Abstract

The objective of this project is to develop the chassis of an electric motorcycle that takes part in the international competition Smart Moto Challenge 2016, showing the work that has been done inside the e-Ride ETSEIB team. It focuses on the design of the frame and the swing arm, their FEM simulation and the manufacturing process to obtain them.

Design is done taking in account the different requirements that must accomplish the motorcycle, such as the components that must hold the structure or the desired geometry of the chassis. Final design not only includes the frame and the swing arm, but also all the commercial parts that form the chassis assembly: wheels, fork, suspension, brakes, bearings, handlebar, footrests...

The FEM study includes stiffness simulations of the frame and the swing arm in order to prove the dynamic properties of the motorcycle. It also has been considered several resistance simulations of the parts of the chassis that receive the higher loads to guarantee that they will resist any unforeseen critical stresses during the life of the motorcycle. All the simulations and the consequent optimization process have been done with the aim of keeping the weight of the tested parts as low as possible.

The manufacturing process of both frame and swing arm is explained with detail and has been proved by the manufacturing sponsor that is going to build these parts.

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1. Motivation

Since I was a kid I've loved cars and motorbikes and my dream has always been to work in the automotive industry. Being able to participate in the development of a vehicle that later will be on public roads is a feeling that I want to experience since I can remember. For that reason, when I finished high school, I decided to study this particular engineering degree. After a few years of tough work and nearly losing the faith that this degree had something to do with what I really liked, I finally came across with the automotive projects of ETSEIB: Formula-Student, Moto-student and Smart Moto Challenge. Last year, I finally decided to apply for one of them and I tried for the Smart Moto Challenge team.

I luckily was accepted and entered the dynamic department. I tried my best, as well as my mates did, but for reasons that are not relevant for this project, the final result wasn't as good as expected. In my department, we all were new and knew nothing about the chassis design. Moreover, we had no special tutor to guide the dynamic tasks, so the job was hard and inefficient. When the competition was over, I ended with a bittersweet taste because although we had made it to the race, we didn't make a good job.

For that reason I took the decision of following in the team the next year in order to design a proper bike this time; and as I was finishing my degree I saw I could center my final project on the development of the new chassis. This way, I could center myself even more and invest a lot of more time on this. Besides, a professor would guide my work and I could learn the real methodology followed by the industry. I saw I couldn't leave this opportunity that would benefit me as well as the rest of the team.

2. Objectives

The objective of this project is the design of the chassis of an electric motorcycle that will take part in the Smart Moto Challenge 2016. As the responsible of the frame in the team e-Ride ETSEIB, this project serves as a window to show all the work that must be done in order to obtain a reliable design of the dynamic part of the bike.

Although the motorcycle won't be ready when this project is defended, one of the main objectives is to have clear every single detail related to the frame in order to have a complete overview of the work. The idea is to embrace all the different stages of the chassis design, from conceptual design to the fabrication. However, the project focuses specially on the FEM simulation and optimization of the frame and the rest of structural parts of the bike in order to ensure the mechanical properties keeping the weight as low as possible.

Thus, this project should bring at its end a detailed design of the chassis that meets the given requirements, that passes all the simulation tests and that is ready to be manufactured.

It is remarkable that this project has another underlying objective a part from the ones mentioned before: it's a document written for the future members of the e-Ride ETSEIB that will face the same challenge of designing the chassis of a motorcycle from scratch. It is almost impossible to obtain a good result if every year, with every new edition, the unexperienced new members have to figure out which are the different tasks that must be done and how they must be done. For this reason, this project is done to transfer the know-how and set the basic guidelines for a proper chassis design.

3. Scope of the project

The scope of this project couldn't be well understood without knowing first how the team works and which are the competences of the members. e-Ride ETSEIB is a group of 12 students and each one has his own responsibilities: some take care of the powertrain, others write code for smart components, other manage the treasury... In my case, I am responsible of the structure of the motorcycle. The competences of each member are well-defined and although there's a good feedback between departments, they cannot be transgressed. This means that the particular decisions of the different departments must be taken inside the particular department. However, general decisions that concern all the team must be taken by all members and because the development of an entire motorcycle is a very complex and interdisciplinary activity, the particular decisions of a department usually affect the rest.

This project shows my particular input in the totality of the team and, according to my responsibility, this means the development of the chassis. The scope of this project, thus, involves all the different tasks that have to be done to accomplish that goal. Roughly, these tasks include the study of the structural requirements of the bike, the design of the frame and the swing arm, FEM simulation and optimization, the election of the other components that are part of the chassis and the definition of the fabrication process.

As it's been already said, the design of the entire motorcycle is an interdisciplinary activity and throughout the development of this project, the barrier of other departments has been reached in several occasions and some particular suppositions have had to be taken in order to progress with the work. However, these suppositions have always been recorded and justified in this project.

4. State of the art

4.1. The evolution of motorcycle frames

Although some people may point that there were other inventions before this one, it is widely considered that the first motorcycle was introduced in 1867 by French blacksmith Pierre Michaux and his sons. The main goal they were looking for, was to replace the human power needed to move a bicycle in order to improve the machine's performance and the rider's comfort as well; to accomplish that, they mounted a steam engine over a velocipede. In terms of the chassis, this motorcycle was made of wrought iron tubes and there were no suspensions nor tires because they weren't invented yet.

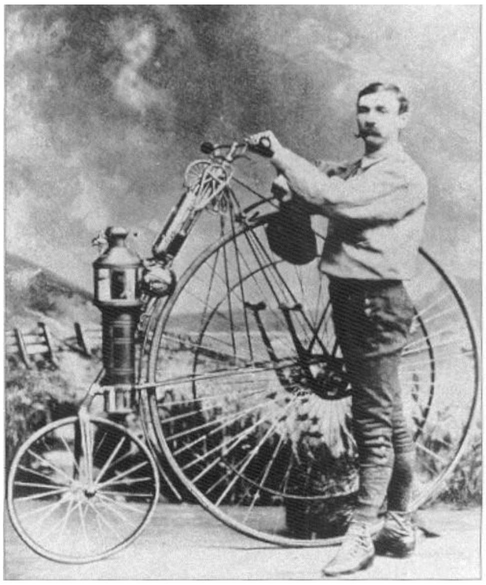


Fig.1 Pierre Michaux and his motorcycle

From that moment on, many industrial manufacturers decided to design their own motorcycle adapting the chassis of a velocipede. But it didn't took long before they realized that the geometry of a velocipede didn't fit with the performance that a steam engine could give, and as technological advances overtook, they started to modify proper bicycles. What they mainly did was introducing a cradle in the typical steel tube diamond structure of a bicycle to accommodate the engine. Ignoring obvious differences, it's not difficult to see that this kind of frame is not far from current double-cradle structures.

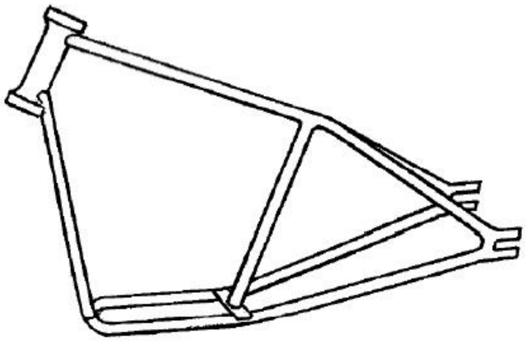


Fig.2 Common cradle modification in a diamond frame

During the late 1870's and early 1880's, technological advances in combustion engines enabled the possibility to apply these sources onto motorcycles. One of the most significant inventions was called *"Petroleum Reitwagen"*, designed and built by Gottlieb Daimler and Willheim Maybach in Germany in 1885. It was the first motorcycle powered by a gasoline internal combustion engine. Although it became an inflection point for its advanced engine, the cycle part of this motorbike wasn't so noticeable: the frame was made of wood and it still didn't have any shock absorber (also called dampers).

Fig.3 Petroleum Reitwagen replica

Another important milestone is the first production motorcycle, known as *Hildebrand & Wolfmüller .* It was first launched in 1894 in Germany and it became a real advance in comfort, reliability and performance. It was powered by a liquid-cooled four-stroke gasoline engine and, although its fork and rear axle were rigid, it incorporated pneumatic tyres. The chassis had nothing to compare with a diamond bicycle one and it was made of steel tubes.

Fig.4 Hildebrand & Wolfmüller motorcycle

Despite the climax of electric motorcycles hasn't happened yet, and unlike most of the population may think, the design and development of the first electric motorcycles happened almost in parallel with the internal combustion engine ones. Although the real origin is somewhat untrue, the first patent of an electric motorcycle was introduced in 1895 by Ogden Bolton Jr. in the U.S.

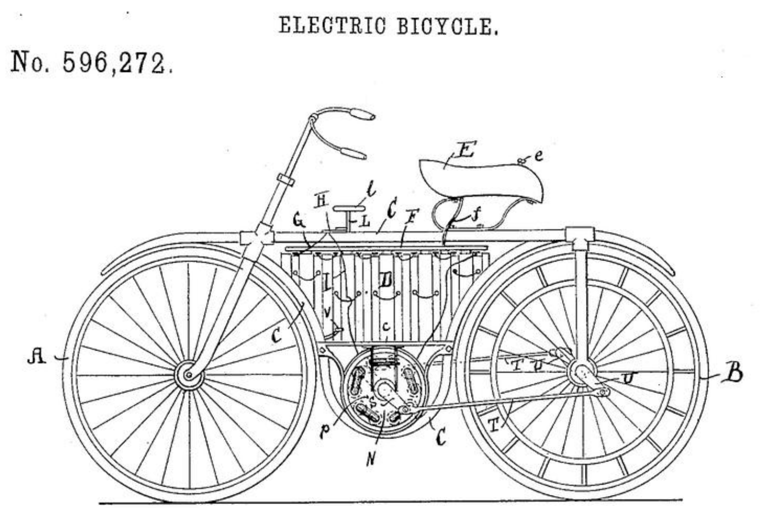


Fig.5 Patented drawing by Odgen Bolton Jr.

With the entrance of the new century, manufacturers started creating motorcycles with specific bodywork and wider wheels to mark aesthetically the difference between motorbikes and simple bicycles. Bigger engines were mounted and the increase of power required stiffer structures: the double-cradle frame and other tubular steel geometries appeared.

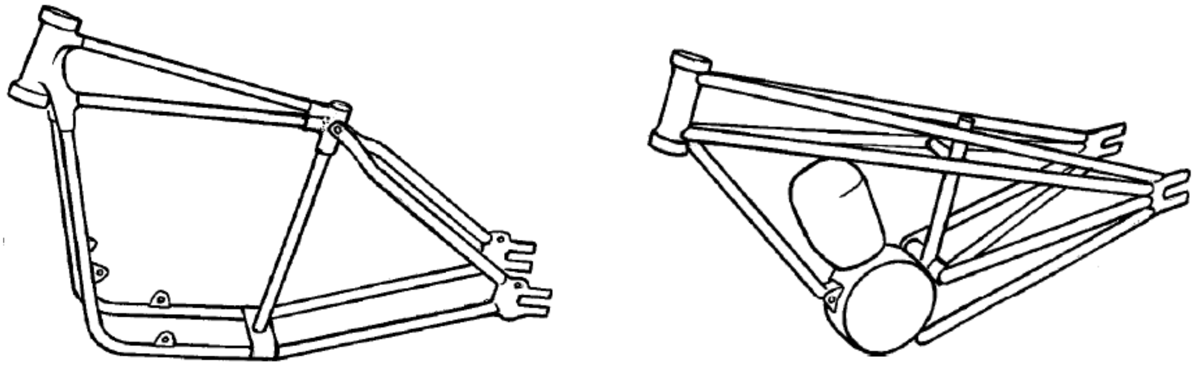


Fig.6 Double-cradle frame (left) and early triangulated frame (right)

During WWI, motorcycles became really useful because they were smaller, simpler and cheaper to run than cars; that helped them get consolidated in the market afterwards. Nevertheless, people noticed that they weren't very comfortable, especially because roads were in bad conditions and all the irregularities and bumps got absorbed by the rider. To solve that problem, manufacturers begun gradually to incorporate suspension systems in the fork (trailing link, leading link,...) and a swing arm with other kinds of systems in the rear axle (plungers, shocks...) .

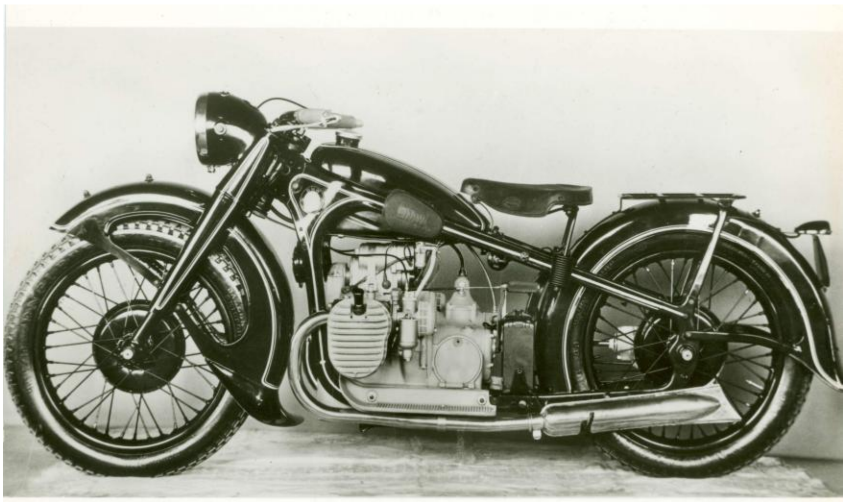


Fig.7 BMW R12, the first motorcycle to mount a telescopic fork

In 1939, BMW launched the first motorcycle with a telescopic fork; nowadays it's the most common choice for manufacturers, due to its simplicity and good features. It's curious that one of the brands that don't usually install this kind of forks in current motorcycles is BMW itself.

After WWII until the 1960's European and American brands expanded their market and consolidated as the cutting edge of the motorcycle sector. With each new motorcycle designed, a new quality standard was described in terms of power, style and reliability. Many advances and inventions were made during this period. As a matter of fact, in 1968 Spanish manufacturer OSSA built a racing motorcycle with a monocoque structure made of magnesium, in which the fuel tank and the most part of the bodywork constituted the frame itself.

Fig.8 OSSA grand prix 250c.c. with monocoque

But in the early 1970's, Japanese manufacturer Honda introduced in the market motorcycles with much more sophisticated engines that were also more reliable and affordable. These motorcycles contributed nothing new related to the chassis: double cradle frame, telescopic fork and double rear shock. Nevertheless, it didn't stop buyers from getting one because soon, Japanese manufacturers became the most popular option.

The last most significant event in the history and evolution of motorcycle frames takes place in 1982 when Antonio Cobas, a Spanish race technician, designs and builds a new kind of chassis that had never been thought before: the double aluminium beam frame. This fact is very significant because this type of frame has been used from that moment in the very most part of race and sports motorbikes.

Fig.9 Antonio Cobas' aluminum prototype

As science and technological advance never ceases, the design and manufacturing of motorcycle frames has never stopped evolving. With the appearance of new materials and manufacturing processes, this sector takes advantage of all these possibilities and is constantly improving. Nowadays, the most innovative brands are studying the application of high resistance composites such as carbon fiver or honeycomb structures.

4.2. Current types of frames

After all the evolution shown in the past chapter, nowadays it's possible to see new motorcycles with a lot of different frame structures; In opposition to what some people might think, the vast majority of current bikes have mounted a kind of frame that has been used during dozens of years; however, the incorporation of new materials in the automotive industry and the new manufacturing processes have brought to the market some cutting-edge creations. Like it always happens, these creations are incorporated only in the high-end brands; for the rest of costumers, one of the classic structures is the only option.

Here are presented the main types of frames that can be found nowadays on a new motorcycle:

-**Scooter frame:** the characteristic shape of scooters in which there is a flat platform to carry things between the seat and the handlebar turns the design of the frame into a real nightmare for the engineers. The result has always worse resistance and stiffness than any other kind, and it is always heavier. Normally it is made by steel tubes.

Fig.10 Scooter and scooter frame

-Single cradle frame: it's the simplest type of frame and it is used for small and off-road motorcycles. It is made of steel tubes; from the steering head one tube goes down to form a small cradle that usually holds a single cylinder engine and the other goes directly to the spine. The mechanical properties and relative weight aren't precisely good.

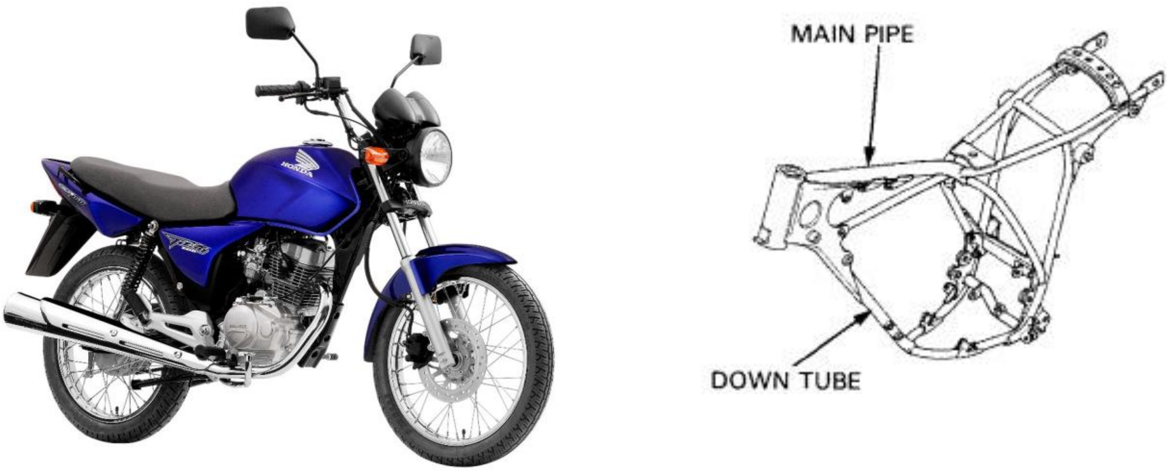


Fig.11 Motorcycle with single cradle frame and drawing

-Double cradle frame: it's the evolution of the single cradle and it is used for bigger and more powerful motorcycles; instead of having a single tube going down from the steering head, here there are two. It's made of steel as well and its properties are decent but do not stand out.

Fig.12 Motorcycle with double cradle frame and drawing

-Twin beam (or twin spar): this one presents one of the best mechanical properties and it's usually made of cast aluminum or extruded profiles. For this reason, it is the common option for the greatest part of sports motorcycles. Normally it consists of two structures that go from the steering head to the swing arm axis, surrounding the engine (in case of having one). The part that holds the seat, the subchassis, is normally made of steel and is attached to the frame with screws and bolts.

Fig.13 Motorcycle with twin spar frame

-Trellis: this one offers mechanical properties that are similar to the twin beam and has a similar weight. The main idea is also the same: a structure that goes from the steering head to the swing arm axis surrounding the engine. But in this case, the structure is formed by a triangulation of thin steel tubes. As it can be seen, one of the main problems with this kind of frames is the complexity of fabrication.

Fig.14 Motorcycle with trellis frame

-Monocoque: these frames are not very common, especially for street motorcycles, because the fabrication is really complex and the materials involved tend to be more expensive. The idea of this frame is to have structural bodywork; components like the fuel tank, the seat or the tail become structural. The first ones were made of aluminum but nowadays it is usually made of carbon fiber.

Fig.15 Racing motorcycle with monocoque

4.3. Electric motorcycles

The ever-changing nature of industry has finally understood that our dependence on fossil fuels cannot last forever because it is running out. For that reason, during the past few years, the different automotive brands have put a significant amount of their time and money in the development of vehicles that could use another source of energy to run. Different options came out but it seems that the future passes through the electric. It's true that the details of that future remain uncertain: are we going to relay on Li-Ion batteries? is the hydrogen cell an effective solution?...But the common denominator is electricity.

Maybe these questions will take time to answer but meanwhile, there are already viable options in the market and possibly in the future, they will be seen as the first step to the change.

In this chapter, some of the most representative electric motorcycles that are now in the market are shown. The intention here is to manifest that the change of powertrain has meant a real challenge for engineers in terms of chassis because electric motorcycles present different mechanic requirements that must be satisfied. For instance, the combustion engine was usually part of the whole structure and improved a lot the overall mechanical properties; in electric motorcycles this feature is no longer possible. The fuel tank disappears as well and, in some cases, even the transmission is eliminated because the motor is in the wheel. Because this market is still very young, the different brands offer a very diverse range of options to solve these new requirements and it is interesting to comment them here.

