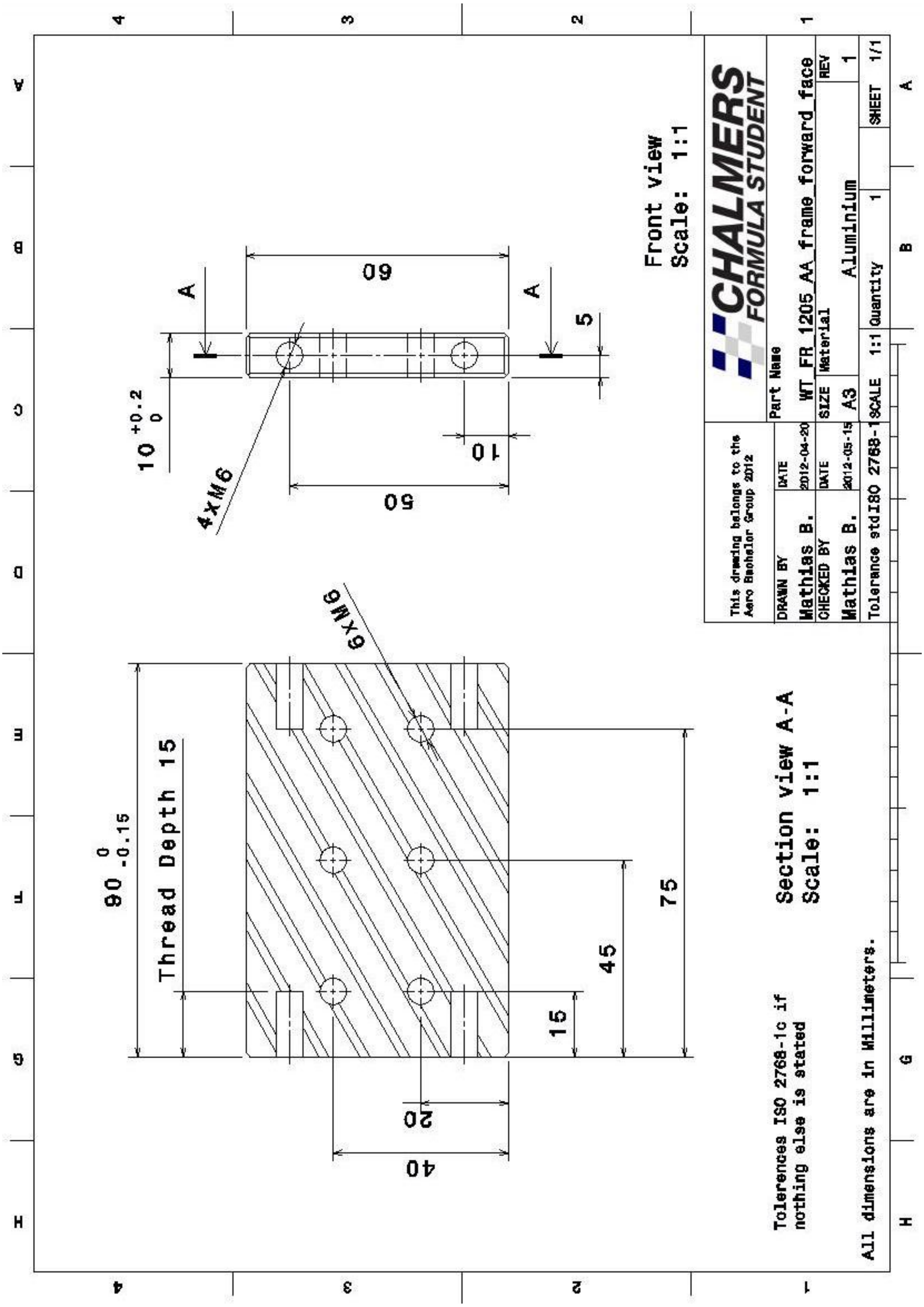
2xR4
51
100
Se drawing for WT_FR_1201_AA_frame_side_plate
for the rest of the dimensions
Tolerances according to ISO 2768-1c
if nothing else is stated
All dimensions are in Millimeters.
This drawing belongs to the Aero Bachelor Group 2012
DRAWN BY
Adam Jareteg
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-15
Tolerance std. ISO 2768-1
SCALE 1:2
Quantity 1
SHEET 1/1
CHALMERS FORMULA STUDENT
Part Name
Symmetry of WT FR 1201 AA frame side plate
SIZE
A4
Material
Steel
REV
1
A
B
C
D
E
F
G
H
1
2
3
4