-Zero SR: Zero is one of the biggest manufacturers of electric motorcycles and has been in this market for a long time now. The SR model is the most powerful they offer and presents a really impressive performance. It has a direct transmission without gears that transfers directly the power from the motor to the wheel trough a belt. The frame is a cast aluminum twin-beam with double cradle that embraces a box where the batteries are placed.

Fig.16 Zero SR

-Bultaco Rapitan: after years of disappearance, Bultaco has reborn with the aim of building electric motorcycles. The Rapitan is still not available but it is meant to be on the marked very soon. With this bike, Bultaco wants to show to the world the capabilities of the new brand. It is a very uncommon bike in all aspects. In terms of chassis, the highlights are the steel trellis frame and the front telelever suspension.

Fig.17 Bultaco Rapitan

-Brammo Empulse R: Brammo has been developing racing electric motorcycles for a long time and during the past years, has introduced in the market different road models. This one in particular is the direct competitor of the Zero SR, although the approach is different. This one is the only commercial electric motorcycle that has a classic transmission of six gears with clutch. Some people think that it is totally unnecessary because the motor is capable of taking off even in sixth gear and the clutch is only used when the bike is moving; however, Brammo is proud of offering a *real* electric motorcycle and not a scooter. The frame is an aluminum twin beam that embraces and holds the batteries and the motor.

Fig.18 Brammo Empulse R

-**Volta BCN:** this Catalan company has just launched their first bike, the BCN. The frame is based on the classic design of the double-cradle and the battery goes where the engine was normally mounted. This decision, among other, has made possible to have a final price a lot lower than the competitors.


Fig.19 Volta BCN

-BMW c-evolution: this bike is really a game changer in terms of chassis because the frame is in fact the housing of the batteries and all the other components (seat, fork, suspension, swing arm...) are attached to it; that is, a structural battery. BMW has been the first, and for the moment only, manufacturer to accomplish this kind of frame has meant a revolution in the industry.

Fig.20 BMW c-evolution

-Mission RS: this motorcycle is done by a very small company in California and represents an exercise of power to show the possibilities that can offer an electric bike. The frame is a strange combination of steel trellis structure and huge aluminum milled parts. Besides, engineers managed to introduce the electric motor to the structure. The transmission is direct through chain and the most part of the fairing is made of carbon fiber.

Fig.21 Mission RS

4.4. Smart Moto Challenge 2016

Here is presented the aim of the competition and the main highlights of the regulation that affect to the chassis' design. For further reading, it is possible to download the whole document of rules of the Smart Moto Challenge 2016 at www.smartmotochallenge.org.

Smart Moto Challenge is an international competition in which universities around the world design, build and test an electric smart motorcycle. It focuses on the performance of the motorcycle itself, but also on the product development and production plan. Every edition the purpose of the competition changes slightly and this year in particular, universities have to make a motorcycle for the local police department.

The competition takes place in the facilities of the *Circuit de Catalunya* and different tests are carried out during the weekend: first, motorbikes must past a common technical inspection, for they must be ready to ride on public roads. After that, motorbikes are tested in the dynamic events to proof its capabilities; these events consist on drag races between teams, a timed lap through a closed circuit, a timed lap through cones and an endurance race. Finally the project plan is presented and defended in public.

In conclusion, Smart Moto Challenge is a fantastic platform that encourages the technological development of electric mobility and signifies the first step to the automotive industry in the career of the competitors.

Fig.22 Poster of the competition

5. Design requirements

5.1. Geometry of the chassis

When developing a motorcycle chassis one of the most remarkable points, if not the most important one, is the design of its geometry. There are some characteristic measures in a motorcycle that determine its handling, responsiveness, maneuverability and stability; so it's important to have them clear from the beginning of the process, to finally obtain a chassis that suits the requisites that we're looking for. Coming up next, a presentation and short explanation of the main measures of a motorcycle is done:

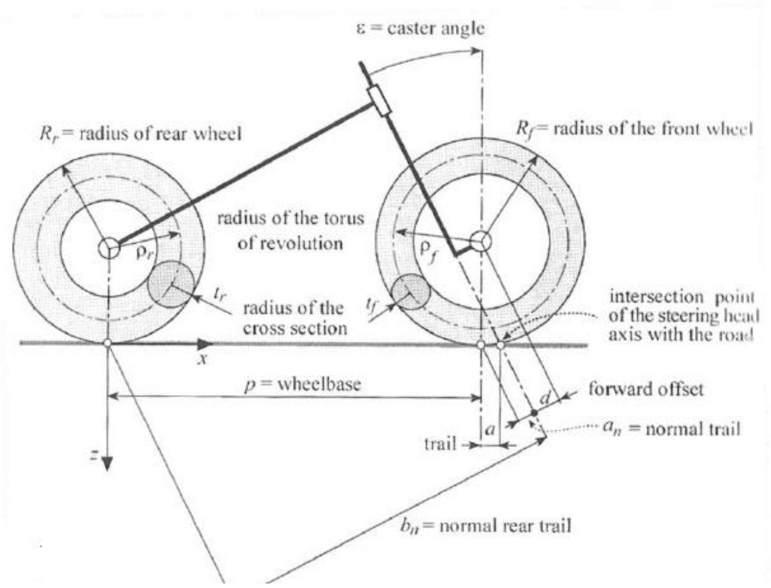


Fig.23 Scheme of the main dimensions of a motorcycle (*Motorcycle handling and chassis design, Tony Foale*)

-Wheelbase: It's the distance between the contact points of the tires on the road. Its value varies from 1200mm in small scooters to 1600mm in customs and touring motorbikes. The increase of the wheelbase implies:

·A higher flexional and torsion deformability of the frame.

·A higher turning radius, which worsens the maneuverability.

·A higher directional stability at high speeds.

-Caster angle: It's the angle between the vertical axis and the rotation axis of the fork. It affects to the inclination of the wheel that happens during steering, which is directly related to the hardness of the direction and its responsiveness; normal values of the caster angle are between 21º in sports motorcycles and 30º for touring motorcycles.

-Trail: It's the distance between the contact point of the front wheel and the intersection point of the steering head axis with the road measured in the ground plane. It has a deep relationship with the caster angle because the change of one of these measures can't be done without the change of the other. It affects to the stability of the front end in straight line conditions: the higher the trail is, the higher is the returning moment of the steering that self-aligns the wheel. Normal values of the trail vary between 80mm to 120mm.

Keeping the importance of these dimensions in mind, it's time to choose their values according to the performance that is going to have the motorcycle. Due to the characteristics of the races, the most important requisite of the motorcycle is that it has to be very responsive and has to be able of turning tightly; this traduces into a short wheelbase and a slightly small caster angle. Because it won't be very powerful and won't reach high speeds, the possible stability problems of having a small caster angle (and trail) won't appear. However, in order to have a coherent whole, the particular election of these dimensions has not been taken freely; they have been taken from a commercial motorcycle that suits those characteristics. Yamaha TZR50rr is a small sports bike with specifications that are similar to the ones that will have our motorcycle. It has a short wheelbase of 1330mm, a caster angle of 25º and a trail of 92mm.

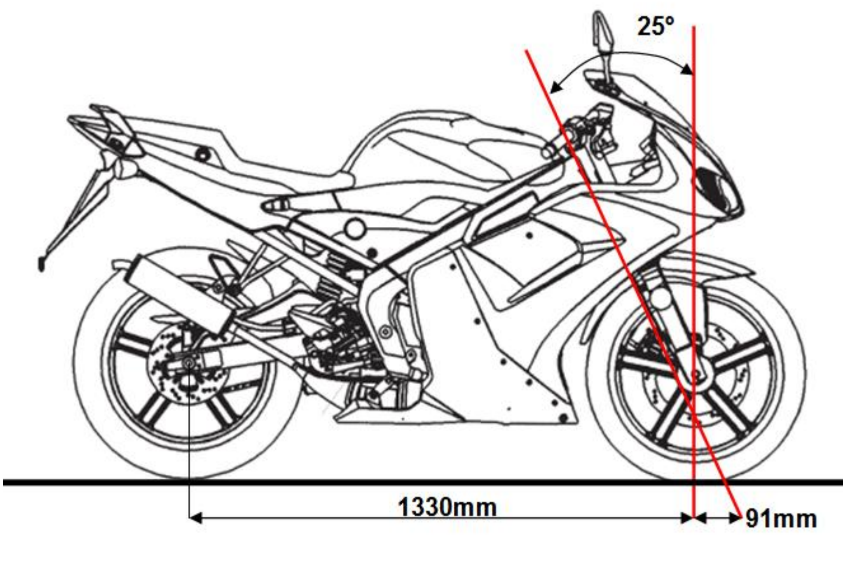


Fig.24 Main dimensions of the Yamaha TZR50rr

This decision makes the design a lot easier, and unlike some may think, is a common strategy in the automotive industry when creating a new model; manufactures always try to deduce and copy the geometry of competitors in a process called inverse engineering so as to achieve a similar handling performance. Furthermore, basing the geometry of the motorcycle on one that is already in the market enables the possibility of using spare parts of this bike to create a coherent chassis that has no incongruence. This, of course, can be done in this case only because it's a prototype; if it was a final commercial bike, all the components would be specially manufactured for the company. In this case, as it will be presented later, the size of the wheels, the braking system and the fork are taken from this Yamaha TZR50rr.

Fig.25 Yamaha TZR50rr

5.2. Ergonomics

Although the Yamaha TZR50rr is a good model to look to in terms of handling, there's an important aspect that doesn't fit with the target of our motorbike: ergonomics. The ergonomics of a motorcycle are defined by the triangle formed by the rider's seat, handlebar and footrests. It's important to mark that this triangle, in fact, is not in 2-D but in 3-D, which means that the width of the motorcycle is an important factor in terms of ergonomics. However, for this project, it has been considered that the 2-D triangle with the hypothesis that the width of the motorcycles treated are alike.

The ergonomics of the Yamaha TZR50rr are too sporty for the final target of our bike: the rider takes a forward position and the footrests are set in a very backward position; this enables a better control of the bike and reduces aerodynamic drag force but entails a not very comfortable position if the bike has to be ridden a few hours because it causes a lot of arm fatigue when braking and lumbar pain.

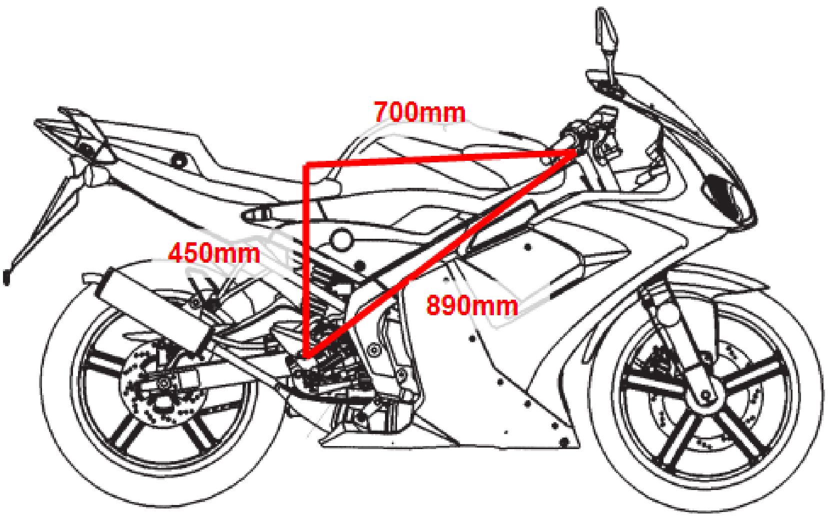


Fig.26 Ergonomic triangle of the Yamaha TZR50rr

To solve this problem, another commercial motorcycle has been considered: the Honda Varadero125. It's a comfortable touring bike with a relaxed position for the rider that, even it's more powerful than the Yamaha, it has a similar width. Looking at its ergonomic triangle, it's easy to see the difference between both bikes.

Fig.27 Ergonomic triangle Honda Varadero 125

Hereby, the goal that has been but in terms of ergonomics is to obtain a ergonomic triangle similar to the one that has the Honda. It won't be easy to adapt the geometry of the Yamaha into these specifications but the position of the handlebars, footrests and seat can vary slightly without much change in the frame of the bike.

5.3. Mass distribution

If there's another important factor that defines the handling of a motorcycle a part from its geometry, it is the mass distribution. Depending on the position of the center of masses and its moments of inertia the performance of a motorcycle can vary a lot. It must be said that the overall features of the motorcycle cannot be defined only with the physical properties of the bike because the mass of the rider cannot be neglected. However, the control over the mass of the rider is very low in a road motorcycle because the range of weights that the possible riders could have is too large; the only thing that can be slightly controlled is the relative position of its center of masses through the design of ergonomics. As the ergonomics of this bike have already been defined and are not done to satisfy a sports riding, the object of this chapter will focus on the mass distribution of the bike alone.

The first idea is simple and clear: the bike has to be as light as possible. Given certain acceleration, the lower it is the mass, the lower it has to be the force applied to achieve the acceleration. Reducing the weight improves the performance of the bike in any condition: it makes it faster, easier to ride, cheaper to run, more reliable.... However, it is the hardest goal to achieve.

In terms of handling, the position of the center of masses affects mainly to the turning easiness of the bike; that is the ability to lean the bike to go through a curve. Literature shows that motorcycles present two different instantaneous rotation axis when the leaning happens: one takes place in the begging of the turn for a short period of time and goes from the point of contact with ground of the rear wheel to the swing arm pivot (IRA 1); then it changes until it becomes the second one, which passes through the center of both wheels (IRA 2).

Fig.28 Scheme of the instantaneous rotation axis

The basic idea of mass distribution to obtain a nimble and easy to lean bike is to center the masses as much as possible to the instantaneous axis's; that means, having a low moment of inertia respect the IRA1 and IRA2. However, it is not indistinct if the masses are over or under the rotation axis; if there's a mass over the IRA, it will help the force that makes the rider to lean the bike but if it is under it, the opposite effect will take place. To simplify as much as possible the objective of mass distribution, the IRA1 is usually neglected because it appears during a very small period of time.

Having this clear, when it comes to the design of the bike, the heavier components of the bike should be as near as possible to the imaginary line that create both wheel centers and trying to avoid putting them under it. For the heaviest components of the motorbike are the electronics of the powertrain (battery pack, supercap pack and ECU), the most suitable place for them is there.

5.4. Powertrain components

Although the design and implementation of the powertrain stays out of the scope of this project it signifies a very important boundary condition when designing the frame of the bike; it must be clear where the components are going to be placed, its restrictions, its approximate weight... For the design of the powertrain is always evolving and it will not be totally clear until it's physically carried out, it will not be possible to specify in this project all the electronic components that will be on the bike. Nevertheless, it has been possible to specify the main ones that will affect to the design of the chassis; here are presented:

-Elmoto motor: it's a brushless AC motor with 2kW of power, a torque of 28Nm and a voltage of 48V. These values are for nominal and static conditions but electric motors can handle much higher voltages or currents during a certain period of time. It's a HUB motor, which means that it must be attached directly on the wheel without the need of any transmission. The rotor is fixed in the axle and the stator is set to the rim and makes the wheel turn through the spokes. It has an approximate weight of 8kg.

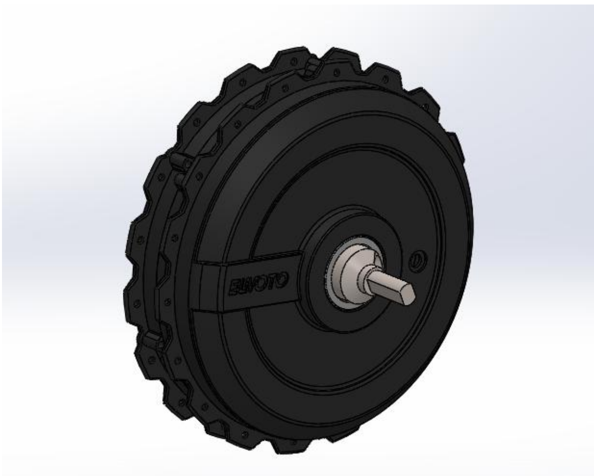


Fig.29 Picture and 3D CAD of Elmoto HUB

-Kelly KBL 48101: it's the controller of the powertrain and manages the current that goes from the batteries to the motor. It weighs about 3,5kg.

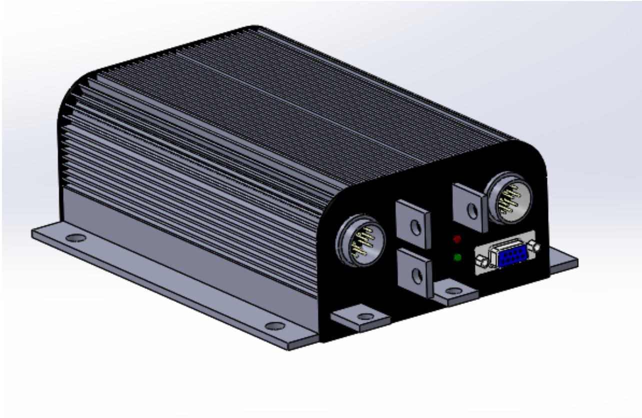


Fig.30 Picture and 3D CAD of Kelly controller

- Elmoto battery pack: it is supplied by the competition and it's formed by Li-Ion cells (Panasonic CGR-18650CG) connected in parallel inside stacks (14 cells each stack). These stacks are connected then in series to create the entire battery pack. It has a nominal voltage of 46,8V and a capacity of 31,5Ah. The total weight is 15kg.

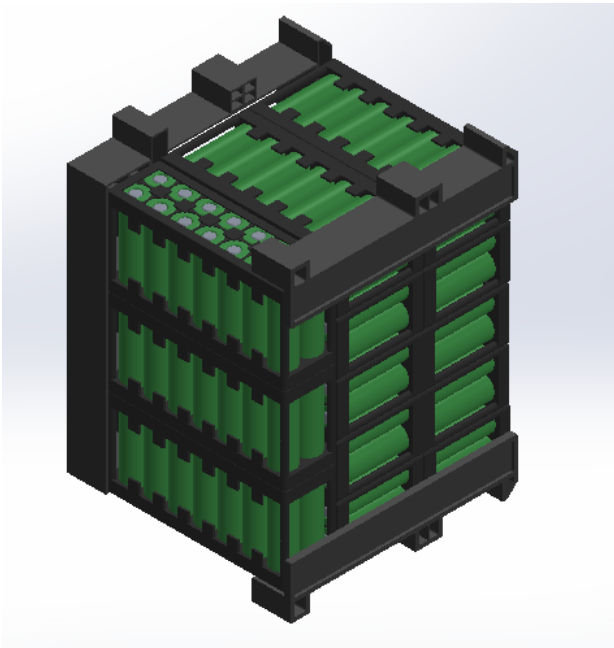


Fig.31 Picture of one stack and 3D CAD of all the battery pack

-Supercapacitor pack: supercaps are used in powertrain applications because they can deliver a high amount of current during a certain period of time, which translates into a "boost" of torque in the motor. Furthermore, they can be used to store the energy that recovers when braking, which makes the bike more efficient and increases its mileage. The supercapacitor pack will consist on 60 supercaps LSUC 350F with 2,5V organized in 5s12p. It weights 6Kg.

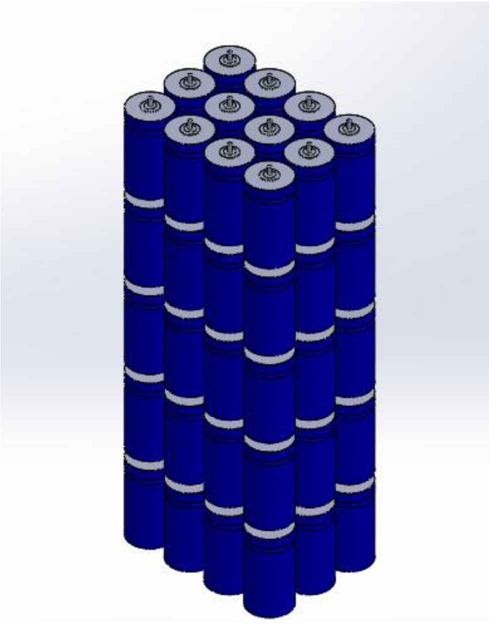


Fig.32 3D CAD of the supercapacitor pack

Other components must be taken in account despite not knowing exactly their shape, weight or the amount of them that will finally be in the motorcycle; these components might be Arduinos, wires, connections, relays... For this reason, the chassis must guarantee enough room for them.

5.5. Manufacturing limitations

A good product designer always draws having in mind which will be the manufacturing process with which the geometry will be done; in this project in particular, this idea has been followed strictly because it will *really* be carried out physically. The manufacturing process of the frame, swing arm and subchassis, among others, will be done by the team's sponsor ISMOTIVE BCN www.ismotive.com, a medium sized company located in

Sant Fruitós del Bages that specializes in metalworking and welding. They manage to obtain the materials needed and work them to obtain the final parts. Although they offer a very wide range of manufacturing processes and almost any geometry could be done, it's important to list them in order to know the limitations of the design:

-laser cutter

-water jet cutter

-electrical discharge machining

-band saw

-bending machine

-CNC milling machine

-drill

-CNC lathe

-TIG, MIG, electrode and arc welding of all materials.

Fig.33 Company logo

From the list of above can be seen that pretty much any geometry could be done to design the bike. However, it's important to mark that because it's a prototype, other manufacturing processes that are used in series production motorcycles are discarded, like casting.

In terms of raw materials, they are in contact with several suppliers that can offer from commercial structural profiles to vast pieces of metal to machine. As a matter of fact, the design of the bike must be done taking in account the availability of these materials and profiles.

Finally, and as a personal point, it's remarkable that all the work that is done in ISMOTIVE is done in reward of the sponsorship with the team, and no cash charge is done for all their work; with that being said, the manufacturing process should be as simple as possible so as not to abuse of their kindness and guarantee their participation with our team in the following editions of the competition.

6. Final design

6.1. Introduction

In this chapter the final design of the chassis is shown and explained. The main idea is to have clear every single component that is going to form the body of the bike. The frame, the subchassis and the swing arm constitute de basic parts of the chassis and have been developed for this project; however, other important parts of the chassis assembly such as suspensions, wheels or braking systems are spare parts or components from other companies and have been incorporated in this final design. It's remarkable the fact that the design of bodyworks is out of the scope of this project, and components such as the false fuel tank, the fairing that covers the powertrain box and the subchassis, the seat... have not been introduced nor considered, including the possible appendixes to hold them.

Fig.34 Renderings of the final design of the chassis

6.2. Frame

The type of frame that has finally been chosen has been the twin beam of aluminum. Different options were considered in the beginning: single cradle, double cradle, twin beam, trellis... but due to the low performance of the rest of options, the final decision stayed between the aluminum twin beam and the steel trellis. Discarding other expensive options that involve composites materials or that carry a very difficult manufacturing process, for example in a monocoque, these two options present the better relationship between stiffness, resistance and weight. Finally, after getting in contact with the manufacturer, the steel trellis was discarded as well; one of the reasons was that, in terms of welding, the process is much tougher because it involves a much complex jig. The second reason was that the range of steel qualities available for the sponsor wasn't very wide and the highest resistance they could provide was the S355JR. That made the decision even easier because the steel trellis that are able to compete against the twin beams are made of high resistance chrome-molybdenum steel. And finally, the third reason was a matter of packaging; the twin beam presents a structure more suitable to introduce a powertrain pack, as it we'll be shown further on. The particular alloy used is 6063T5.

As it was explained before, the design of the chassis has been based on the geometry of the YAMAHA TZR50rr; the wheelbase has a size of 1330mm, the caster angle is 25º and the trail is 91mm. The whole design process has been around these dimensions.

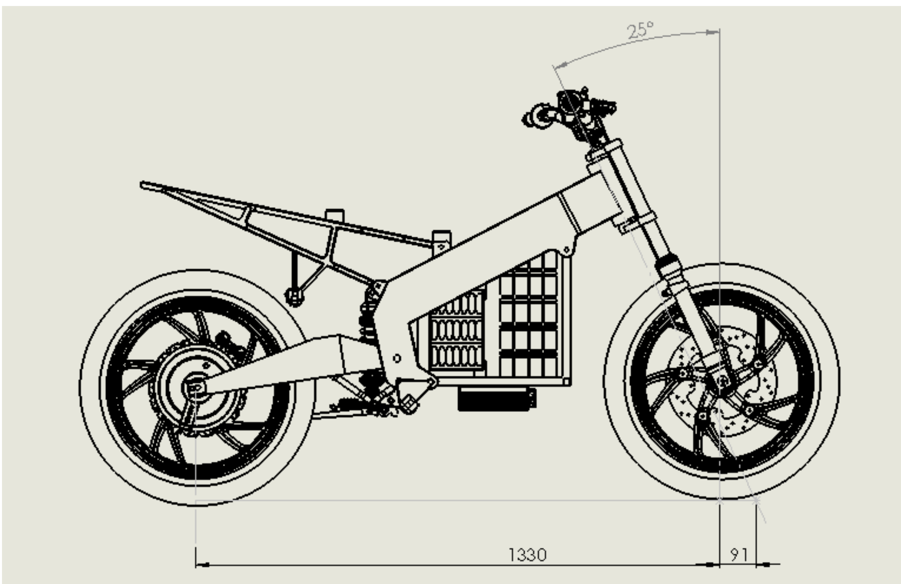


Fig.35 Main dimensions of the frame

One of the main intentions of the design of the frame was obtaining a good place for the electronic powertrain components, which constitute the biggest weight that has to hold the frame. With this design, these components take the place where the combustion engine is normally attached in classic motorcycles; this way, the greatest amount of mass is very near to the instantaneous rotation axis of the leaning bike which will make it more nimble and easy to ride. The only difference with a combustion engine bike is that batteries are not structural and need an auxiliary body to hold them and improve the overall mechanic properties; in the case of classic ones, the engine is normally attached to the frame with bolts and, because the engine is usually a heavy block of steel, it improves a lot the stiffness of the frame. In this case it has been designed a double cradle of aluminum that is attached to the frame with two steel bars that are threaded in the ends to put nuts.

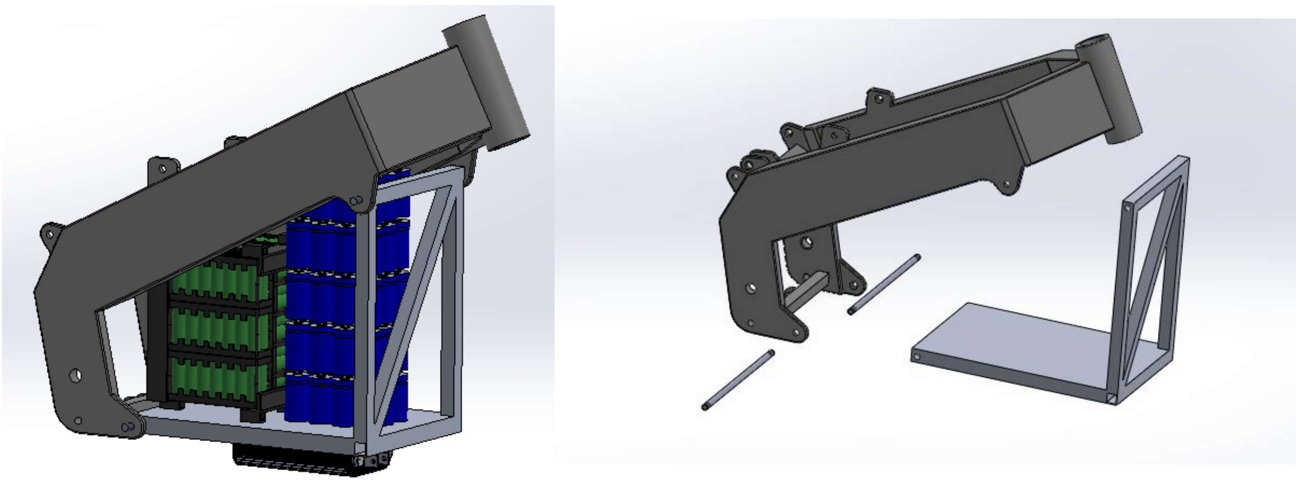


Fig.36 Frame with the cradle and powertrain components (left), Disassembly of the cradle (right)

This way, the powertrain can be easily assembled and disassembled from the chassis. The cradle has been designed to have enough room for the biggest components (batteries, supercapacitors and ECU) and still leaves space for cables and other possible small components. The floor of the cradle is flat and allows the attachment of these components. The ECU is placed under the cradle with screws because it is one of the parts that need more refrigeration and a good design of the fairing will easily rise the amount of air flow that goes under the cradle. Inside, there's the supercapacitor pack and the battery pack and both can be attached to the flat floor through belts and brindles. The battery pack, which weighs more than the supercap pack, is located nearer to the swingarm pivot axis to center as much as possible the masses; meanwhile, the second one has a bigger height and fits perfectly in this forward position of the cradle.

Another particularity of the frame is that it is not strictly necessary to disassemble the cradle to remove the powertrain components; it's been designed to have the chance to access from the top, with the only condition of removing the false fuel tank before; this way, the process is much easier because it's not necessary the tedious work of lifting all the powertrain (near 30kg) and aligning the holes in order to introduce the bars.

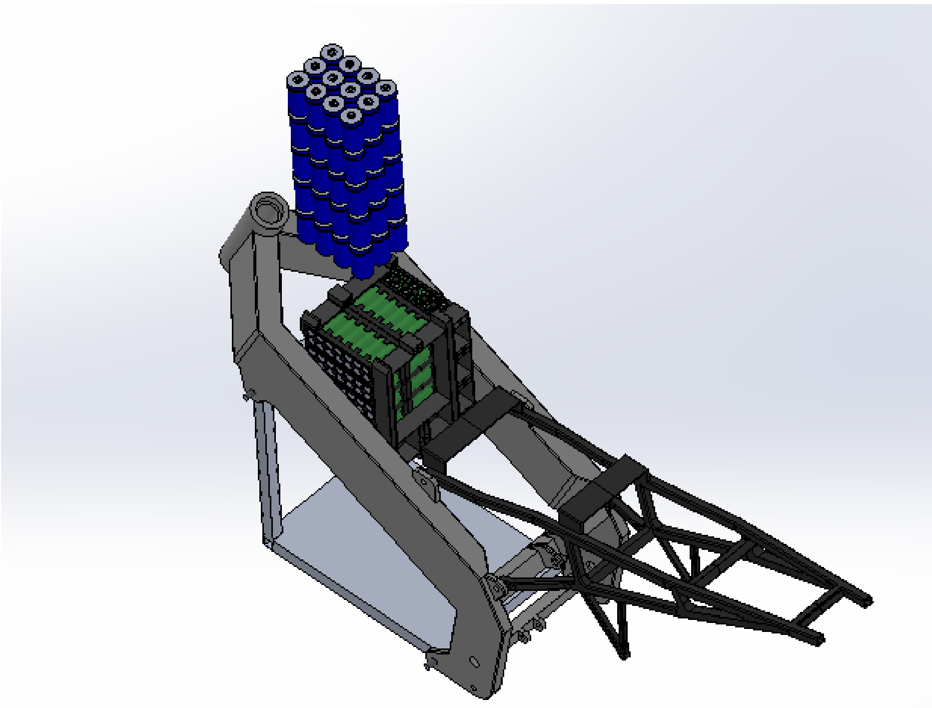


Fig.37 Top disassembly of the powertrain components

6.3. Subchassis

Like in the great part of motorcycles with a twin beam aluminum frame, the subchassis is not welded to the frame and it's made of steel tubes. In this case in particular, the alloy used is S355JR. Although the final result could be a little heavier than if it was made of aluminum, using steel ensures that the structure won't be too big because it has a stiffness/volume ratio much bigger; thanks to this fact, it will be easier to cover the subchassis with fairing. For steel and aluminum cannot be welded, the subchassis is held in the frame with the help of screws and bolts. Furthermore, this fact makes the welding process more effective because the work becomes more manageable, thermal tensions can be more easily controlled and the final result usually has better tolerances. It's been designed to carry the rider and an occasional passenger and incorporates a structure to place the passenger's footrests. On its top, there are a couple of plates that are designed to fit the seat; as it can be seen, the position of the subchassis will have a strong effect on the overall ergonomics of the bike. The approximate height of the seat will be 800mm, which is not particularly low, but the structure is very narrow, which signifies that a standard rider would be able to control the bike without any problem.

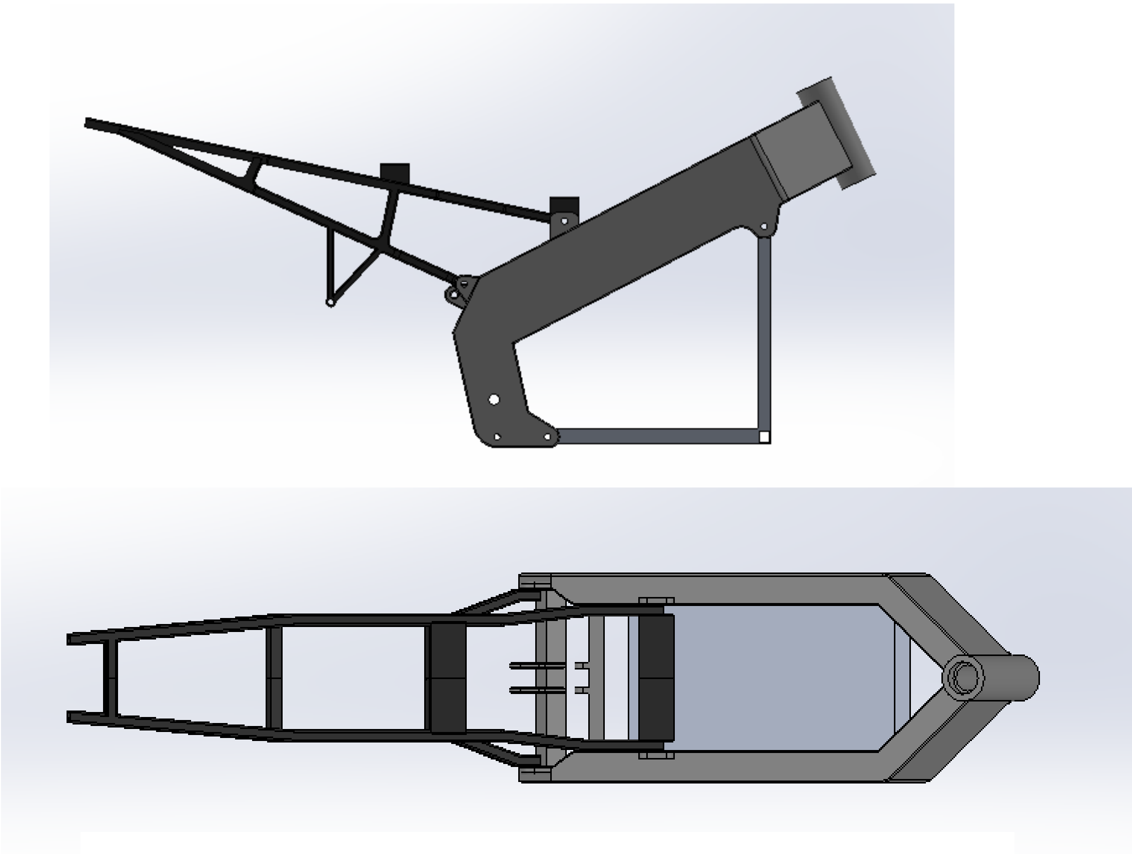


Fig.38 Front and top view of the frame-cradle-subchassis assembly

6.4. Rear suspension

In order to obtain enough space for all the components, the election of the right type of rear suspension has been a real challenge. The packaging doesn't leave much space for the shock and standard systems in which the mono-shock is attached directly from the swing arm to the frame were literally not possible to introduce in the design. On the other hand, the option of introducing an old-school dual-shock suspension that goes from the wheel axis in the swing arm to the subchassis wasn't very appealing due to the increase of weight that it would involve and the low performance that present these kinds of systems. For this reason, the only option that could fit was a mono-shock suspension system with rockers.

This system consists of a single shock that is attached to the frame in the superior part and the part of below is attached to a couple of rockers; one of these rockers is at its time set from the other extreme at the frame and the other one is fixed in the swing arm. All the fixations are done with screws and bolts, allowing relative rotations between bodies (if the bodies were bonded, there wouldn't be any shock-absorbing effect) . It's a sophisticated solution that makes the calculation of the parameters of the shock far more difficult and needs a specific multibody simulation; however, finding those specifications is not part of the scope of the project. In addition to the benefits in the packaging, the shock is placed very low and near to the battery, which improves the mass centralization.

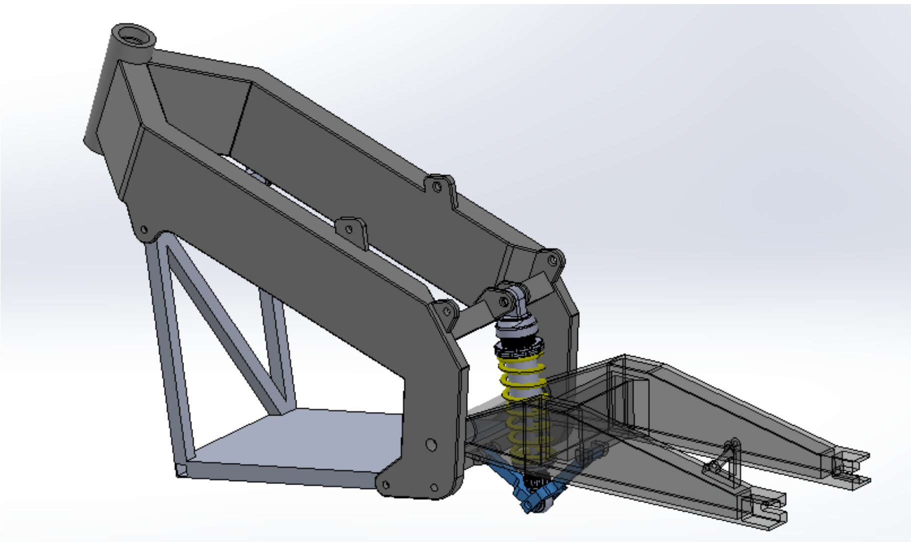


Fig.39 Detail of the chassis with the suspension system mounted

6.5. Swing arm

The design of the swing arm follows the language of the frame and it is also made of aluminum 6063T5. Both bodies are attached with a steel bar that is threaded in the extremes and two bolts. Between both bodies there must be a needle roller thrust bearing in order to avoid the friction between them; in this case, the reference name of the bearing is SKF AXK1730. Between the steel bar and the moving swing arm, another bearing must be introduced, particularly, a drawn cup needle roller bearing called SKF HK1712.

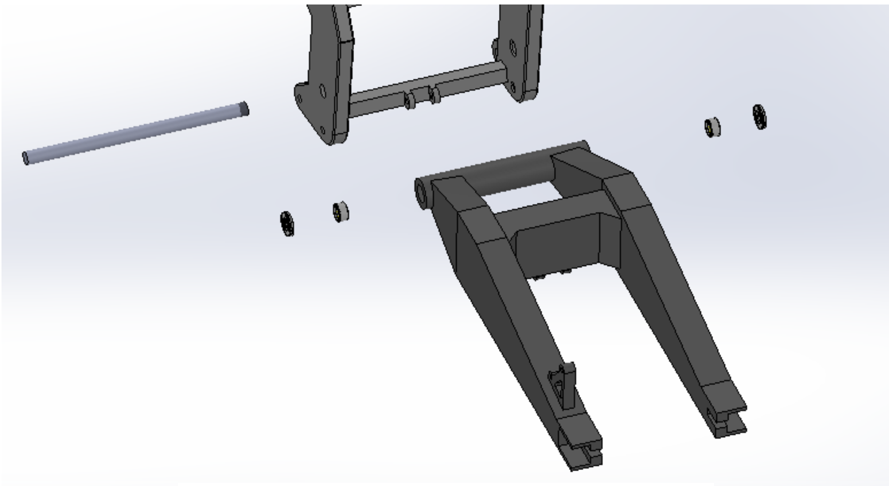


Fig.40 Swing arm disassembly

The design process hasn't been easy because of the requirements of the suspension. The shock must be able to pass widely through the whole at any possible angle that could have the swing arm. Besides, it must have a linkage to the rocker.