We will by efficient engineering and methodical work, design and manufacture an adjustable Wind Tunnel model before 18th May 2012, which will assist future CFS-teams.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Scale: 1:1
A
A
60
5
10 +0.2 0
4xM6
10
50
Section view A-A
Scale: 1:1
6xM6
90 0 -0.15
Thread Depth 15
75
45
15
20
40
Tolerences ISO 2768-1c if nothing else is stated
All dimensions are in Millimeters.
This drawing belongs to the Aero Bachelor Group 2012
DRAWN BY
Mathias B.
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-15
Tolerance std ISO 2768-1
Part Name
WT_FR_1205_AA_frame_forward_face
SIZE
A3
SCALE
1:1
Material
Aluminium
Quantity
1
REV
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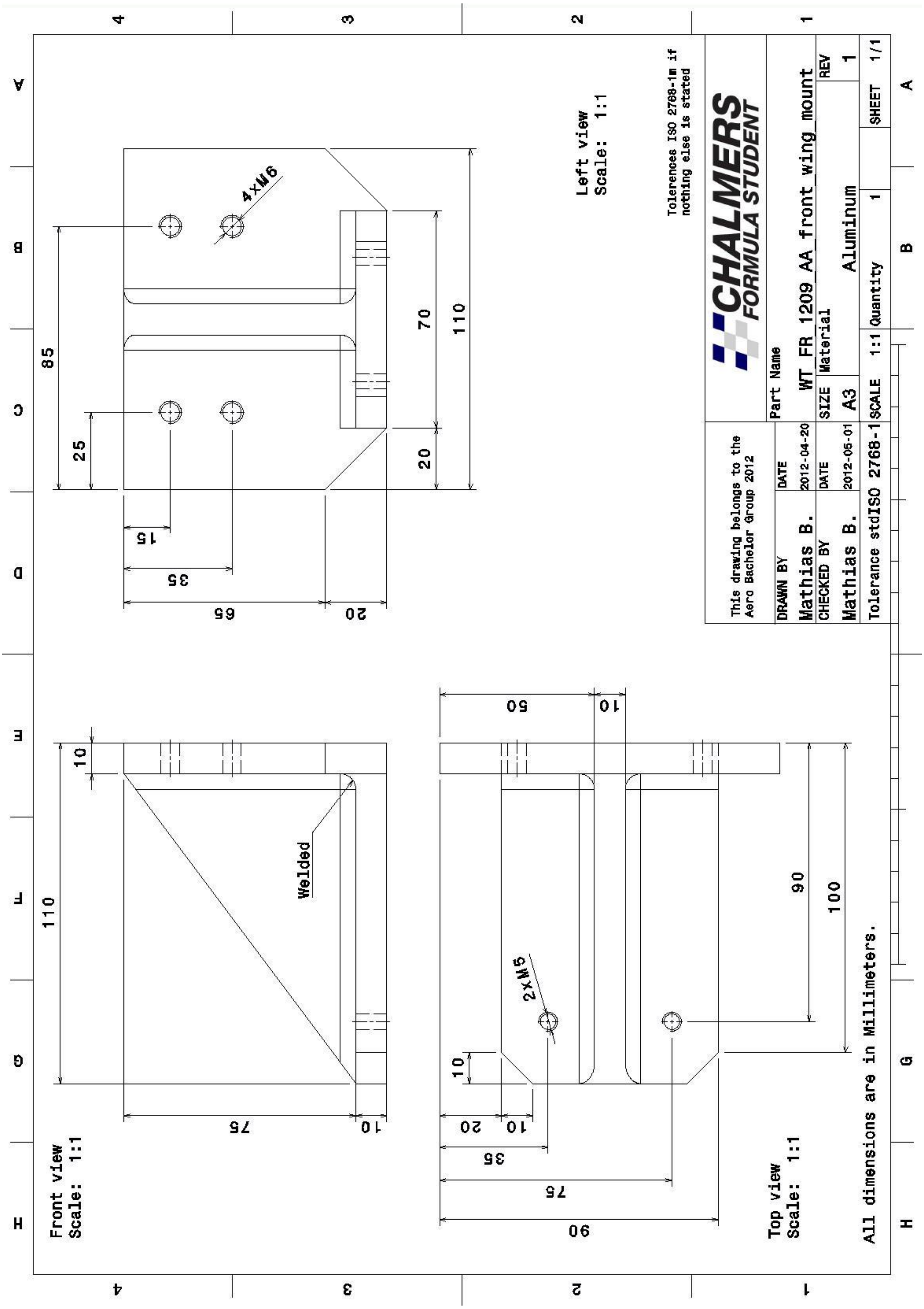
CHALMERS FORMULA STUDENT
A
B
C
D
E
F
G
H
1
2
3
4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Scale: 1:1
4xM6
85
25
15
35
65
20
70
20
110
Front view
Scale: 1:1
Welded
110
10
75
10
Top view
Scale: 1:1
2xM5
50
10
90
100
10
20
10
35
75
90
All dimensions are in Millimeters.
Tolerences ISO 2768-1m if nothing else is stated
CHALMERS FORMULA STUDENT
This drawing belongs to the Aero Bachelor Group 2012
DRAWN BY
Mathias B.
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-01
Part Name
WT_FR_1209_AA_front_wing_mount
SIZE
A3
Material
Aluminum
REV
1
Tolerance std ISO 2768-1
SCALE
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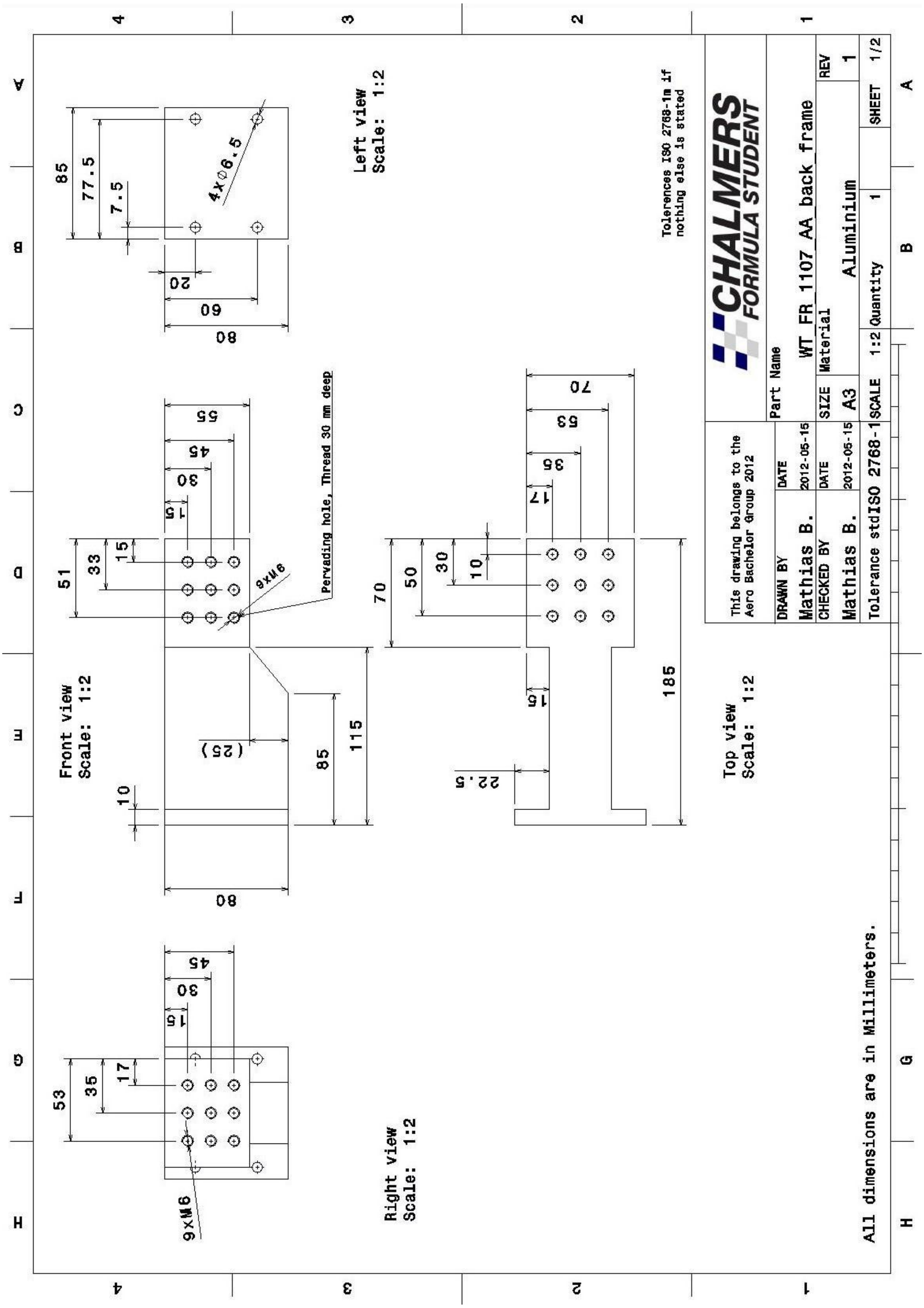
Quantity
1
SHEET
1/1
1
2
3
4
A
B
C
D
E
F
G
H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Scale: 1:2
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77.5
7.5
20
60
80
4xØ6.5
Front view
Scale: 1:2
55
45
30
15
51
33
15
9xM6
Pervading hole, Thread 30 mm deep
70
115
85
(25)
10
80
Top view
Scale: 1:2
70
53
35
17
50
30
10
15
22.5
185
Right view
Scale: 1:2
45
30
15
53
35
17
9xM6
Tolerences ISO 2768-1m if nothing else is stated
This drawing belongs to the Aero Bachelor Group 2012
DRAWN BY
Mathias B.
DATE
2012-05-15
CHECKED BY
Mathias B.