The rear part of the swing arm presents some particularities compared to common motorcycles. Because there's no chain that goes to the wheel, the overall geometry of the swingarm can be totally symmetric. Furthermore, the brake caliper support can be fixed directly on the body because the relative position of the caliper is not subject to the tightness of the chain (in common motorcycles, the caliper must be attached to a special support that moves with the wheel). Another particularity is that the wheel shaft is part of the HUB motor and cannot be removed to mount it on the swing arm. To mount the wheel on the swing arm, the shaft has to be introduced in both grooves until it reaches the end, and then it is fixed with bolts.

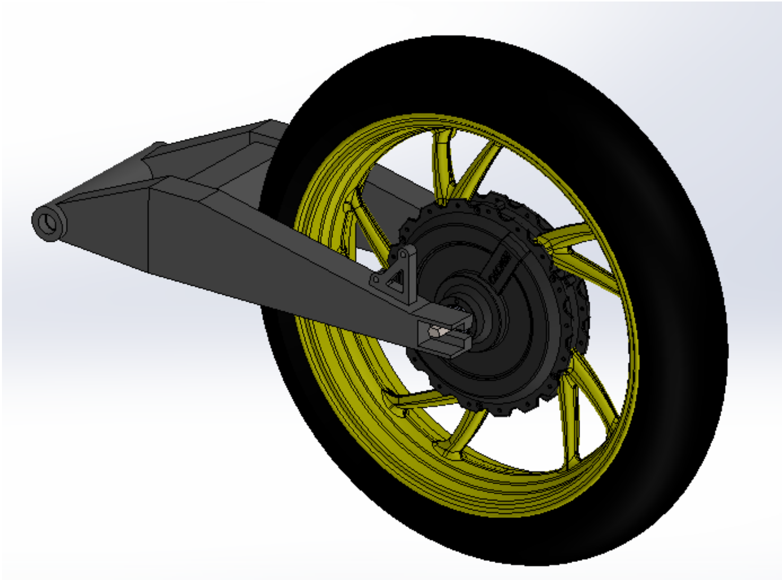


Fig.41 Swing arm with the rear wheel (and the HUB motor)

6.6. Fork

To have a coherent chassis and really obtain a similar handling to the Yamaha TZR50rr, some of its components have been introduced in this motorcycle. The most important one is probably the fork; it would be almost impossible to obtain the geometry presented without incorporating this fork in particular.

It is a traditional telescopic fork with steel yokes that has already a support for the brake caliper and other ones for the mudguard. In the superior and inferior part of the steering head, between the frame and the lower yoke, must go a ball bearing that supports angular loads. In this case, according to the characteristics of the fork, the model of bearing is SKF 7205BEP.

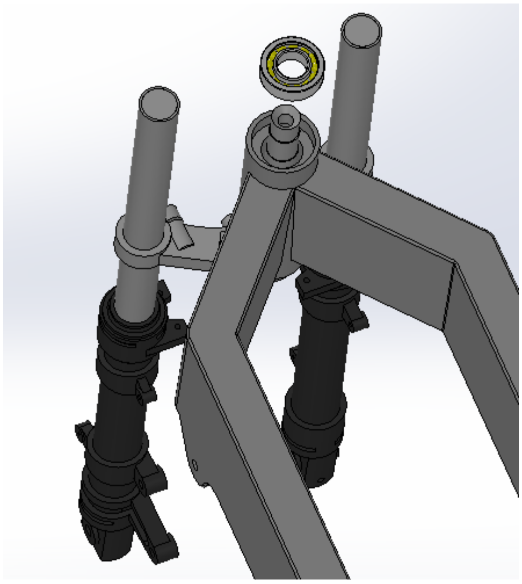


Fig.42 Disassembly of the top yoke and the bearing

However, some changes must be done to adapt the fork to the ergonomics that we are looking for. The superior yoke of the factory bike is designed to put up semi-handlebars, a kind of handlebars used in sports motorcycles that forces the rider to go very forward. To solve that problem, another top yoke has been designed that incorporates the fixation of a classic handlebar. In this case, it's been incorporated a rather standard one that provides enough height to have a comfortable riding position. Even so, one must not forget that the ergonomics are not only defined by the handlebar position.

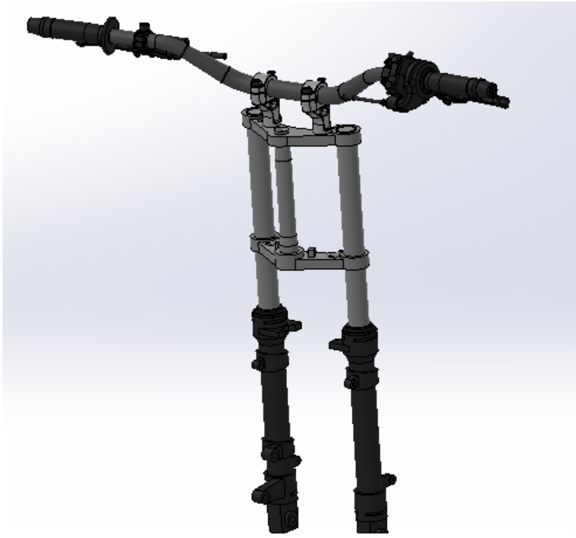



Fig.43 Picture of a yoke with semi-handlebars (left), 3D CAD of the modified fork (right)

6.7. Wheels

The size of the wheels has been kept from the Yamaha as well. In the front, it wears a 100/80-R17 tire and the rear one is a 130/70-R18. Rims are given by one of the sponsors of the competition, MORAD, and although in the CAD design the ones shown are alloy wheels, the real ones will be the classic wheels with spokes because the HUB motor is designed to be connected to the rim through the spokes.

Fig.44 Detail of the 3D CAD, where the holes for the spokes can be seen

6.8. Footrests

The last part of the ergonomic triangle that remains unexplained is the position of the rider's footrests. Having in mind the position given by the Honda Varadero 125, the footrests have been put in a similar place but without compromising too much the design of the bike. To accomplish that, it has been designed a stainless steel (AISI 304) part that is attached to the frame and allows lowering the footrests. Besides, on the left side of the bike this part is significantly different and also serves as a support for the kickstand that holds the bike when it is parked.

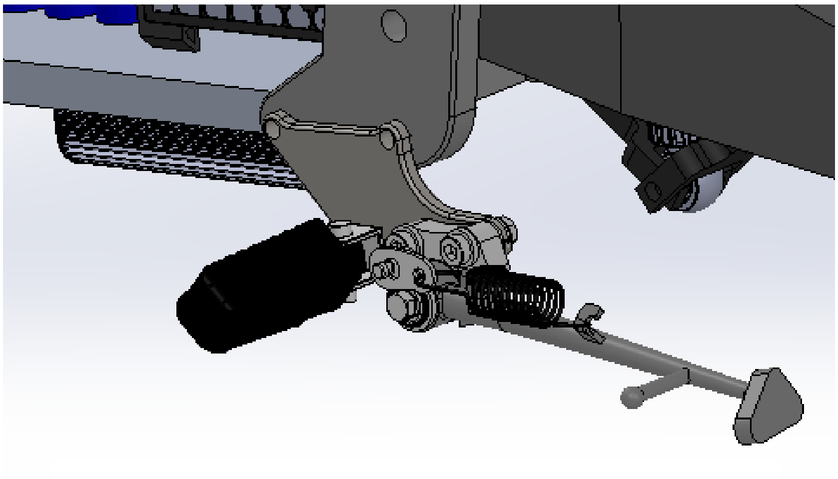


Fig.45 Left footrest with kickstand

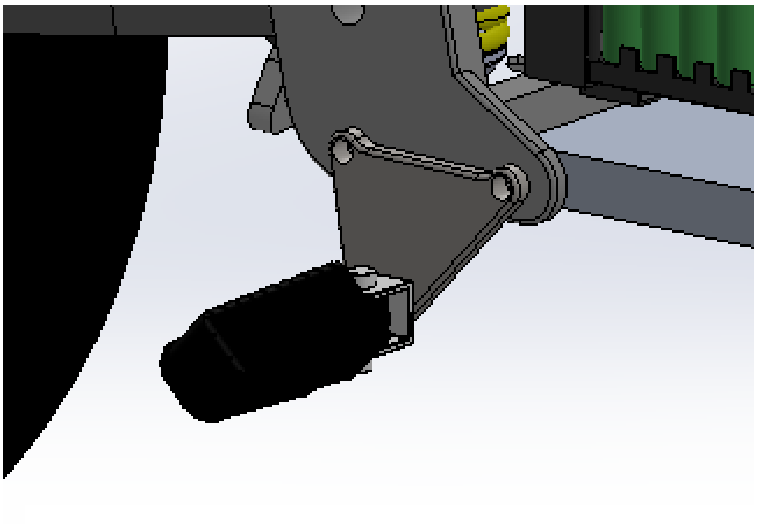


Fig.46 Right footrest

As it can be seen below in the final result, the ergonomic triangle has a proportion very similar to the Honda. However, in terms of values, all the dimensions are rather smaller.

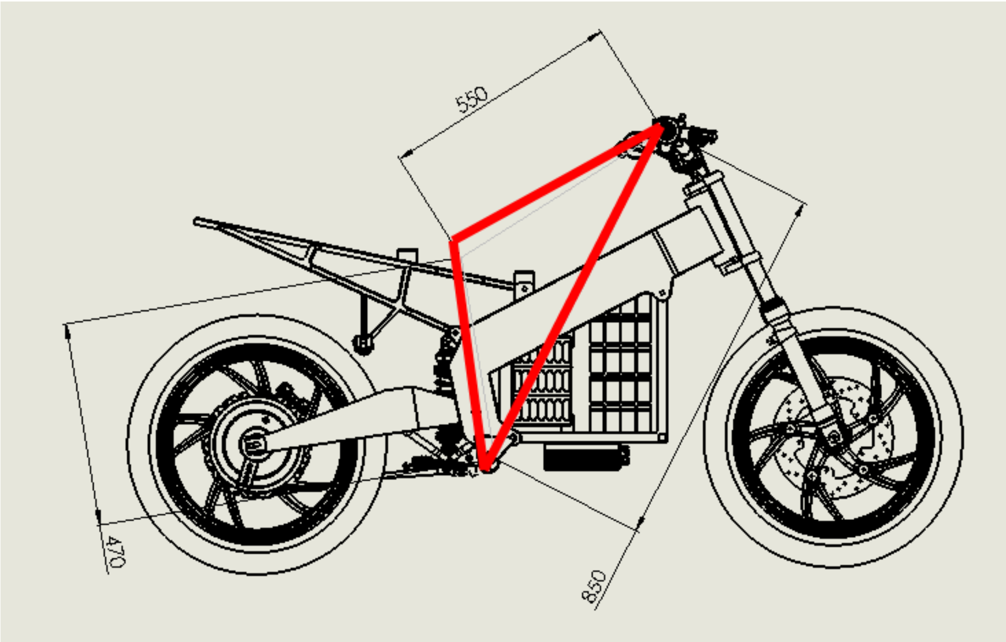


Fig.47 Ergonomic triangle of the chassis

6.9. Brakes

The brake system, which includes pumps, cables, calipers and levers, is supplied by one of the sponsors of the competition, J.Juan. Although the first idea was to put a brake pedal for the rear brake, like in motorcycles and not like scooters, the company informed that they were told by the competition organization to give only levers and not pedals and foot pumps. With that, the brake design gets much simpler. The front caliper is a double piston floating caliper, whilst the rear one has only one piston and is also floating. Like it has been said, the fork comes with the support for the caliper and the rear brake support has been specially designed for the caliper that J.Juan is going to supply. The brake cables are going to be attached to the frame and swingarm with bridles.

Fig.48 Front and rear calipers (from left to right)

Discs are not given by J.Juan, and this time, again, the best option was to put the same brakes that have the Yamaha TZR50rr. In this case, discs are made by NG brakes and have a dimension of 280mm for the front wheel and 220mm for the rear wheel.

Fig.49 Front and rear discs (from left to right)

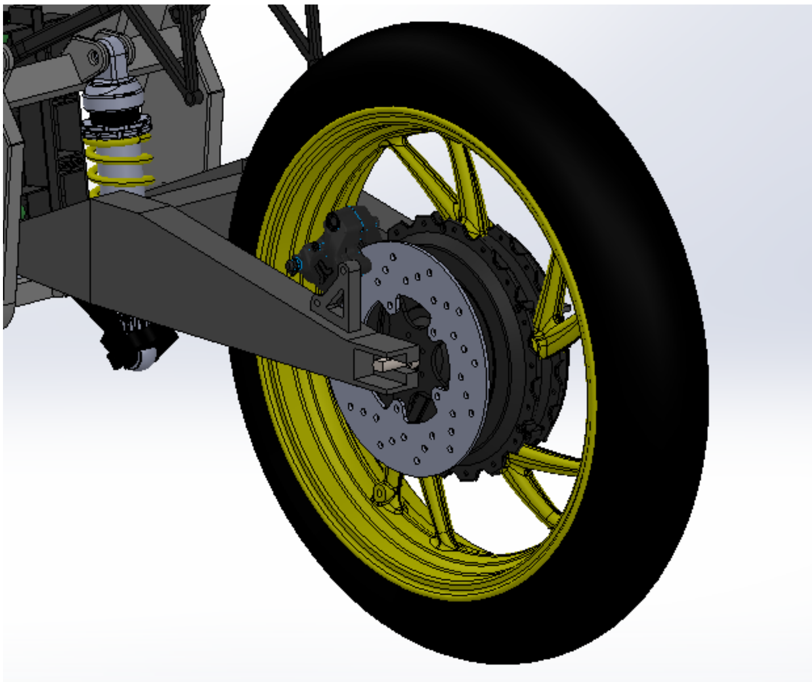


Fig.50 Assembly of the rear end

There's one modification that must be done in the rear wheel to hold the brake of above. The HUB motor comes with a hole pattern in order to attach a brake disc, but this pattern is different to the one that has the disc that is going to have. To solve that problem, an auxiliary part has been designed that connects both patterns and allows the normal use of the rear brake.

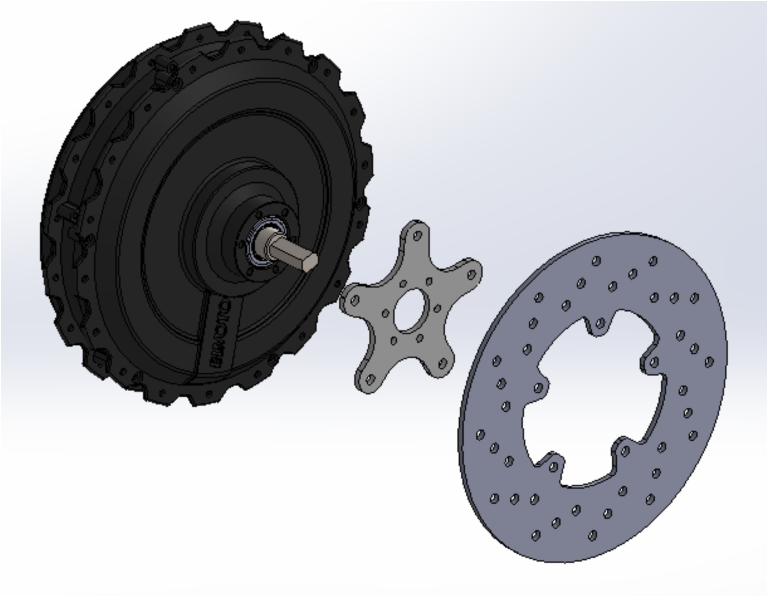


Fig.51 Disassembly of the disc and the disc adapter

6.10.General specifications

Dimensions:	**Wheelbase**	1330mm
	Caster angle	25º
	Trail	91mm
	Total lenght	1830mm
	Seat height	800mm
	Handlebar height	1050mm
	Footrests height	300mm
Frame:	**Type**	Twin beam with cradle
	Material	Aluminum 6063T5
	Weight	10,5kg
Subchassis:	**Type**	Tubular
	Material	Steel S355JR
	Weight	3,25 kg
	Num. Passengers	2
Swing arm:	**Material**	Aluminum 6063T5
	Weight	3,5kg

Front suspension:	**Type**	Telescopic fork
	Brand	Yamaha
	Length	660mm
Rear suspension:	**Type**	Mono-shock with rockers
	Brand	Betor
	Lenght of the shock	270mm
Wheels	**Type**	Aluminum rim with spokes
	Brand	MORAD
	Front size	110/80-R17
	Rear size	130/70-R17
Brake system	**Type**	Hydraulic with manual levers
	Brand	J.Juan
	Front caliper	Floating, two pistons
	Rear caliper	Floating, one piston
Brake discs	**Brand**	NG brakes
	Front size	280mm
	Rear size	220mm
Steering bearings (2)	**Type**	Ball bearing with angular load
	Brand	SKF
	Model	7205BEP
Swing arm bearings	**Type 1**	Needle roller thrust bearing
	Brand	SKF
	Model	AXK1730
	Type 2	Drawn cup needle roller bearing
	Brand	SKF
	Model	HK1712

7. FEM simulations

7.1. Introduction

In this chapter, the different simulations that have been done are shown. Simulations are an essential part of the design of the chassis because they enable the chance to guarantee the mechanical properties before building up all the structure and allow the optimization of the design; for this reason, they appear to be one of the trunk parts of this project. For the automotive is one of world's most cutting-edge industries, simulations have been profoundly developed for these applications and the great part of the simulation process has become standardized in order to have reliable results and conclusions.

In this chapter, only the final results are shown and all the optimization process to obtain the desired mechanical properties has been omitted. As an overall look, the different simulations studied are shown below:

-Frame stiffness simulation

-Swing arm stiffness simulation

-Full structure resistance simulation

-Subchassis and powertrain cradle resistance simulation

-Other particularities

As a punctual comment, displacement measures taken during simulations are done in mm and not m, for the values registered are very small.

And here are presented the main mechanical properties of the three different materials that have been used to design the chassis and that have been considered for the different simulations.

	aluminum 6063T5	steel S355JR	stainless steel AISI 304
Density [kg/m3]	2,7	7,85	8
Young modulus [GPa]	70	200	193
Poisson's ratio	0,33	0,26	0,29
Shear Modulus [Gpa]	25,8	75	77
Yield strenght [Mpa]	145	355	210

Fig.50 Table of material properties

7.2. Frame stiffness simulations

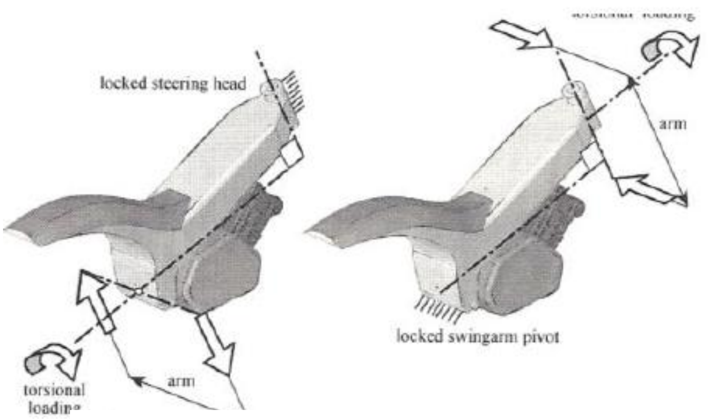
7.2.1. Background

According to Cossalter's *Motorcycle dynamics*, the simulation of a motorcycle frame is done through the study of its stiffness. What manufacturers do is comparing the deformation ratio that suffers the frame under specific conditions with some reference values that they have beforehand. The overall structural stiffness is a key factor in defining the performance with regard to handling and maneuverability of the bike; that's the reason why the optimization process focuses on this property.

There are basically three different kinds of stiffness when defining the rigidity of a motorcycle frame. These are defined by the boundary conditions that have the frame when simulating and each one gives valuable information of the handling performance of the bike. The final goal is to obtain a ratio between the stress and the deformation, which does not depend on the particular value of the input forces of the simulation.

In common motorcycles, these simulations are done with the combustion engine fitted to the frame because it contributes a lot to the total stiffness. In this case, for there is no combustion engine, simulations are done with the powertrain box structure attached to the frame. The subchassis might be also considered in these simulations, but if it is not welded to the frame, it's a common option to dispense from it. This decision is not counterproductive because the subchassis will always give even more stiffness to the structure and simulating the frame without it ensures an even more rigid body.