DATE
2012-05-15
Part Name
WT_FR 1107_AA back_frame
Material
Aluminium
SIZE
A3
REV
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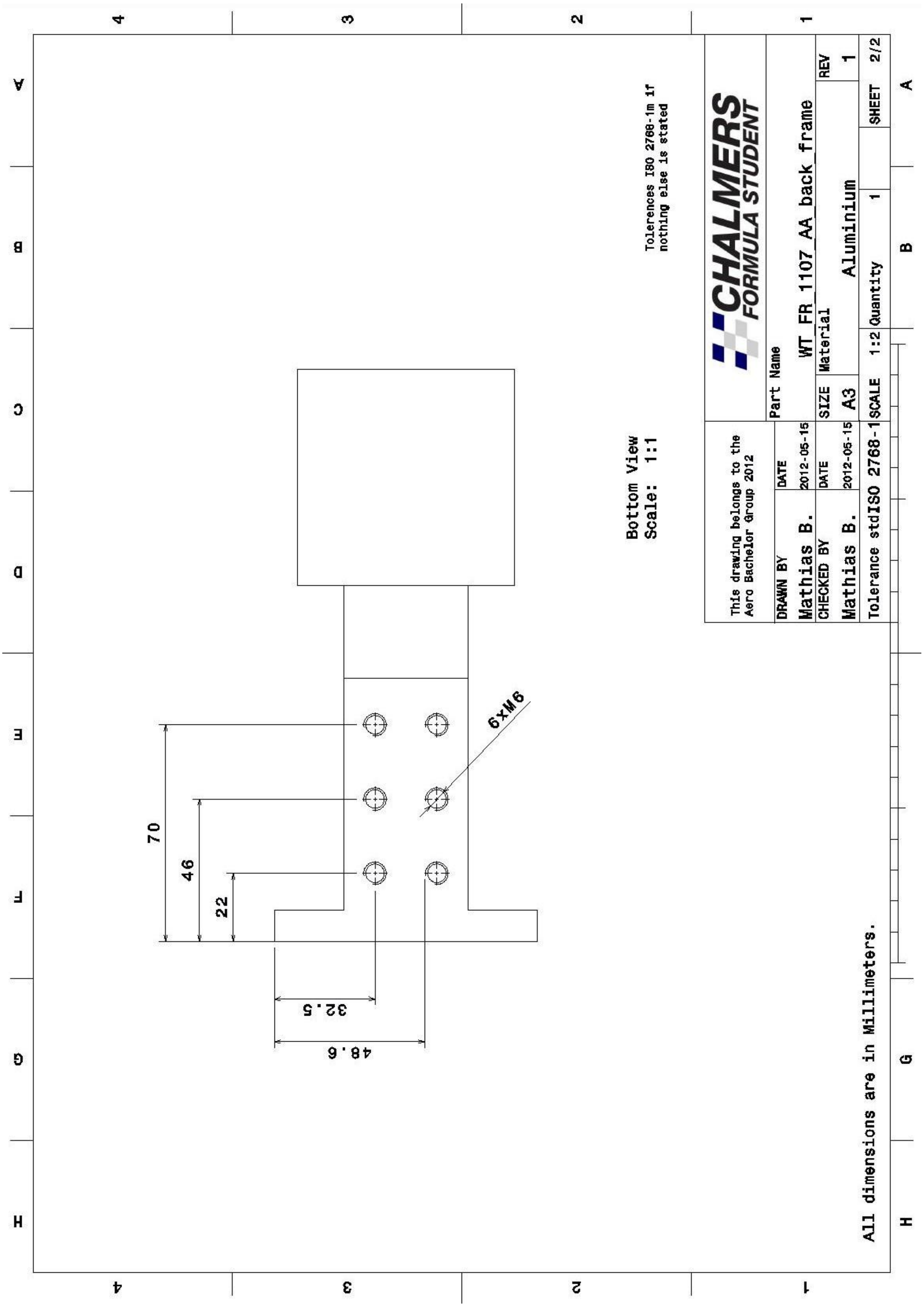
SCALE
1:2
Quantity
1
SHEET
1/2
Tolerance std ISO 2768-1
All dimensions are in Millimeters.
A
B
C
D
E
F
G
H
1
2
3
4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nothing else is stated
Bottom View
Scale: 1:1
6xM6
70
46
22
32.5
48.6
All dimensions are in Millimeters.
This drawing belongs to the
Aero Bachelor Group 2012
CHALMERS FORMULA STUDENT
DRAWN BY
Mathias B.
DATE
2012-05-15
CHECKED BY
Mathias B.
DATE
2012-05-15
Part Name
WT_FR_1107_AA_back_frame
SIZE
A3
Material
Aluminium
REV
1
Tolerance std ISO 2768-1
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4
A
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E
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G
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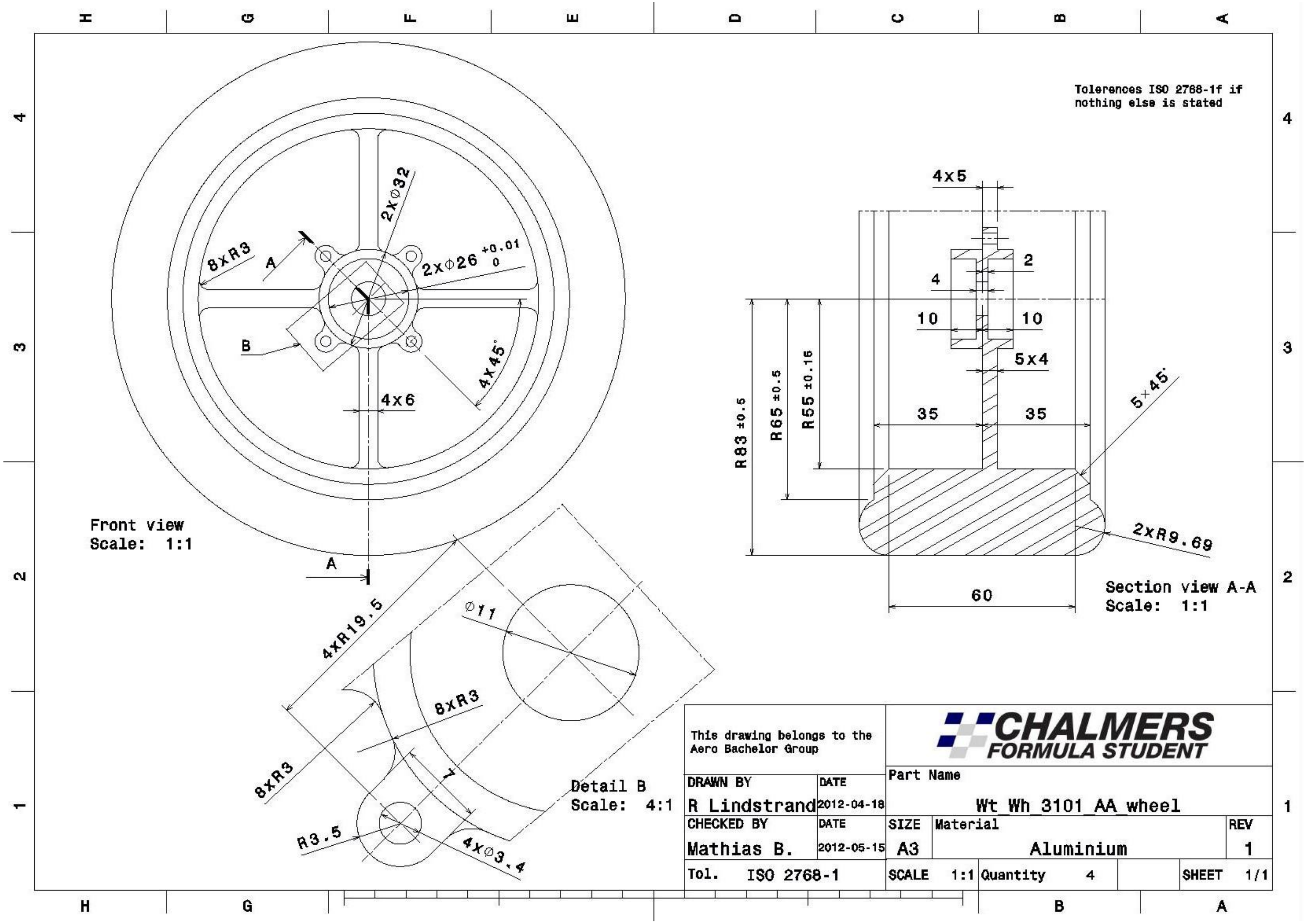
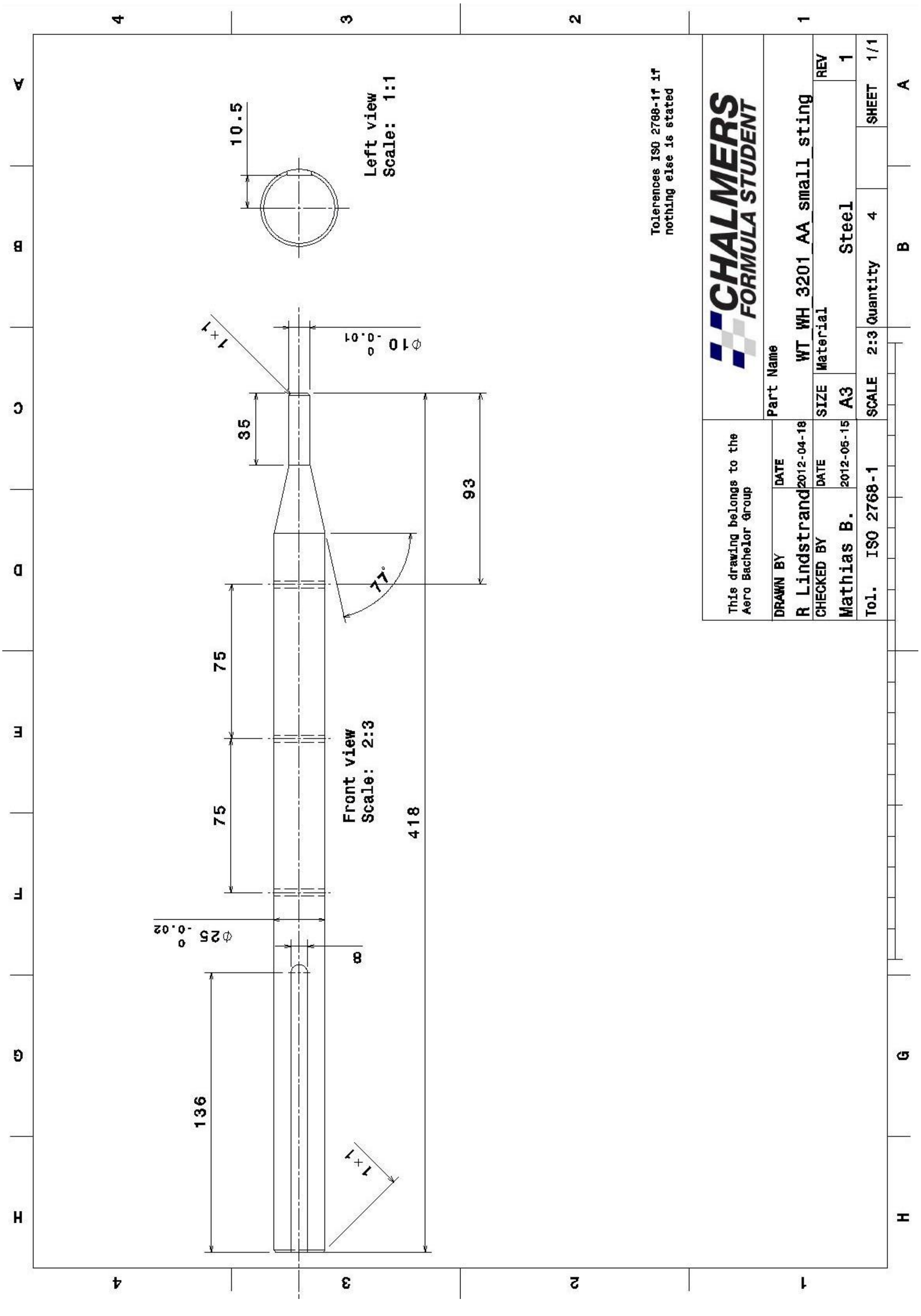


We will by efficient engineering and methodical work, design and manufacture an adjustable Wind Tunnel model before 18th May 2012, which will assist future CFS-teams.



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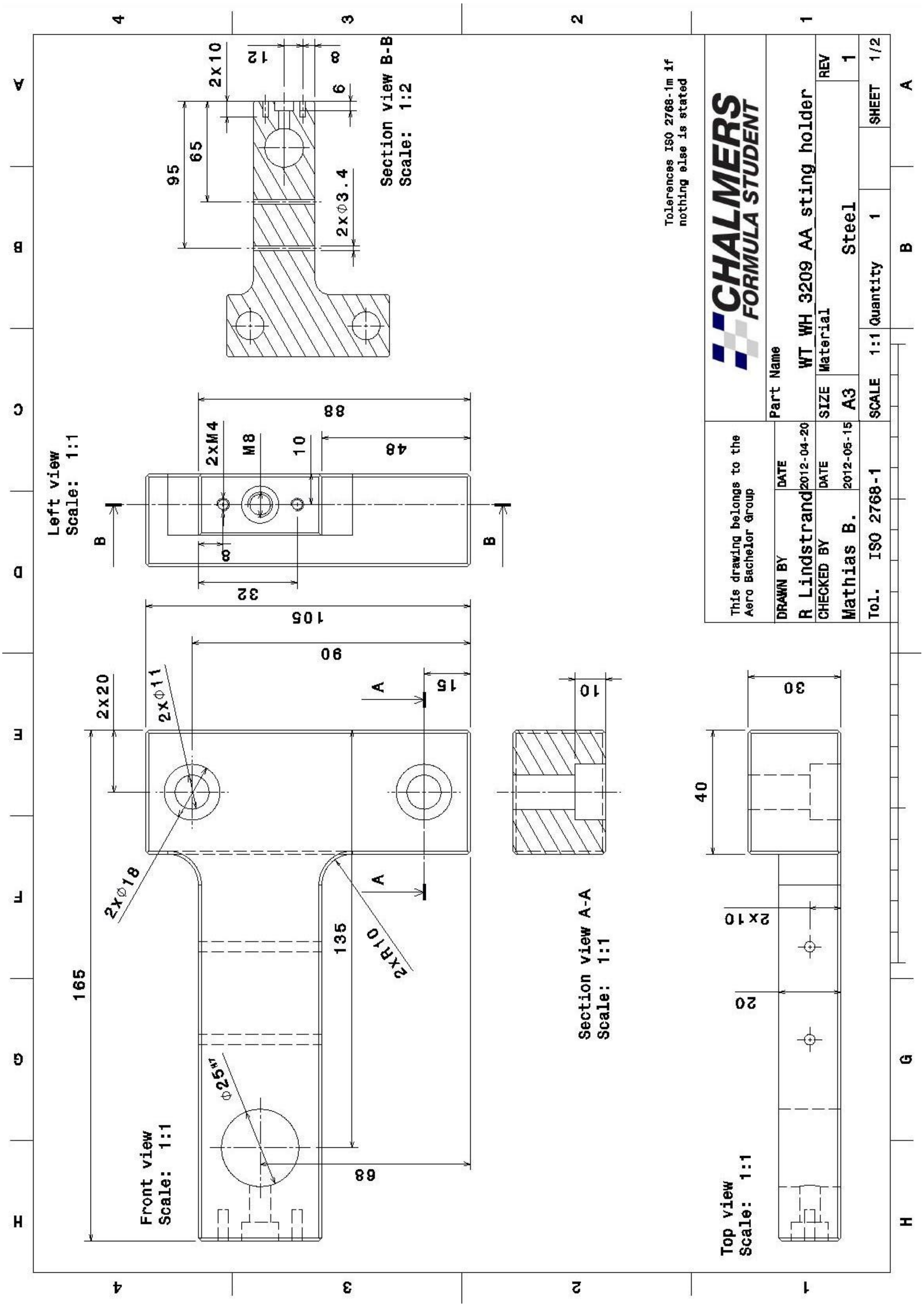
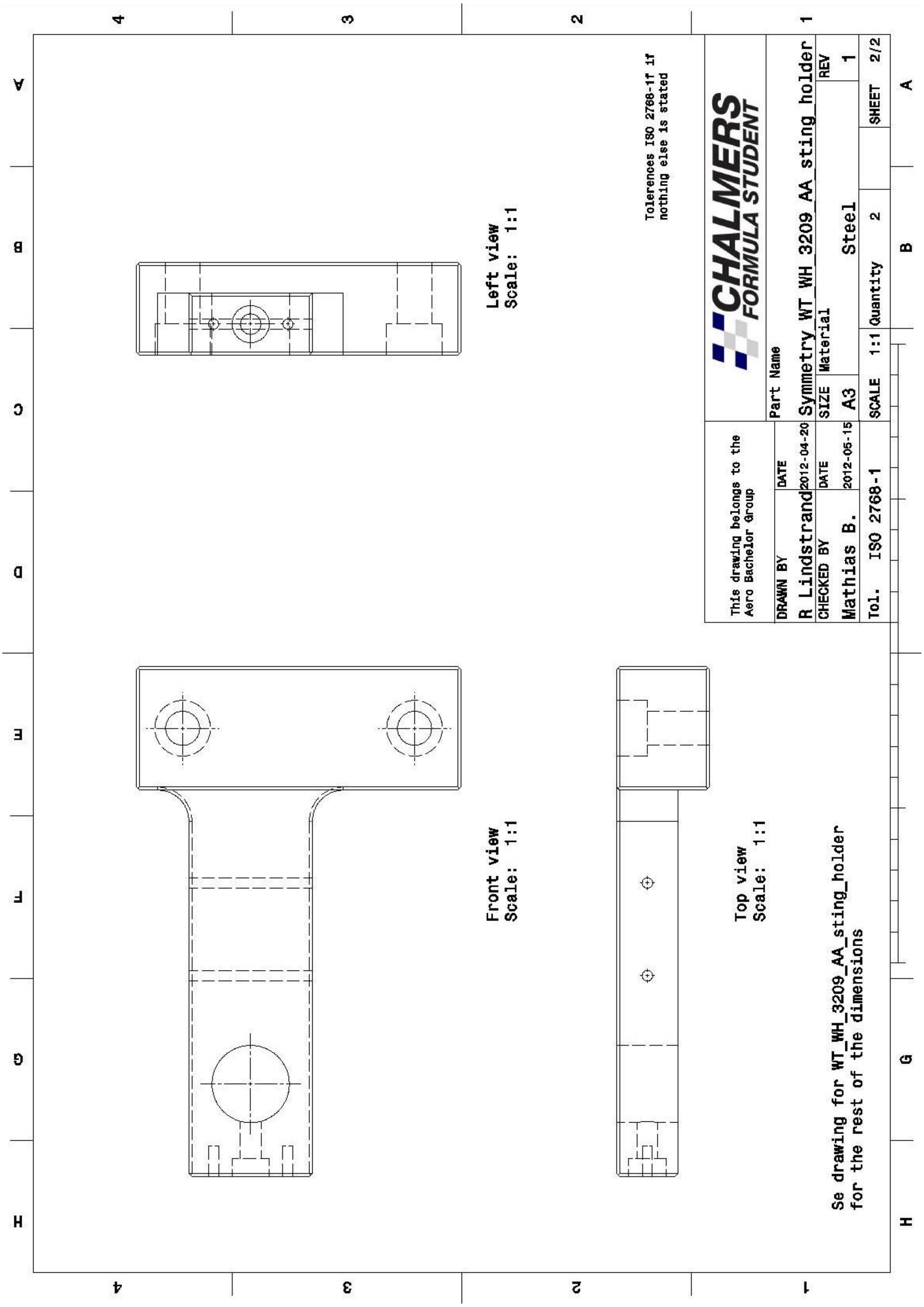
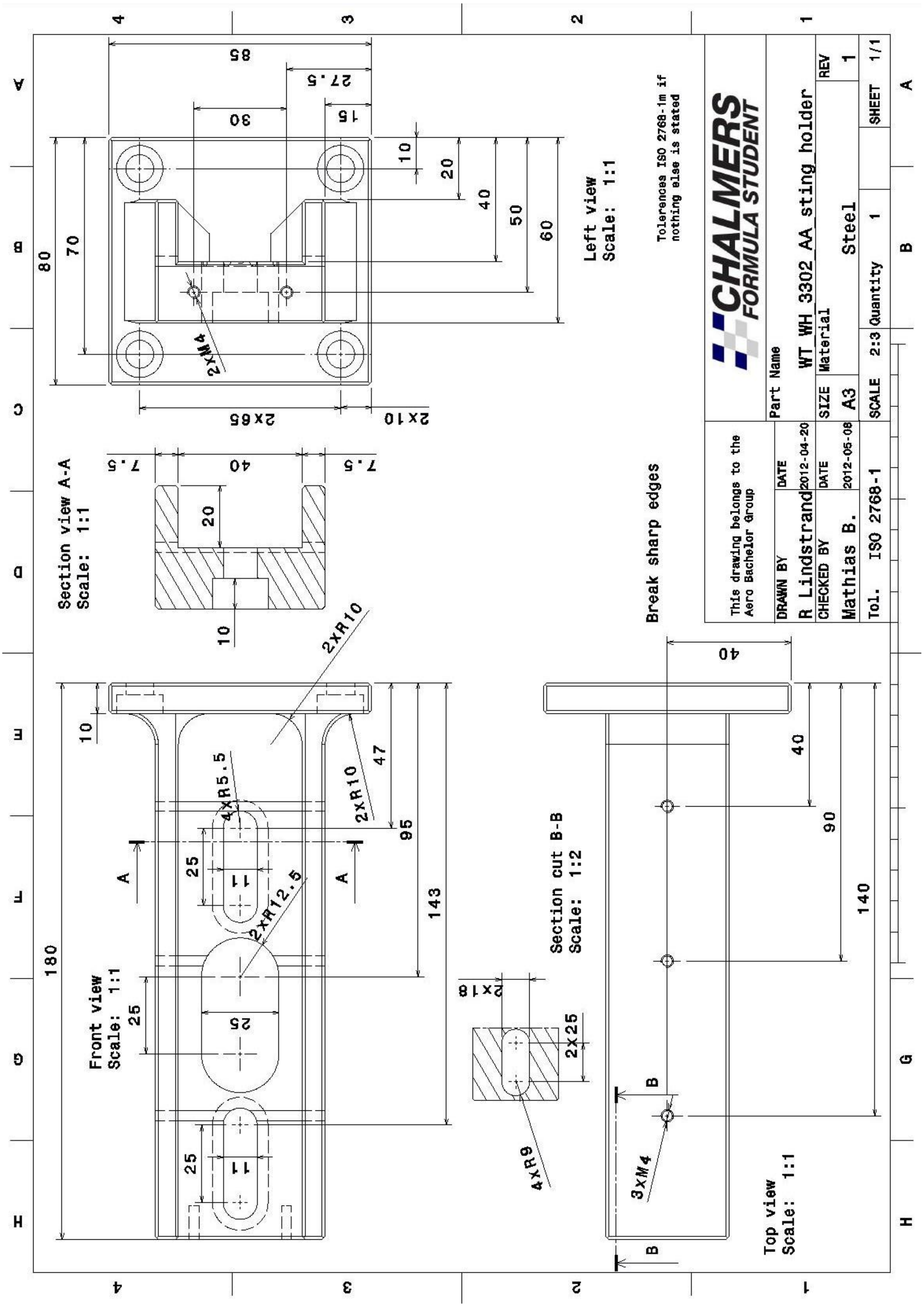
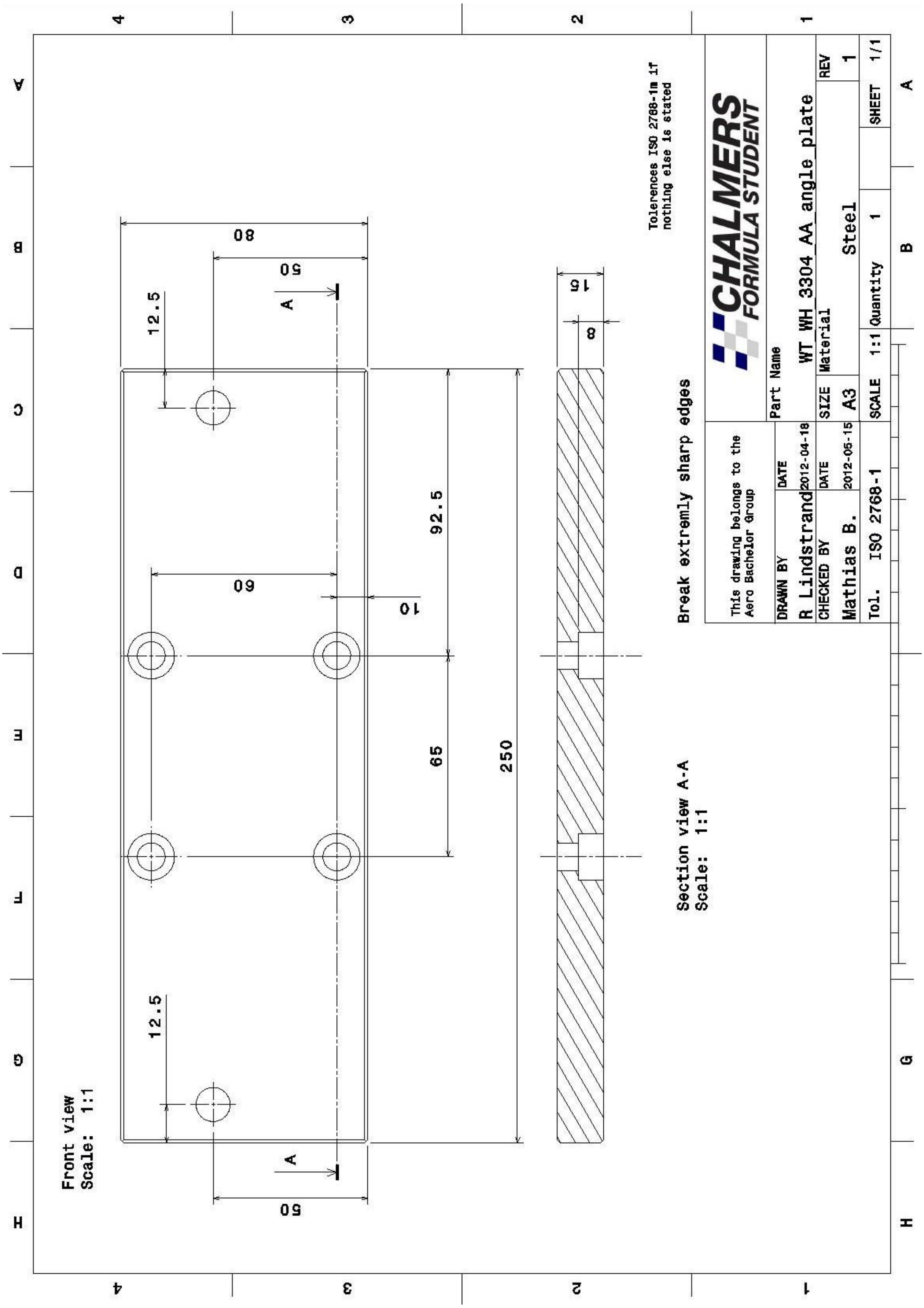
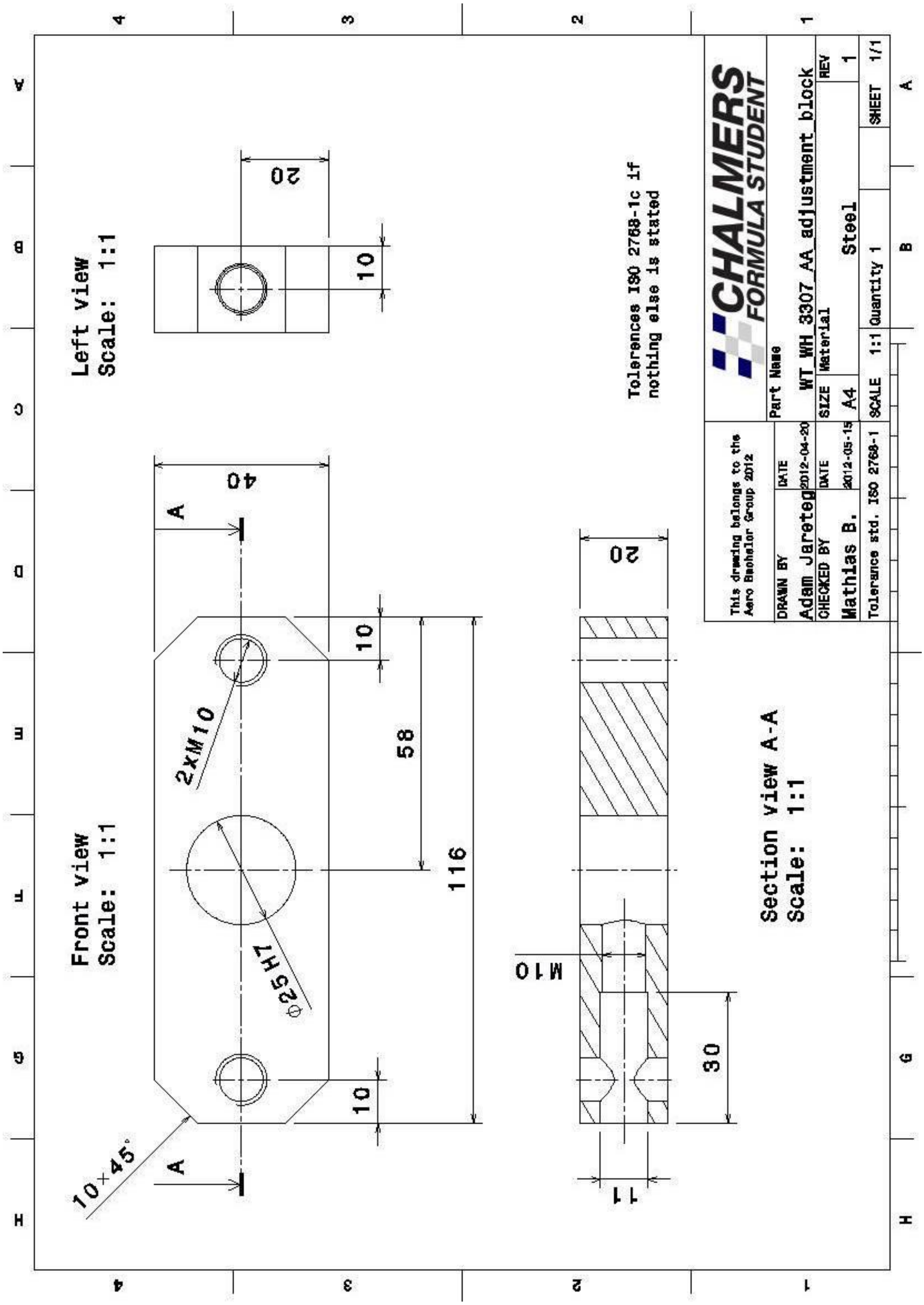