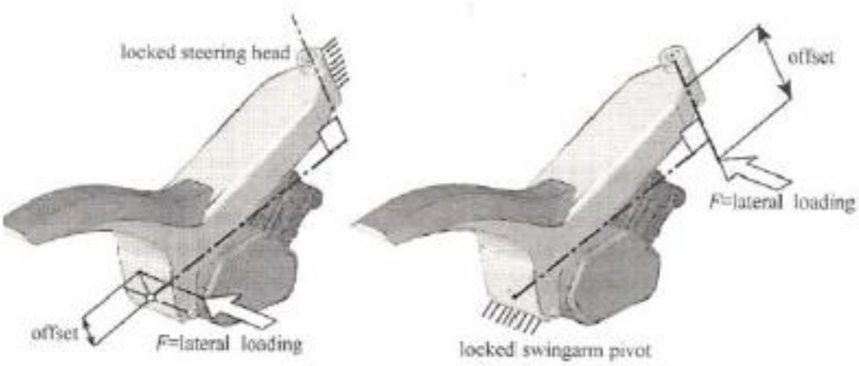
·Torsional stiffness (Ktf): it is calculated about an axis at a right angle to the steering head and passing through the swinging arm pivot axis and applying a torque around this axis.



Normal values of this ratio for sports motorcycles are between 3-7 kNm/º

Fig.51 Definition of torsional stiffness (*Motorcycle dynamics, Vittore Cossalter*)

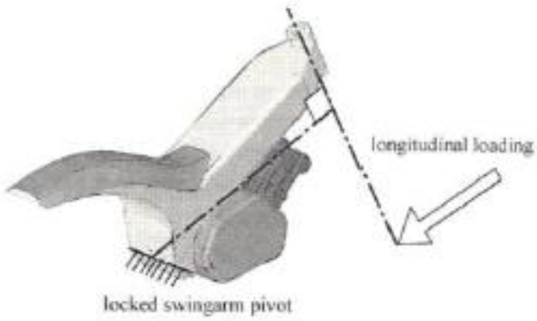
·Lateral stiffness (Kf): it can be represented by the ratio between the force applied along the swinging arm pivot axis and the lateral deformation measured in that direction.



The lateral stiffness ratio presents values inside 1-3 kN/mm

Fig.52 Definition of lateral stiffness (*Motorcycle dynamics, Vittore Cossalter*)

·Longitudinal stiffness (Kzf): it is calculated by applying a force perpendicular to the steering head axis and fixing the swinging arm pivot axis.



Sports motorbikes use to have ratios between 5-10 kN/mm

Fig.53 Definition of longitudinal stiffness (*Motorcycle dynamics, Vittore Cossalter*)

In conclusion, the aim of the design and simulation is to obtain values of stiffness near to the ones mentioned above. However, there's an important property that must be taken in account: weight; the mass of the motorcycle has as much repercussion to the handling as the frame stiffness. For an increase of the stiffness usually implies an increase in the weight, an optimization process must be done to finally have a structure with a good compromise between high stiffness and low weight. In this particular case, it has been considered that the goal should be to obtain the higher stiffness possible having a maximum weight of around 10kg.

Instead of showing directly the results of the simulation, here there is a little explanation of the entire job that has been done to prepare the frame in what is commonly known as pre-process. Part of this consists in adapting the design of the frame, which has been done with *Solidworks 2014*; and the rest of the pre-process is done directly on the FEM software that is going to simulate the structure. For this project, *Ansys Workbench 14.5* has been used. It's remarkable that all this pre-process has been done for all the simulations of this project, but in order to make the result a little less ponderous, it is going to be explained only for this simulation.

It makes no sense to simulate a detailed version of the frame for it will imply a harder CPU calculation and those details will not contribute to the overall stiffness of the structure; that's the reason why a simpler geometry of the frame has been considered, without appendixes nor chamfers. As said before, the frame will be simulated without the subchassis and with the powertrain box attached. The steel bars that work to attach the box to the frame have been introduced as well.

Another important consideration is that the swinging arm axis tube has been introduced to the design even though it's not part of the frame itself. The reason is that it is a key part of the structure that really improves its mechanical properties and not considering it would imply unrealistic results.

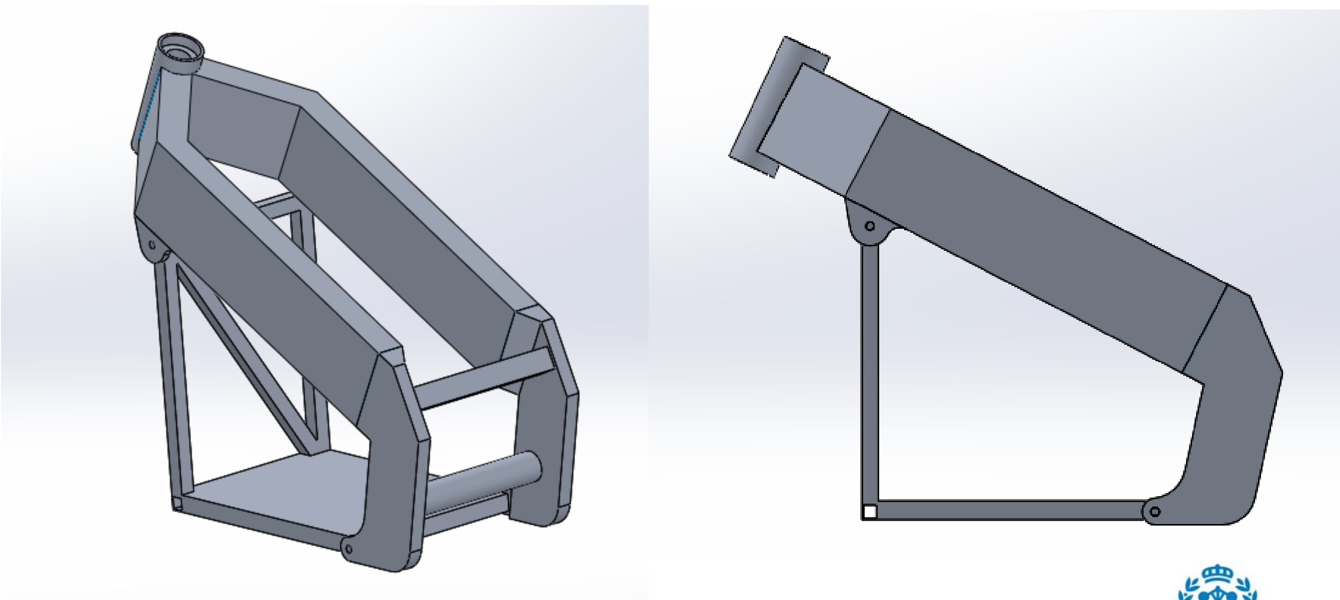


Fig.54 Different views of the simplified geometry of the frame

Finally, another simplification has been done: to speed up the CPU calculation process and to improve the optimization process, both beams of the frame that are made from a commercial rectangular profile have been simplified as surfaces. This simplification can be done because the thickness of the surface is very small compared to the dimensions of the tube and it allows the FEM software to work in 2D on these beams. Thanks to this, a more accurate mesh can be done and the thickness of the surfaces can be changed directly in Ansys without having to change the whole geometry.

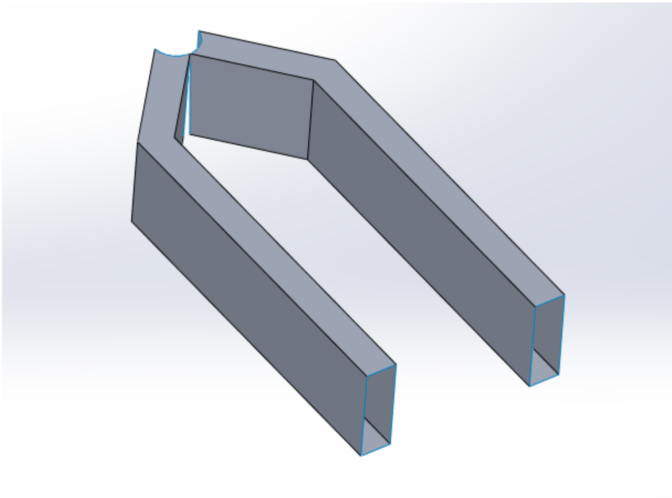


Fig.55 Adaptation of the beams into surfaces

Once the simplified geometry was ready, it was saved in a universal format, such as .STEP or .IGS, and imported to Ansys. There, the materials that have been used must be added to the library and assign them to each body; in this case, steel S355JR for the bars and aluminum 6063T5 for the rest. Because the geometry comes from an assembly of different bodies, the connection between them has to be defined. It has been used the *Bonded connection* to join them.

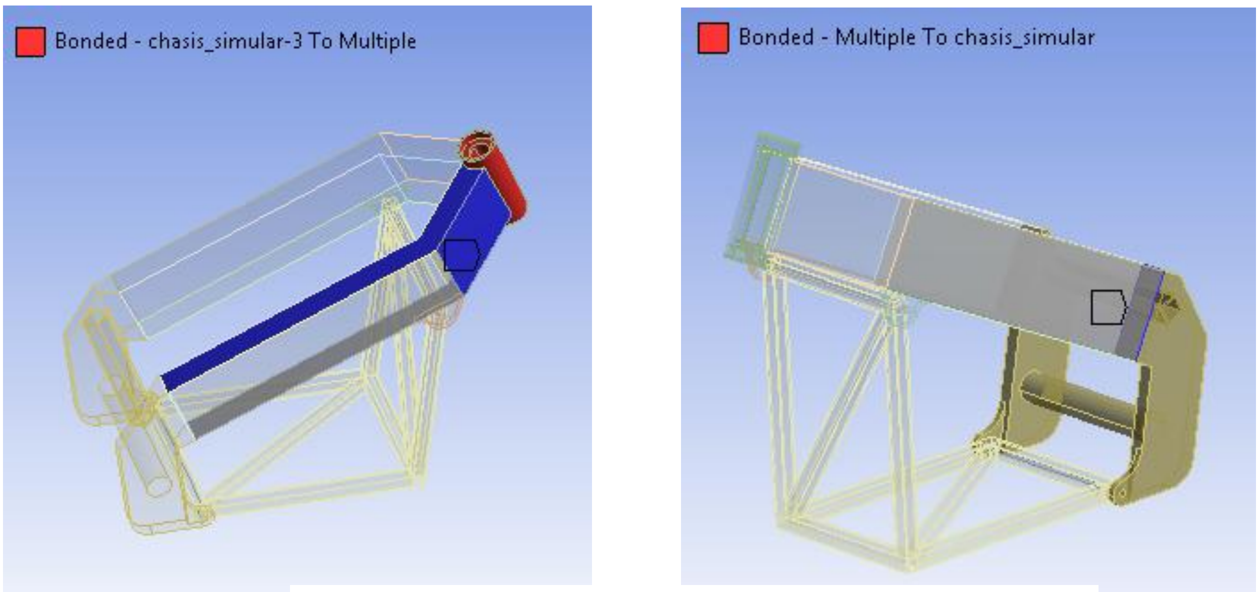


Fig.56 Examples of the connections that have been done

The final step is the mesh. The election of an accurate mesh is vital to have realistic results but it is important not to overcharge the CPU with minuscule elements. For this reason, the size of the elements must be determined through an optimization process that finally gives a mesh with a good compromise between precision and time of calculation. Here is presented the result of this mesh optimization process. The type of element used has been let to the program to decide the most suitable one for each geometry and the size has been defined through different Ansys functions, like *Body Sizing, Refinement* or *Sphere of influence*. Special attention has been put to the connection between the different bodies to obtain no estrange elements or other anomalies.

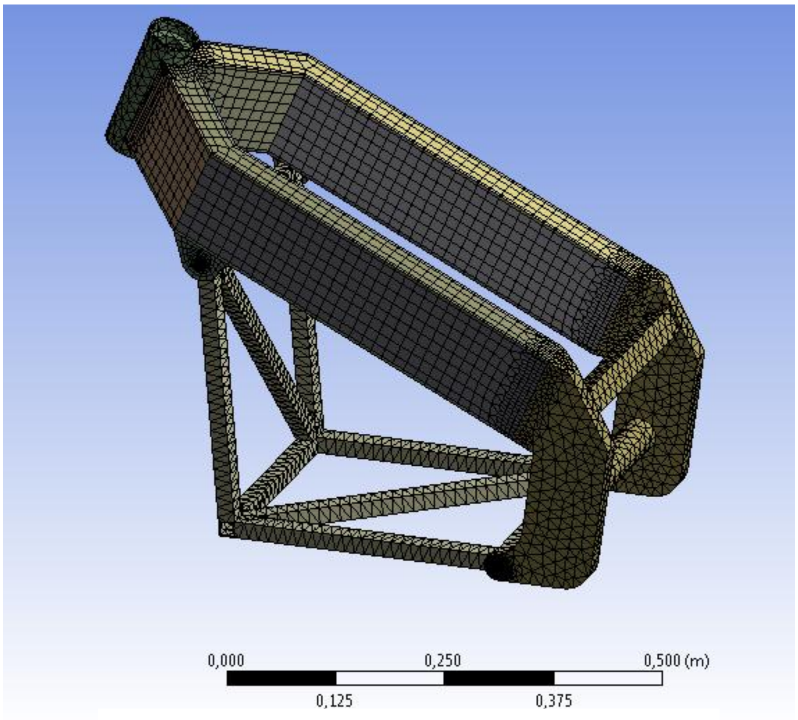


Fig.57 Overall view of the mesh

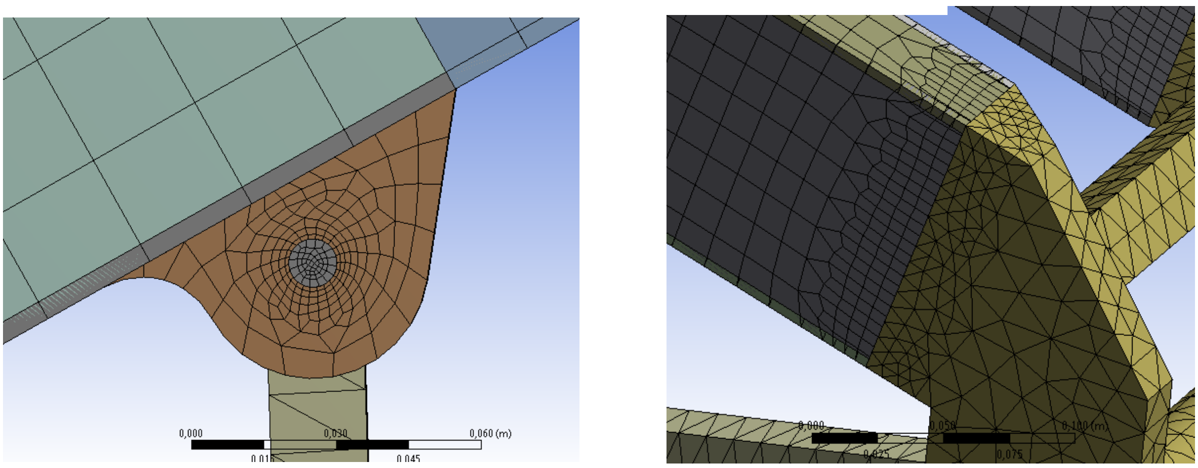


Fig.58 Details of the mesh refinement

7.2.2. Results

·Torsional stiffness (Ktf): the boundary conditions of the torsional stiffness simulation imply the fixation of the steering head and the input of a torque on the swinging arm pivot perpendicular to the axis that goes to the steering head. In this case, the torque applied has a value of 10kNm .

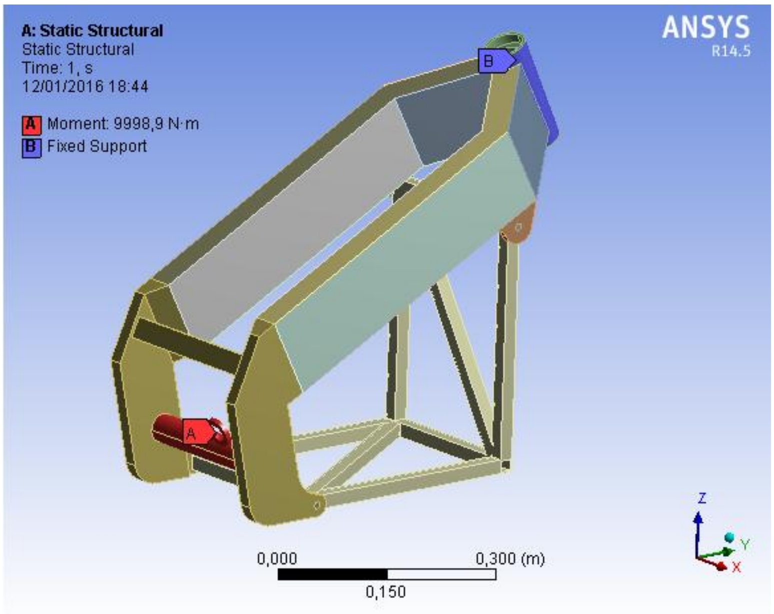


Fig.59 Boundary conditions of the torsional stiffness

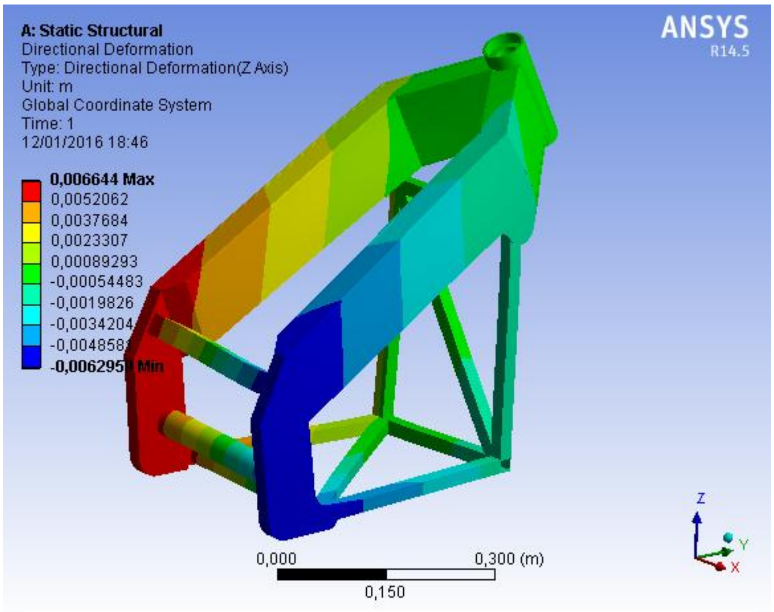


Fig.60 Deformation of the frame

To calculate the Ktf ratio one must measure the change on the angle that forms the swing arm pivot. In this case, results show that the arm moves 5,3mm at every extreme, which traduces into a relative angle of 2,64º. The ratio takes a value of:

$$Ktf = \frac{10kNm}{2,64^o} = 3,79kNm/^o \qquad \text{Ktf between 3-7kNm/}^o$$

Comparing to the given values, it's visible that the torsional stiffness is inside the normal values of sports motorcycles.

·Lateral stiffness (Kf): the boundary conditions of the lateral stiffness simulation involve the fixation of the steering head and the application of a force in the direction of the swing arm pivot axis. In this case, the load has been 5kN.