Section view B-B
Scale: 1:2
2x10
12
8
6
95
65
2xØ3.4
Left view
Scale: 1:1
88
2xM4
M8
10
48
8
32
B
B
105
90
15
A
A
2x20
2xØ11
2xØ18
165
135
2xR10
Ø25H7
68
Front view
Scale: 1:1
10
Section view A-A
Scale: 1:1
30
40
2x10
20
Top view
Scale: 1:1
Tolerences ISO 2768-1m if nothing else is stated
CHALMERS FORMULA STUDENT
This drawing belongs to the Aero Bachelor Group
DRAWN BY
R Lindstrand
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-15
Tol. ISO 2768-1
Part Name
WT_WH_3209_AA_sting holder
Material
Steel
REV
1
SIZE
A3
SCALE 1:1
Quantity 1
SHEET 1/2
1
2
3
4
A
B
C
D
E
F
G
H


A
B
C
D
E
F
G
H
1
2
3
4
Tolerences ISO 2768-1f if nothing else is stated
Left view
Scale: 1:1
Front view
Scale: 1:1
Top view
Scale: 1:1
Se drawing for WT_WH_3209_AA_sting_holder for the rest of the dimensions
This drawing belongs to the Aero Bachelor Group
CHALMERS FORMULA STUDENT
DRAWN BY
R Lindstrand
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-15
Tol.
ISO 2768-1
Part Name
Symmetry WT WH 3209 AA sting_holder
SIZE
A3
Material
Steel
REV
1
SCALE
1:1
Quantity
2
SHEET
2/2