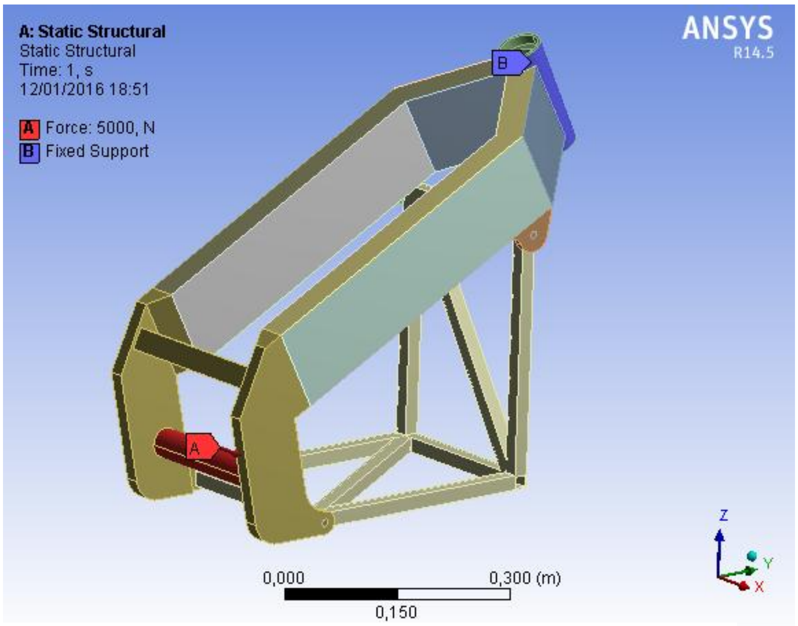


Fig.61 Boundary conditions of the lateral stiffness

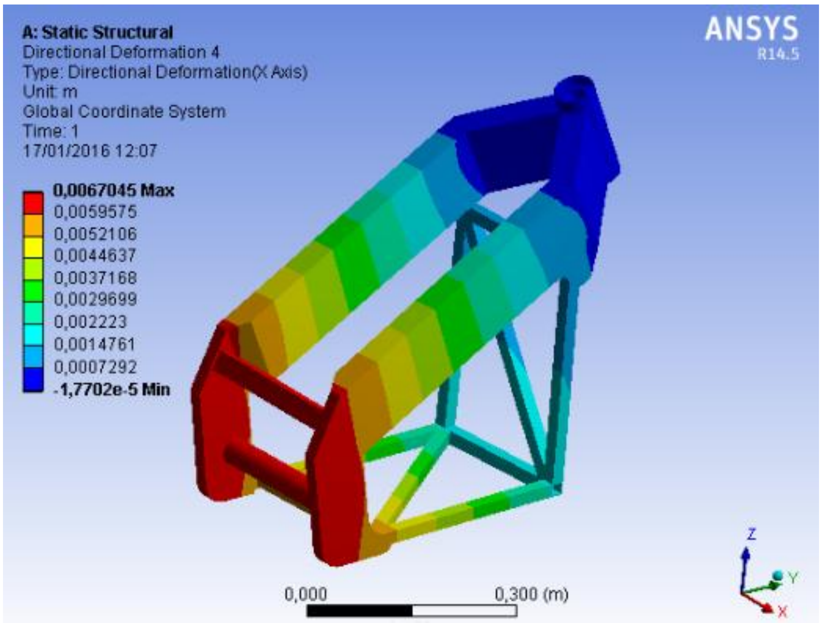


Fig.62 Deformation of the frame

To calculate de Kf ratio, the displacement on the swing arm pivot must be measured. In this case, its value is 6,4mm.

$$Kf= \frac{5kN}{6,4mm} = 0,78kN/mm \qquad \text{Kf between 1-3kNm/mm}$$

As it can be seen, the lateral stiffness ratio shows a final value slightly under the normal range. This is the consequence of not mounting a structural combustion engine on the frame, which would have raised a lot this value. It's remarkable that the one shown before, is the final value after the optimization process; that means that during that process different solutions have been considered and none of them gave a better result than this without compromising too much the final design or increasing overmuch the weight. For this reason, 0, 78 kN/mm has been taken as a sufficient stiffness.

·Longitudinal stiffness (Kzf): the boundary conditions of the longitudinal stiffness imply the fixation of the swing arm pivot and the application of an external force on the steering head in the direction of the swing arm pivot. In this case, the load has taken a value of 5kN.

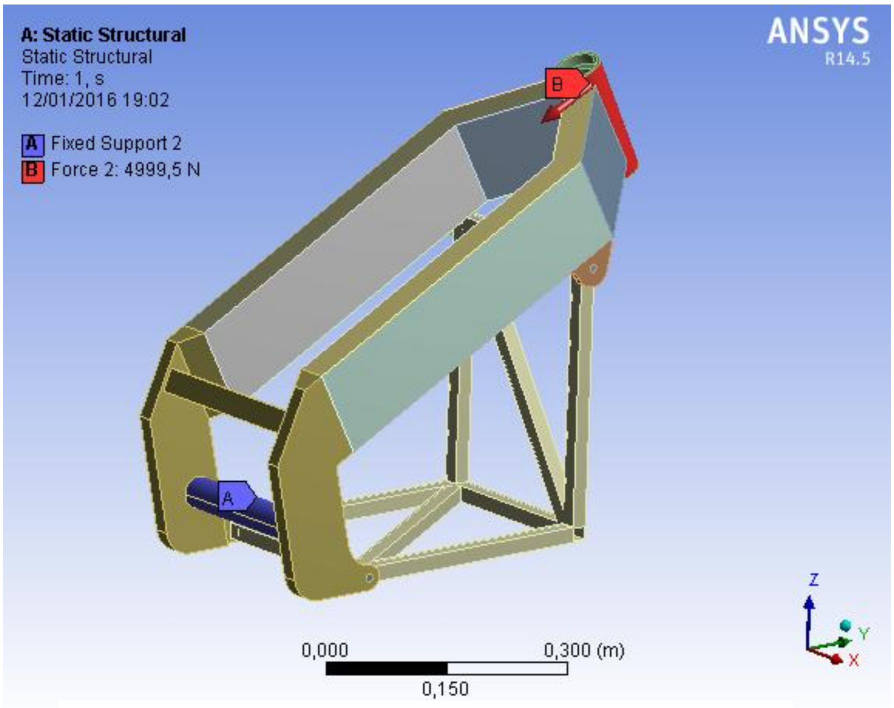


Fig.63 Boundary conditions of the longitudinal stiffness

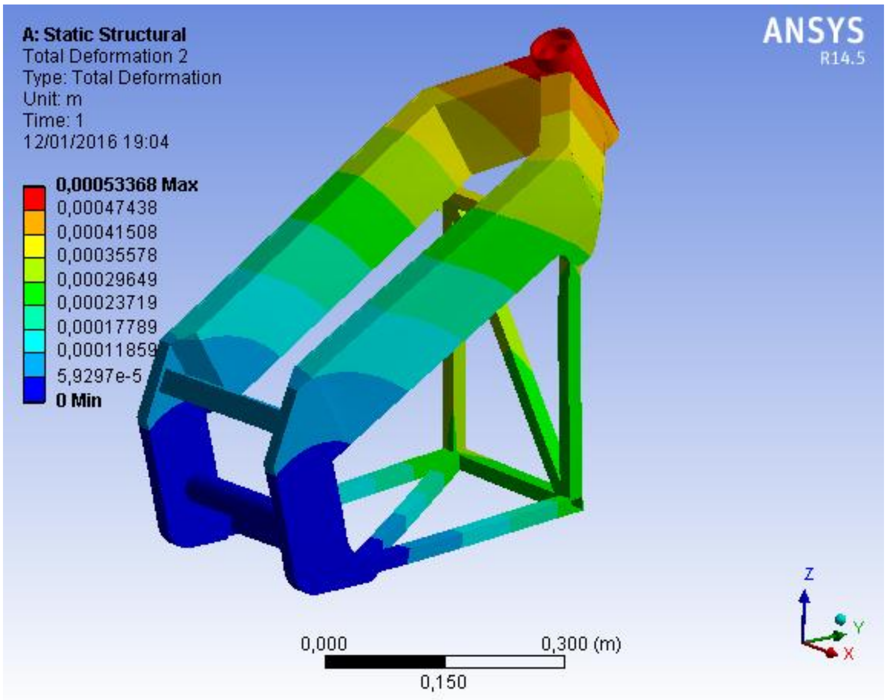


Fig.64 Deformation of the frame

To calculate the Kzf ratio, one must measure the deformation that suffers the steering head that is 0,53mm.

$$Kzf= \frac{5kN}{0{,}53mm} = 9{,}44kN/mm \qquad \text{Kzf between 5-10kNm/mm}$$

As it can be seen, the longitudinal stiffness of the frame has a very high value inside the normal range.

7.3. Swing arm stiffness simulation

7.3.1. Background

According to Cossalter's *Motorcycle Dynamics*, the simulation of the swing arm must be done through the study of its stiffness as well. In this case, two different ratios define its behavior: lateral stiffness and torsional stiffness.

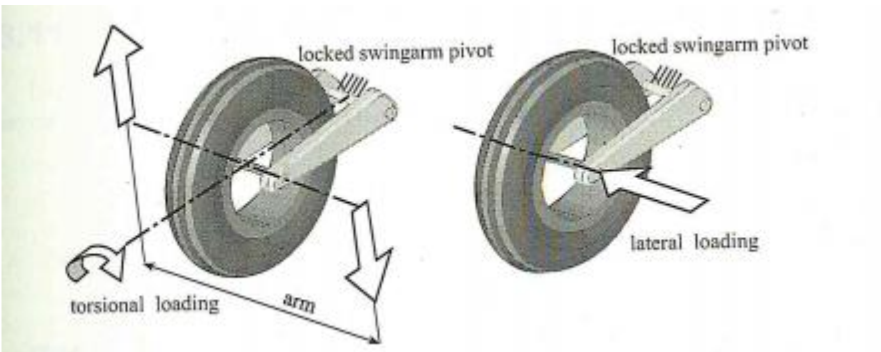


Fig.65 Definition of torsional stiffness (left) and lateral stiffness (right)
Motorcycle dynamics, Vittore Cossalter

·Torsional stiffness (Kts): it is measured with the swingarm pivot axis fixed and a applying a certain torque in the axis of the wheel. This ratio takes values inside 1-2kNm/º.

·Lateral stiffness (Ks): it is measured with the swingarm pivot axis fixed and applying a certain lateral force in the axis of the wheel. Normal values for sports motorcycles are between 0,8-1,6 kN/mm

As it happened with the frame, it's important to understand that this is an optimization that has the aim of reaching those stiffness values but without increasing too much the weight of the body. The maximum weight admissible for this process has been 3,5kg.

After simplifying the geometry and carrying out the meshing, the swingarm can be seen below. The axis of the wheel, that in this case is the axis of the motor, has been introduced in the simulation.

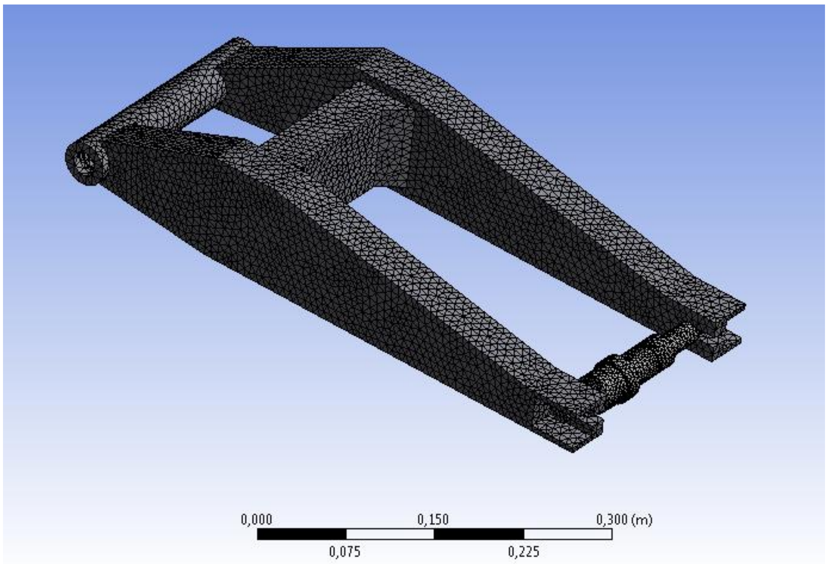


Fig.66 Overall mesh of the swing arm

7.3.2. Results

·**Torsional stiffness (Kts):** the boundary conditions that define this simulation imply the fixation of the pivot axis and the application of a torque on the wheel axis. In this case, the torque used is 10kNm.

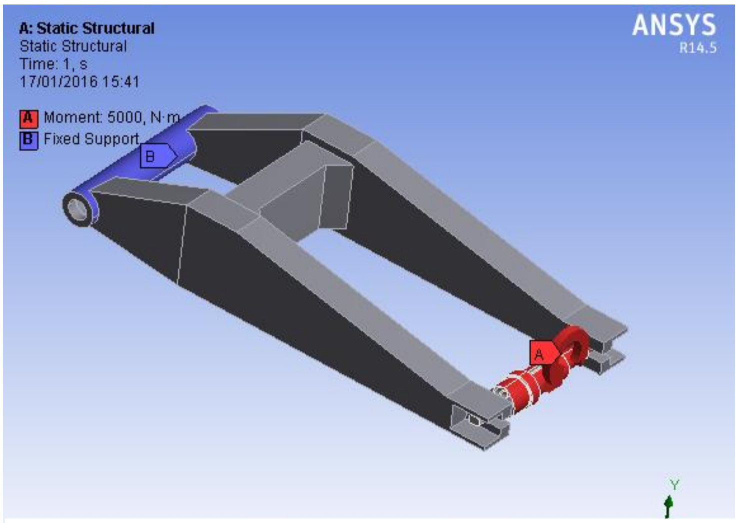


Fig.67 Boundary conditions of the torsional stiffness

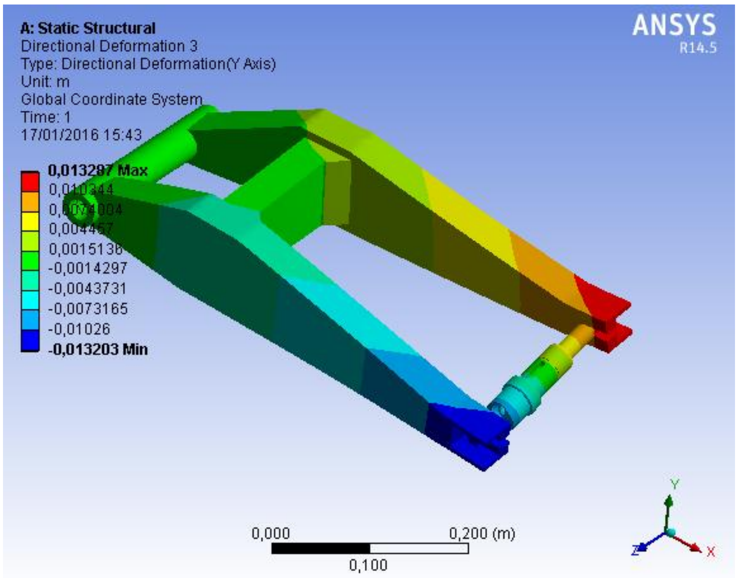


Fig.68 Deformation of the swing arm

In order to obtain the value of the Kts ratio, one must measure the variation in the angle that has suffered the wheel axis. In this case, each extreme of the swing arm has had a displacement of 12mm, which traduces into an angle of 5,98º. Then, the ratio is calculated as follows:

$$Kts= \frac{5kNm}{5,98^{o}} = 0,83kNm/^{o} \quad \text{Kts between 1-2kNm/}^{o}$$

After all the optimization process, the highest value that has been possible to achieve has been these one notwithstanding that it is out of the normal range for a sport motorcycle. For the weight of the swingarm couldn't be further increased, this value, that is not far from the low limit, has been considered sufficient. Besides, the source of these reference values says that is normal that the value of the torsional stiffness of swing arms that mount a mono-shock suspension tend to be worse; whereas the lateral stiffness is usually bigger.

·Lateral stiffness (Ks): in this case, the boundary conditions imply the fixation of the pivot axis and the application of an external force in the direction of the wheel axis; particularly, the load for this simulation has been of 2kN.

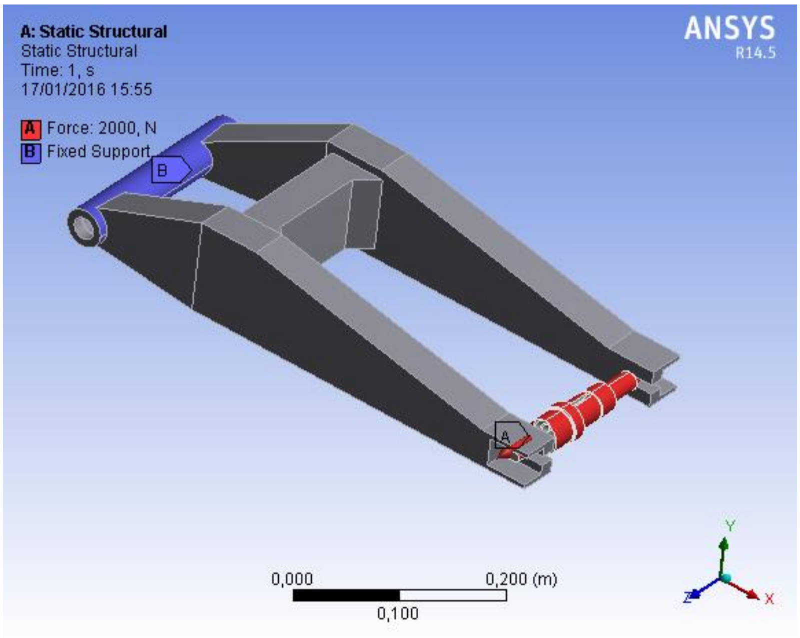


Fig.69 Boundary conditions of the lateral deformation

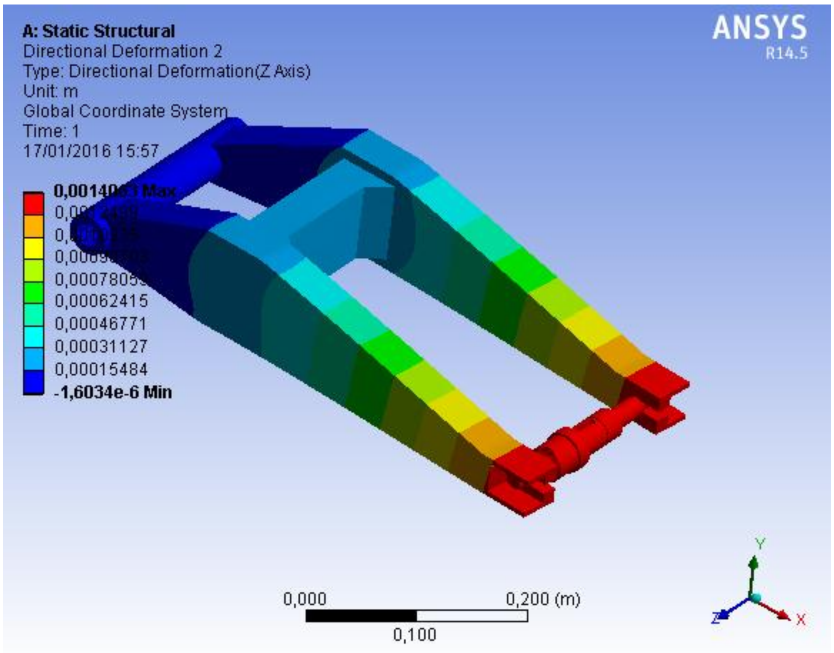


Fig.70 Deformation of the swing arm

To calculate the value of the Ks ratio, the lateral displacement of the wheel axis must be measured and in this case, it has a value of 1,35mm.

$$Ks = \frac{2kN}{1,35mm} = 1,48kN/mm \quad \text{Kts between } 0,8\text{-}1,6kNm/^{o}$$

As it was explained in the last simulation, swing-arms that mount a mono-shock tend to have a high lateral stiffness ratio, and this one is no exception.

7.4. Resistance simulation of the complete structure

Even though the handling properties are already ensured thanks to the stiffness simulations, the resistance of the structure has not been checked. It's true that a good stiffness design usually brings a sufficiently strong structure, but its specific simulation is not disposable. The problem with resistance simulations is that is very difficult to know the boundary conditions to apply because a motorcycle, in the real world, can receive a lot of different critical stresses during its life and they cannot be foreseen. However, in the motorcycling industry, engineers use to make a really harsh simulation in order to provide a structure that is able to support all the unforeseen critical stresses, and it consists on the application of 5G of acceleration to all the masses that supports the structure. Although it may seem exaggerated and a little unprecedented , engineers have proved the validity of this simulation throughout years of experience.

To check all the structure, for this simulation it has been considered the assembly formed by the frame and the subchassis because they are the two bodies that hold the main masses of the motorbike. The idea of the 5G test is that the motorcycle, in standing conditions and with all the masses attached, has to be able to resist an acceleration of five times the gravitational in the same direction as the last one. So, the boundary conditions involve the definition of the main masses: powertrain components (30kg) and passengers (75kg each); an acceleration of 5G and the fixation of the steering head and the swing arm pivot.