Left view
Scale: 1:1
Tolerences ISO 2768-1m if nothing else is stated
Section view A-A
Scale: 1:1
Break sharp edges
Front view
Scale: 1:1
Section cut B-B
Scale: 1:2
Top view
Scale: 1:1
85
27.5
30
15
10
20
40
50
60
80
70
2xM4
2x65
2x10
7.5
40
7.5
20
10
2xR10
10
47
2xR10
95
4xR5.5
25
11
A
A
2xR12.5
143
180
25
25
25
11
2x18
2x25
4xR9
40
40
90
140
B
B
3xM4
This drawing belongs to the Aero Bachelor Group
DRAWN BY
R Lindstrand
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-08
Tol. ISO 2768-1
Part Name
WT_WH_3302_AA_sting holder
Material
Steel
SIZE
A3
SCALE
2:3
Quantity
1
REV
1
SHEET
1/1
CHALMERS FORMULA STUDENT
1
2
3
4
A
B
C
D
E
F
G
H


Tolerences ISO 2768-1m if nothing else is stated
Break extremly sharp edges
Section view A-A
Scale: 1:1
Front view
Scale: 1:1
80
50
12.5
A
92.5
60
10
65
250
15
8
12.5
A
50
This drawing belongs to the Aero Bachelor Group
CHALMERS FORMULA STUDENT
DRAWN BY
R Lindstrand
DATE
2012-04-18
CHECKED BY
Mathias B.
DATE
2012-05-15
Tol. ISO 2768-1
Part Name
WT_WH_3304_AA_angle_plate
SIZE
A3
Material
Steel
SCALE 1:1
Quantity 1
REV
1
SHEET 1/1


Front view
Scale: 1:1
Left view
Scale: 1:1
Section view A-A
Scale: 1:1
A
A
40
20
10
10
10
58
116
2xM10
Φ25H7
10×45°
20
M10
30
11
Tolerances ISO 2768-1c if
nothing else is stated
CHALMERS FORMULA STUDENT
This drawing belongs to the
Aero Bachelor Group 2012
DRAWN BY
Adam Jareteg
DATE
2012-04-20
CHECKED BY
Mathias B.
DATE
2012-05-15
Tolerance std. ISO 2768-1
Part Name
WT_WH_3307_AA_adjustment_block
SIZE
A4
Material
Steel
REV
1
SCALE
1:1
Quantity 1
SHEET
1/1
1
2
3
4
A
B
C
D
E
F
G
H

C Weighted Pugh matrices

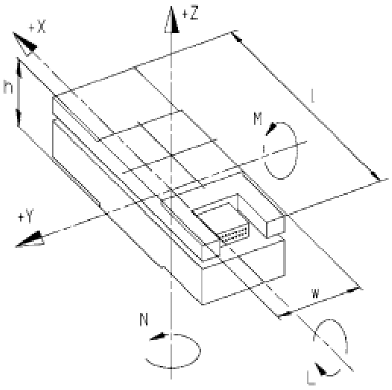
Frame

Importance 1-10	Function		REF	Sol. 1	Sol. 2
9	Stiffness		0	0	-3
5	Weigth		0	3	0
10	Adjustablility		0	-3	-2
4	Time to manufacture		0	-3	2
7	Manufactureablilty		0	-2	-4
			0	-41	-67
Reference: CNCed aluminum					
Solution 1: Carbon fibre spine					
Solution 2: Alunminum profile					

Body features

Importance 1-10	Function		REF	Sol. 1
6	Stiffness		0	0
5	Weigth		0	1
8	Adjustablility		0	0
8	Time to manufacture		0	-4
8	Manufactureablilty		0	-2
5	Strength		0	4
			0	-23
Reference: SLSed plastic				
Solution 1: Carbon fibre				

D Balance orientation



E Bearing life time calculation

```
clear all
close all
clc

% life time calculation ***************************************************
dh=0.165;   % wheel diameter
v=50;       % speed of moving ground system

% data for the SKF 6000* bearing
c=4.75;
c0=1.96;
pu=0.083;
f0=12;

fa=10;                      % axial pretention, too small to contribut
                            % to the equation according to the handbook

frlift=15.6;                % max lift from the cfd
frfs=15;                    % pretension towards road, estimated
frz=frlift+frfs;            % total force z-direction

frdrag=24;                  % max drag from cfd
frfriktion=8.8;             % frictional torque from skf engineering cat.
frx=frdrag+frfriktion;      % total force in x-direction

fr=sqrt(frx^2+frz^2);       % total radial force
fr=fr*2                     % safety factor of two


% speed
n=v*60/(pi*dh);

% bouyancy
b=f0*fa/c0;
e=fa/fr;

p=fr/1000;                  % conversion to kN

% life time
nc=0.7;                     % typical contaminated oil
t54=nc*pu/p;
a1=1;
askf=0.3;
Lnm=a1*askf*(c/p)^3
Lnmh=(Lnm*10^6)/(60*n)
Lnm8h=Lnmh/8
```

F Forces calculated from CFD

	Comment:	LIFT: [N]							
			tot	rw	fw	diff middle	wheel front	wheel rear	Duct
Sim3_wings1	First simulation with a front and rear wing. Duct1 is used		-275	-195	-90	-9,6	15,7	10,3	13,7
Sim4	Guiding plates on RW, two segment FW (duct2?)		-344	-200	-130	-30	9,3	11	2
Sim6_reference	No wings used, no sisdepod/duct, flat undertray		8	-	-	-8	13	-0,2	
Sim7_duct	FW6, RW23, Duct3, no channel diffuser. Ground clearence of the diffuser was 40 mm, 44 mm of the front wing.		-360	-212	-128	-20	9	14,5	2
Sim8	Right ground clearence + other stuff		-354	-186	-148	-23,6	7,9	14,6	-11,7

	Comment:	DRAG: [N]							
			tot	rw	fw	diff middle	wheel front	wheel rear	Duct
Sim3_wings1	First simulation with a front and rear wing. Duct1 is used		191	75	6,5	1	18,5	17	6
Sim4	Guiding plates on RW, two segment FW (duct2?)		200	80	11		14	21	5
Sim6_reference	No wings used, no sisdepod/duct, flat undertray		71	-	-	0	19	9,5	
Sim7_duct	FW6, RW23, Duct3, no channel diffuser. Ground clearence of the diffuser was 40 mm, 44 mm of the front wing.		210	95	15		12,4	24	6
Sim8	Right ground clearence + other stuff		193	75	16	3,4	11,8	21,6	6,48