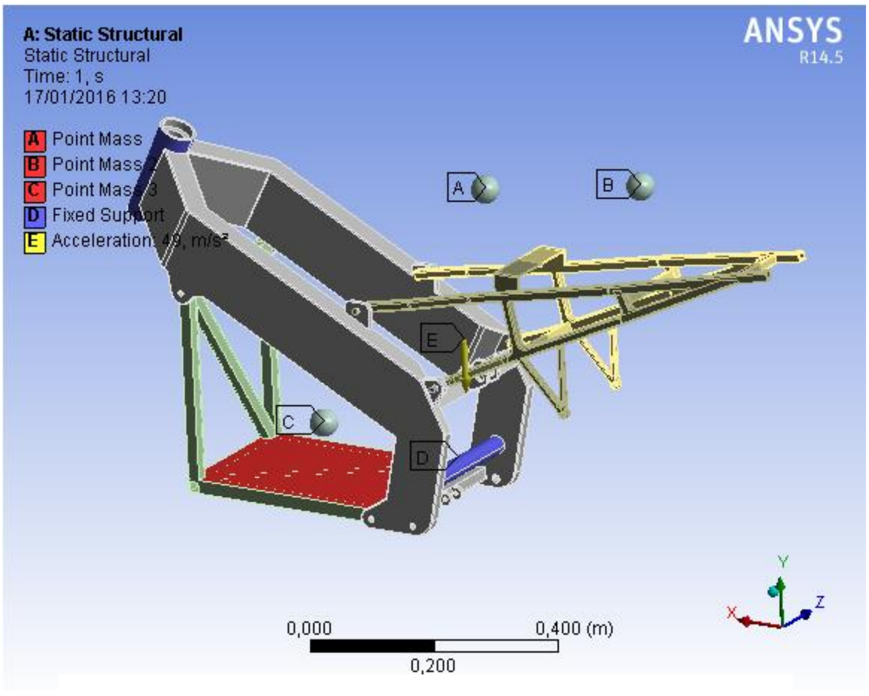


Fig.71 Boundary conditions of the 5G simulation

The results of the simulation are shown in two different representations because both bodies of the assembly are made of different materials: aluminum 6063T5 for the frame and steel S355JR for the subchassis. Pictures show the strength distribution following the von Mises criteria. Although they both show a maximum point with a value that is very high, it is without any doubt a singular point because it takes place in the point of contact between both bodies and the stresses do not expand in the geometry. In order to ensure this fact, the scale of the representation has been changed to show in red color the zones that suffer strength over the yield stress: 145MPa in the aluminum and 355MPa in the steel.

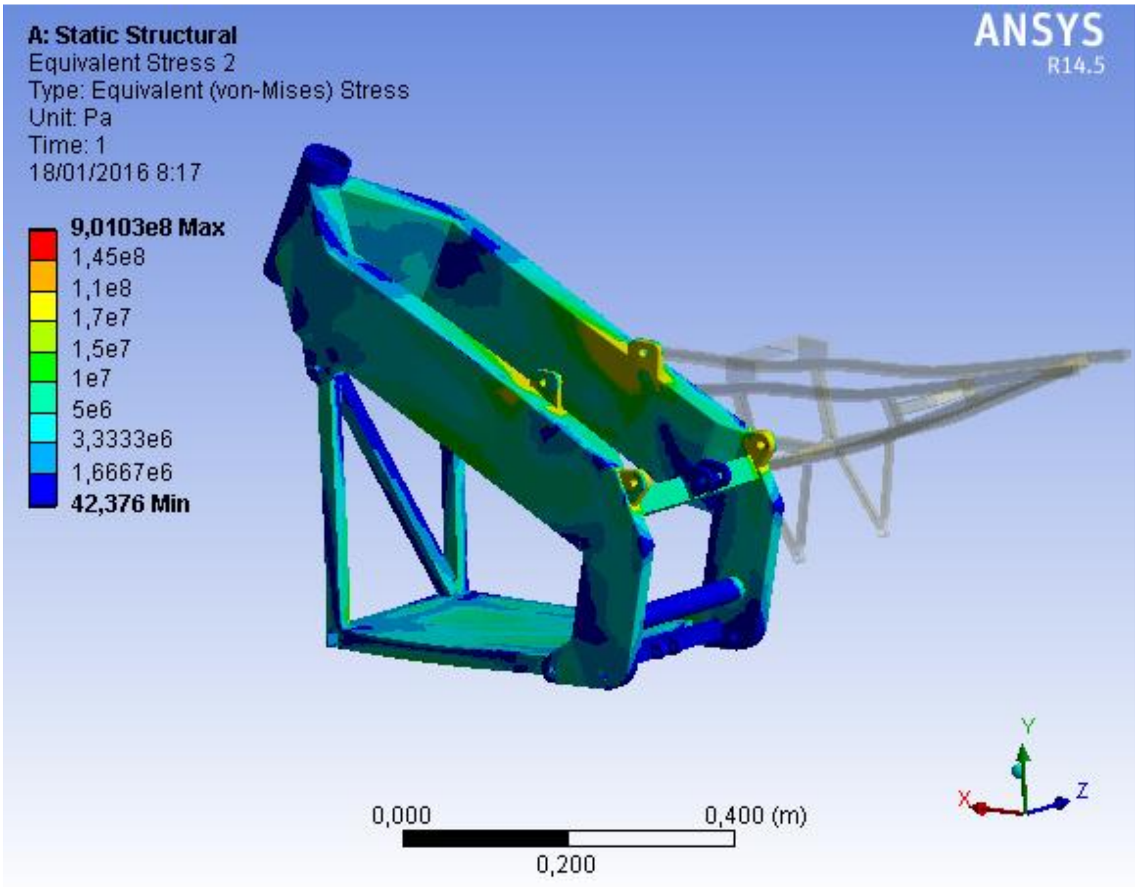


Fig.71 Stress distribution of the frame following Von-Mises criteria

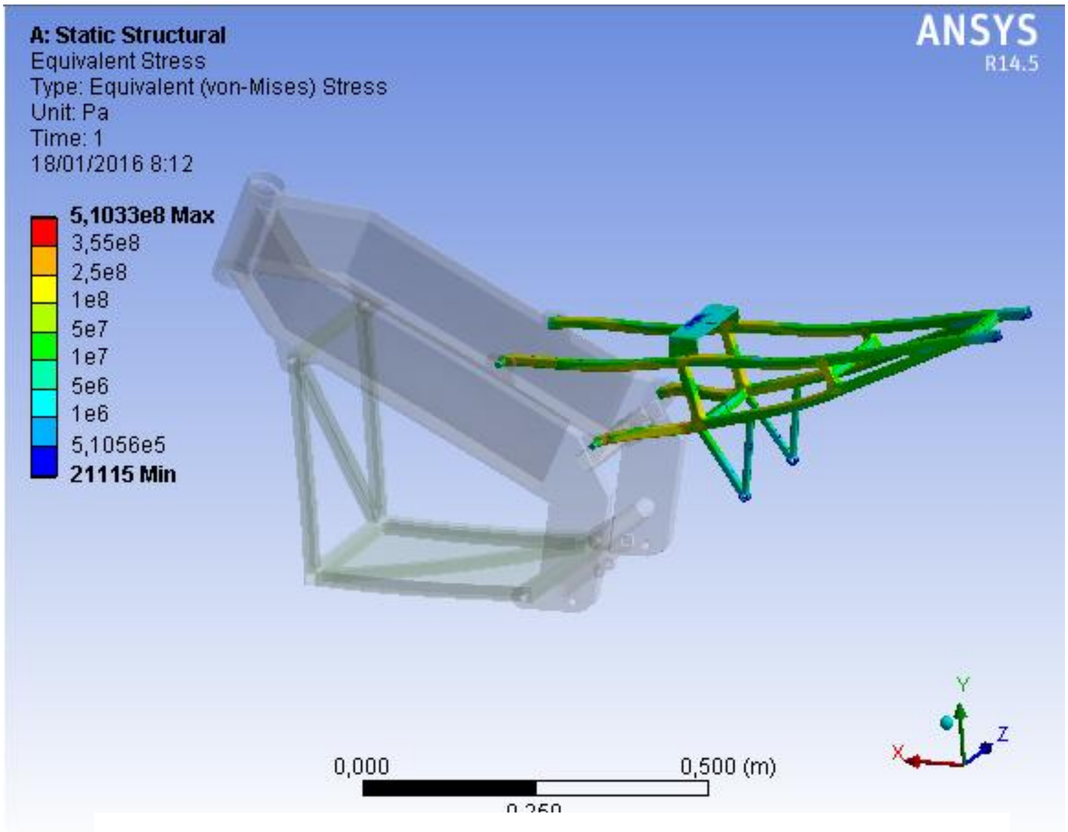


Fig.72 Stress distribution of the subchassis following Von-Mises criteria

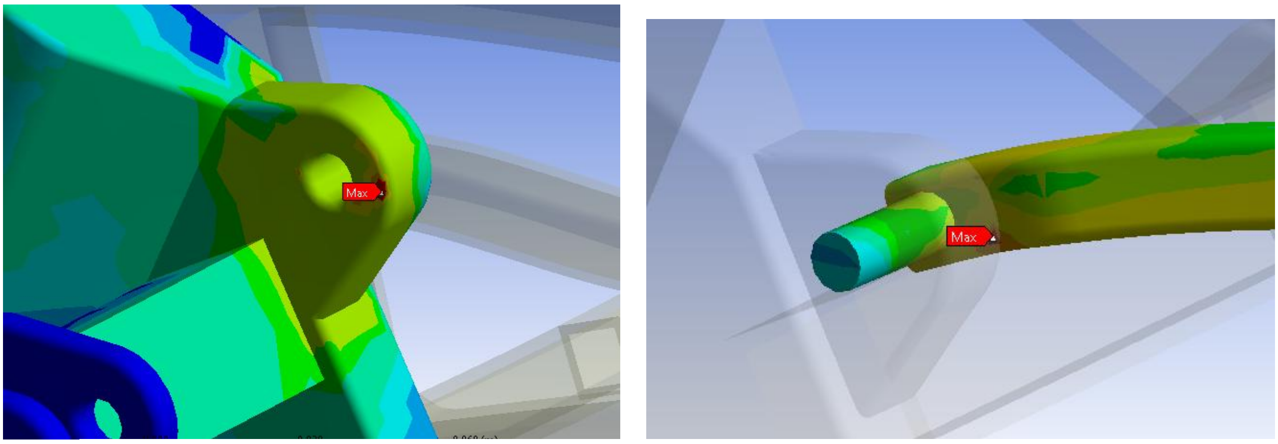


Fig.73 Details of the singular points in the frame (left) and the subchassis (right)

As it can be seen on the pictures, there's no red zone apart from the singularity commented above, meaning that the structure is able to support the 5G test without failure. This fact validates de overall structure for any possible stress that could have the motorcycle and, as a matter of fact, validates the design in terms of fatigue as well.

7.5. Resistance simulations of the subchassis and the cradle

7.5.1. Background

Although it has been said that all the possible stresses that can happen during the life of a motorcycle cannot be foreseen, there are three types of extreme stress that one must make sure that the structure is able to bear: maximum acceleration, maximum braking and maximum cornering. In fact, the 5G simulation was designed to substitute all these particular simulations but it's been considered appropriate to particularize and carry on these simulations for the parts of the chassis that must hold big loads; and the subchassis and the powertrain cradle are the main ones.

Before making a strength study, it's mandatory to make a performance study to obtain the boundary conditions that must be applied in the simulations; this is what has been done for every of the three simulations and it is explained next.

·Maximum acceleration: it happens when the bike, in straight line conditions, starts from standstill with the maximum acceleration possible. There are two ways of considering this simulation: calculating the maximum acceleration from the maximum torque that can give the motor (28 Nm in this case), or calculating it from the maximum force that could give the tire to the road before losing grip. For in this case the maximum torque of the motor is slightly small, it has been considered the second option.

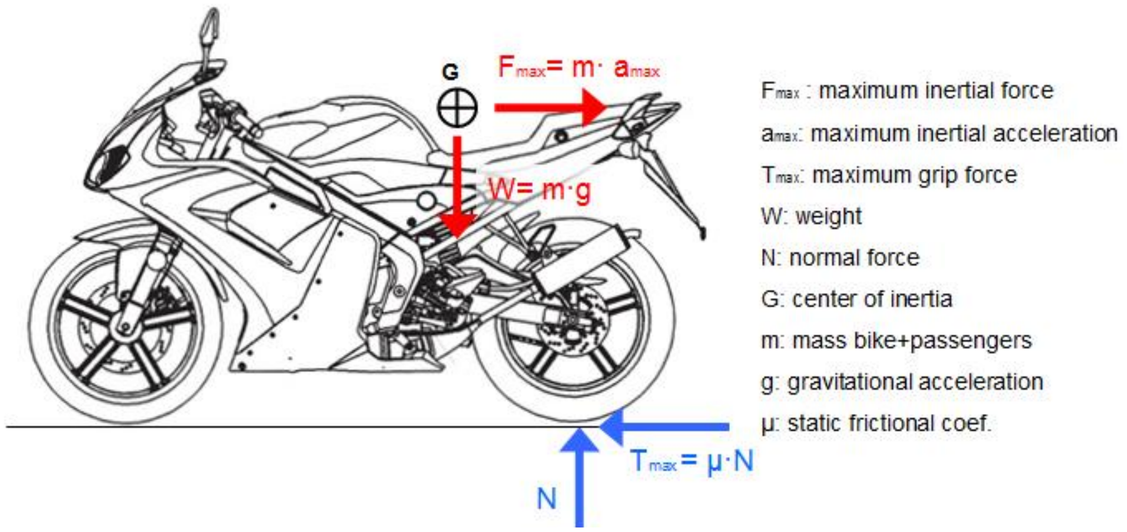


Fig.74 Scheme of forces of maximum acceleration

The scheme of before shows the loads involved in the maximum acceleration conditions. Some hypothesis has been done to simplify the understanding and the calculation; for instance, it has been considered that the rear wheel supports all the weight of the bike and the passengers (that means that the front wheel has begun to lift). Having the scheme clear, it's important to point which external conditions are we looking for to put in our simulation. In this case simulations are going to be defined by accelerations, as it will be presented later on; so the maximum acceleration that constitutes the maximum force of inertia (or d'Alembert force) has to be found from this scheme:

$$F_{max}=T_{max}$$

$$W=N$$

$$m \cdot a_{max}= \mu \cdot m \cdot g$$

$$\boldsymbol{a_{max}= \mu \cdot g}$$

This means that the maximum acceleration that can handle the rear tire before losing grip is directly proportional to the gravity acceleration. However, to obtain a real acceleration value, the static friction coefficient (μ) between the tire and the road must be defined. Specialized literature shows that μ has takes values of around 0,7-0,8 and only in really *grippy* conditions, like in the case of racing slicks over a good circuit pavement, it can present a value over 1. Although in real life this motorcycle will never face such situation, it has been taken a friction coef. of 1 in order to have a really taught acceleration simulation.

Finally it is possible to present the boundary conditions that will support the maximum acceleration simulations of this project: the gravitational acceleration and a longitudinal acceleration with the same value as the gravitational.

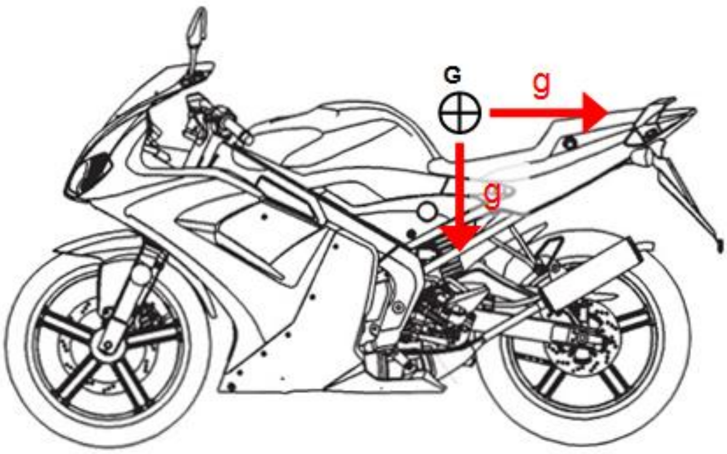


Fig.75 Scheme of accelerations for the simulation

·Maximum braking: it happens when the motorbike, going at a certain speed in straight line conditions, brakes with the maximum power available. Like in the previous case, there are two different approaches: considering the maximum acceleration given by the braking system (which is a really interesting but unnecessary long and complicated way of studying this problem) or considering the maximum force that can handle the tire before slipping. Like before, the second option is the most suitable one. In this case, the scheme is almost symmetrical:

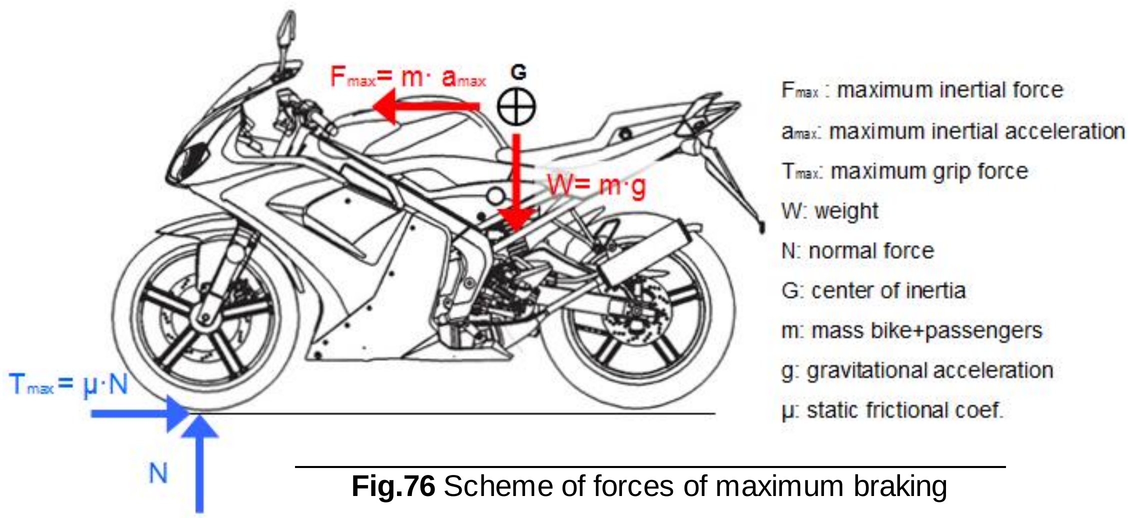


Fig.76 Scheme of forces of maximum braking

In this case, the hypothesis are that the rear wheel has begun to lift and that all the braking is done through the front brake (it would make nonsense otherwise, as the other wheel is not touching the ground). The maximum acceleration is determined as follows:

$$F_{max}=T_{max}$$

$$W=N$$

$$m\cdot a_{max}=\mu\cdot m\cdot g$$

$$\mathbf{a_{max}=\mu\cdot g}$$

And if we consider again that μ takes a value of 1, it's easy to see that the boundary conditions of these simulations are:

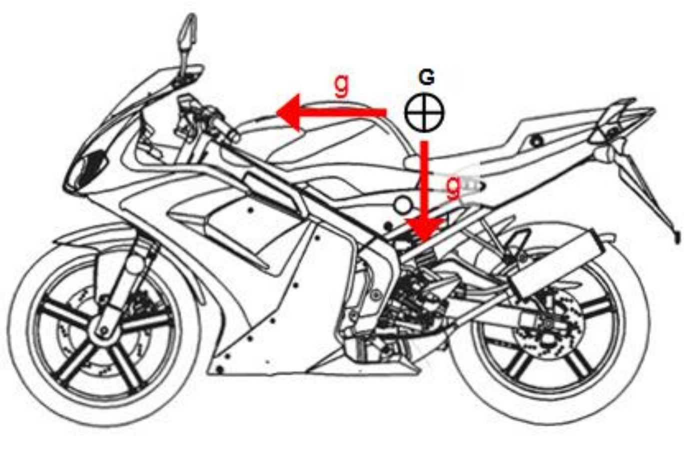


Fig.77 Scheme of accelerations for the simulation

·Maximum cornering: this one happens when the bike is in the middle of the corner and, without applying torque to the wheel, the tire is working on the limit of the grip. The different loads that appear in this case are shown below:

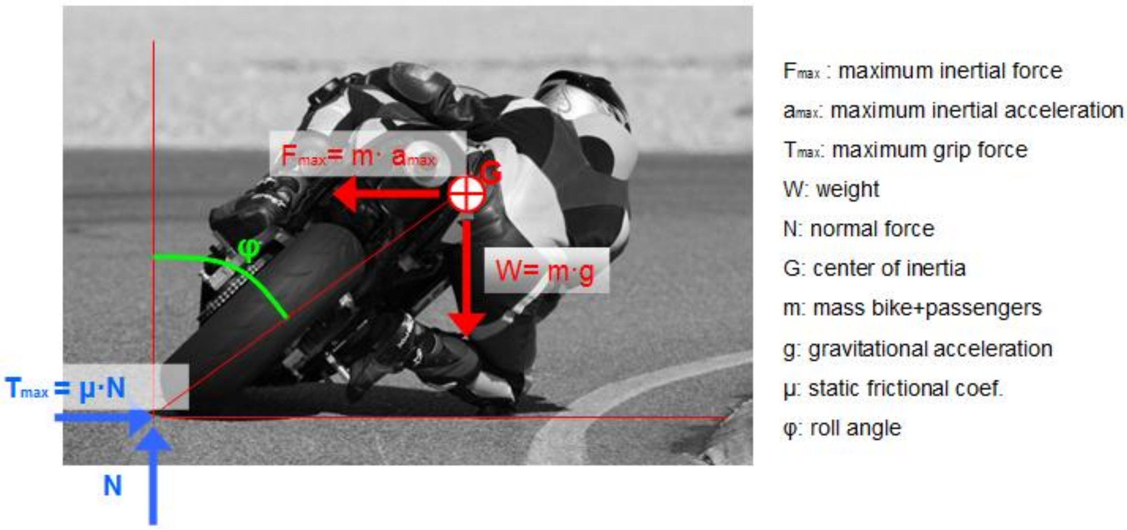
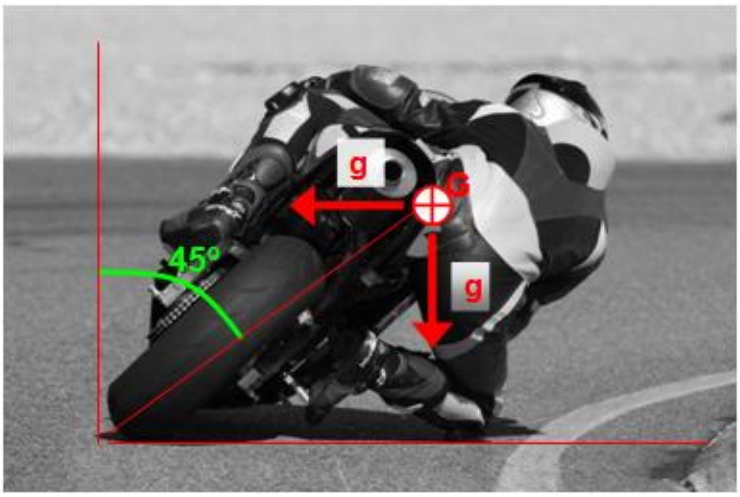


Fig.78 Scheme of forces of maximum cornering

In this case the inertial force corresponds with the centrifugal force, and its acceleration can be defined trough the tangential speed of the bike and the radius of the curve:

If we continue considering that the maximum static friction coefficient is 1, the maximum centrifugal acceleration must be equal to the gravitational one. From here it is easy to calculate that the equivalent roll angle to this acceleration is 45º. That means that the accelerations that must be put in the simulations are:



In the coordinate system of the motorcycle this traduces one single vertical acceleration with a value of

$$\sqrt{2}\cdot\mathbf{g}$$

Fig.79 Scheme of accelerations for the simulation

7.5.2. Subchassis results

It's remarkable that in maximum braking conditions, the simulation for the subchassis makes no sense because the load coming from the weight of the rider and the passenger moves forward and is no longer in contact with the body. For this reason, here is only presented the other two simulations: maximum acceleration and maximum cornering.

·**Maximum acceleration:** the boundary conditions of this simulation involve the definition of the masses of the passengers (75kg each), an acceleration of G in the direction of *y*, another one in the direction of *x* and the fixation of the parts that are in contact with the frame.

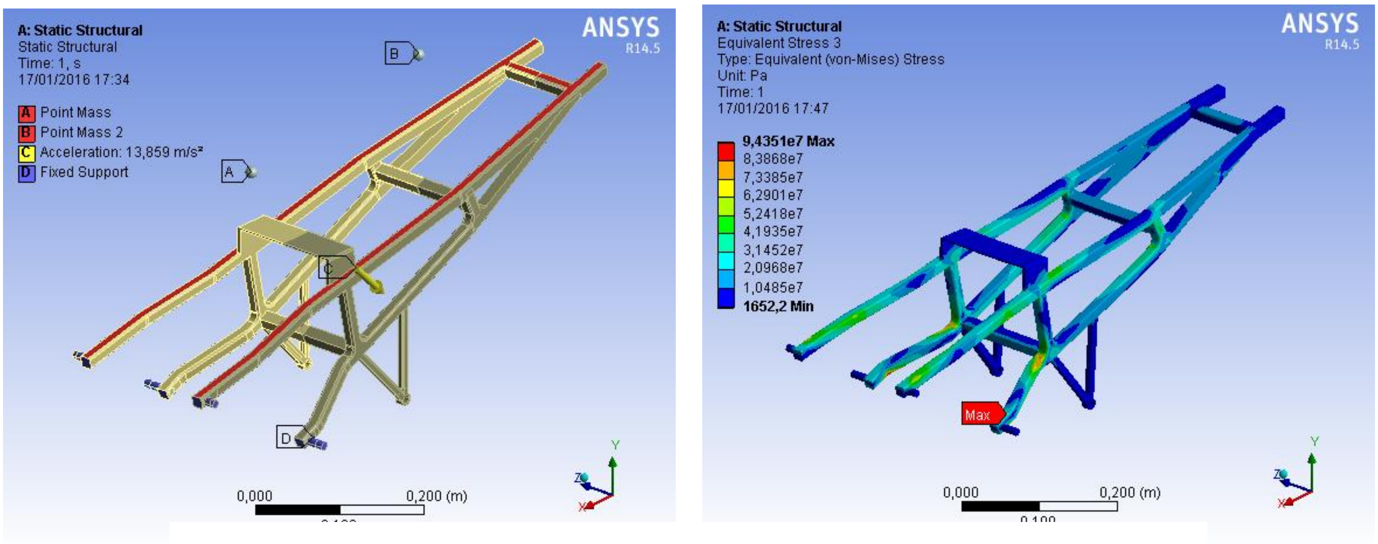


Fig.80 Boundary conditions and stress distribution for maximum acceleration

The safety factor can be calculated as follows:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{355MPa}{95MPa} = 3,73$$

·**Maximum cornering:** the boundary conditions of this simulation implies the definition of the masses of the rider and passenger (75Kg each), the acceleration of 13,8 m/s2 in the direction of *y* and the fixation of the parts that are in contact with the frame

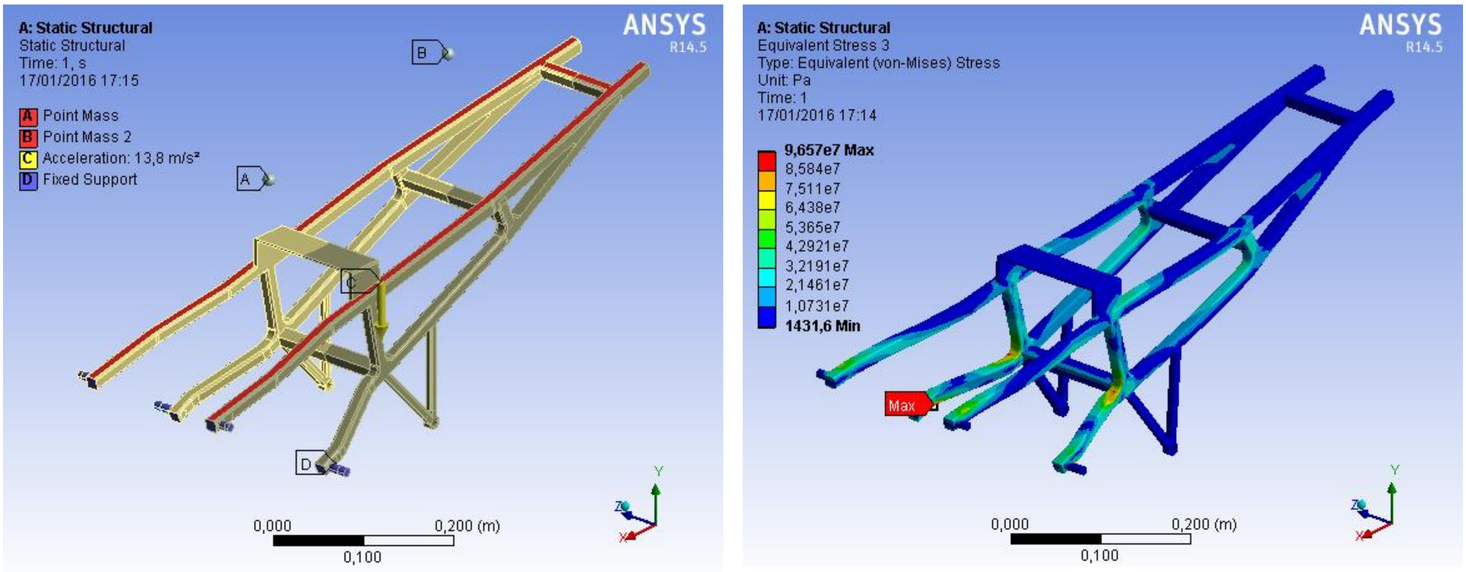


Fig.81 Boundary conditions and stress distribution for maximum cornering

From the stress representation, it is possible to calculate the safety factor:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{355MPa}{97MPa} = 3,65$$

7.5.3. Cradle results

·Maximum acceleration: the boundary conditions of this simulation involve the definition of the masses of the electronic components (30kg), an acceleration of G in the direction of *y*, another one in the direction of *x* and the fixation of the parts that are in contact with the frame.

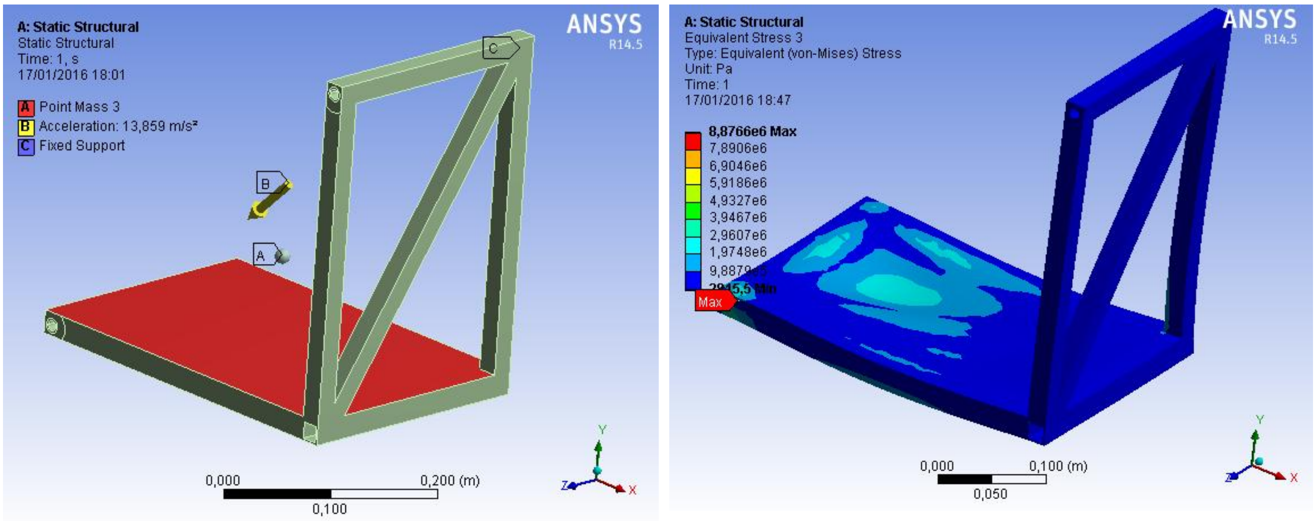


Fig.82 Boundary conditions and stress distribution for maximum acceleration

According to the maximum stress that suffers the body, the safety factor has a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{145MPa}{8{,}87MPa} = 16{,}34$$

·**Maximum braking:** this one has the same boundary conditions as the previous one but the acceleration in *x* has the opposed direction.

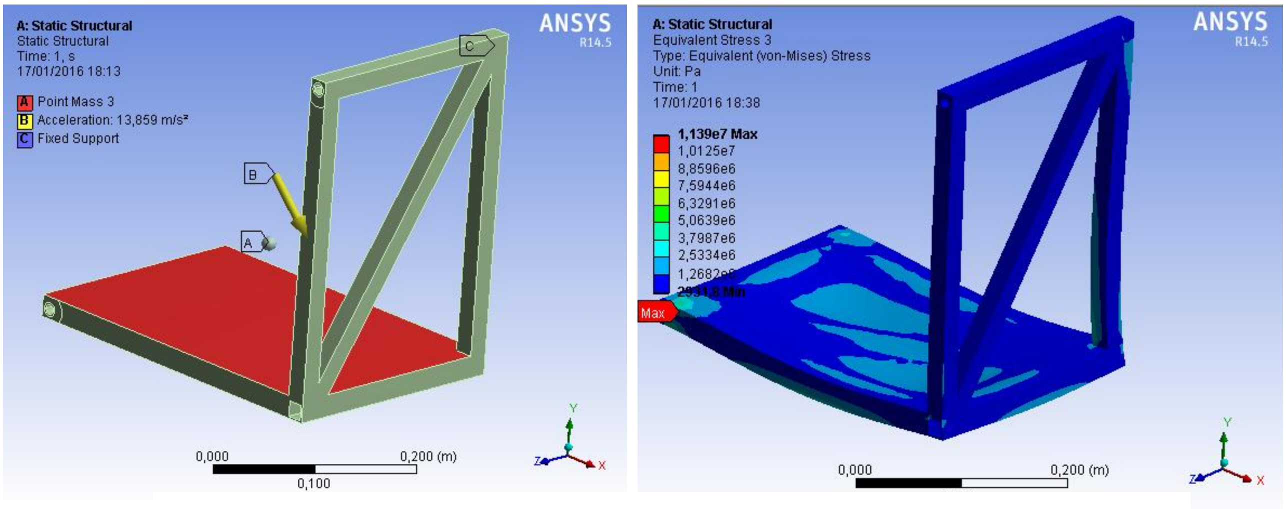


Fig.83 Boundary conditions and stress distribution for maximum braking

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In this case, the safety factor takes a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{145MPa}{11{,}4MPa} = 12{,}71$$

·Maximum cornering: the boundary conditions of this simulation implies the definition of the masses of the electronic components (30kg), the acceleration of 13,8 m/s2 in the direction of *y* and the fixation of the parts that are in contact with the frame

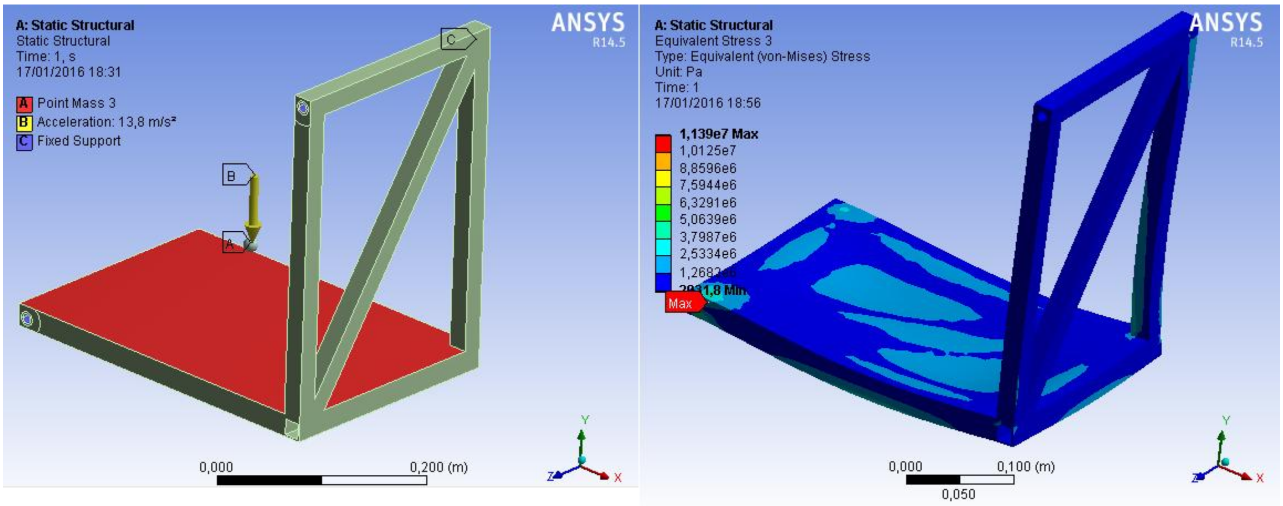

Fig.84 Boundary conditions and stress distribution for maximum cornering

The safety factor, in this case has a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{145MPa}{13{,}4MPa} = 10{,}82$$

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7.6. Other particularities

A part from the main simulations that have been exposed here, there's a lot of small pieces that must be studied to make sure that the loads that are receiving will not make them fail. For instance, the footrest support is a small piece that has to be capable of resisting even though the rider has put all the weight on one single footrest:

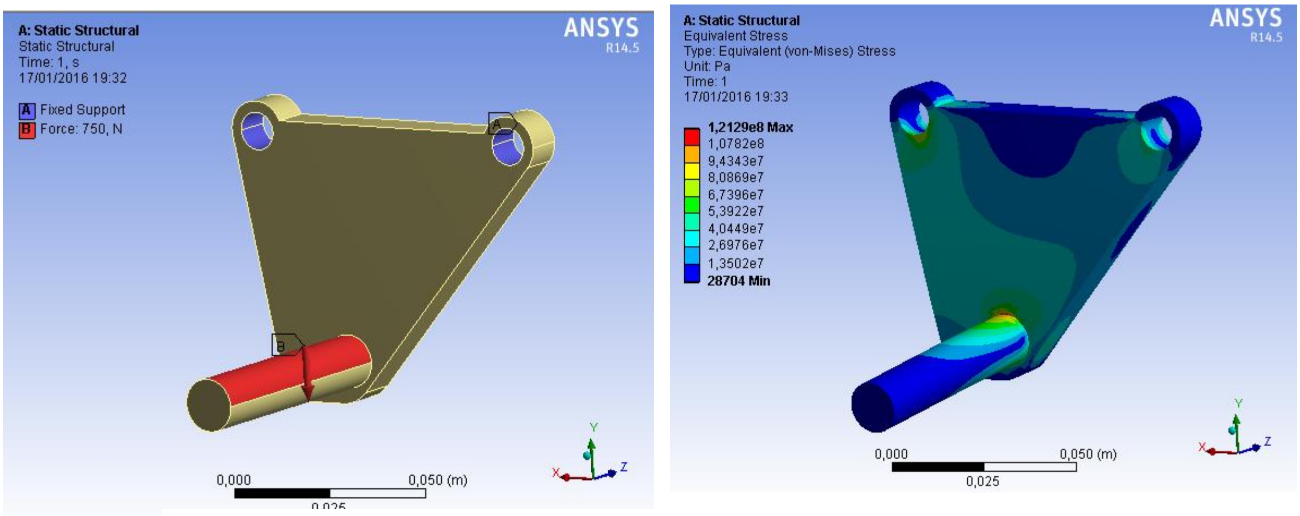

Fig.85 Boundary conditions and stress distribution for the resistance simulation

According to the maximum strength and the yield strength of the stainless steel AISI304, the safety coefficient has a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{215MPa}{121MPa} = 1,78$$

On the other hand, the kickstand support has to be capable of holding the bike and the rider. To make this simulation, some hypothesis have been done: first, the kickstand supports the third of the weight of the bike and the rider (the other 2/3 of the weight is held by the tires); and second, the kickstand makes the bike to lean 15º from the vertical.

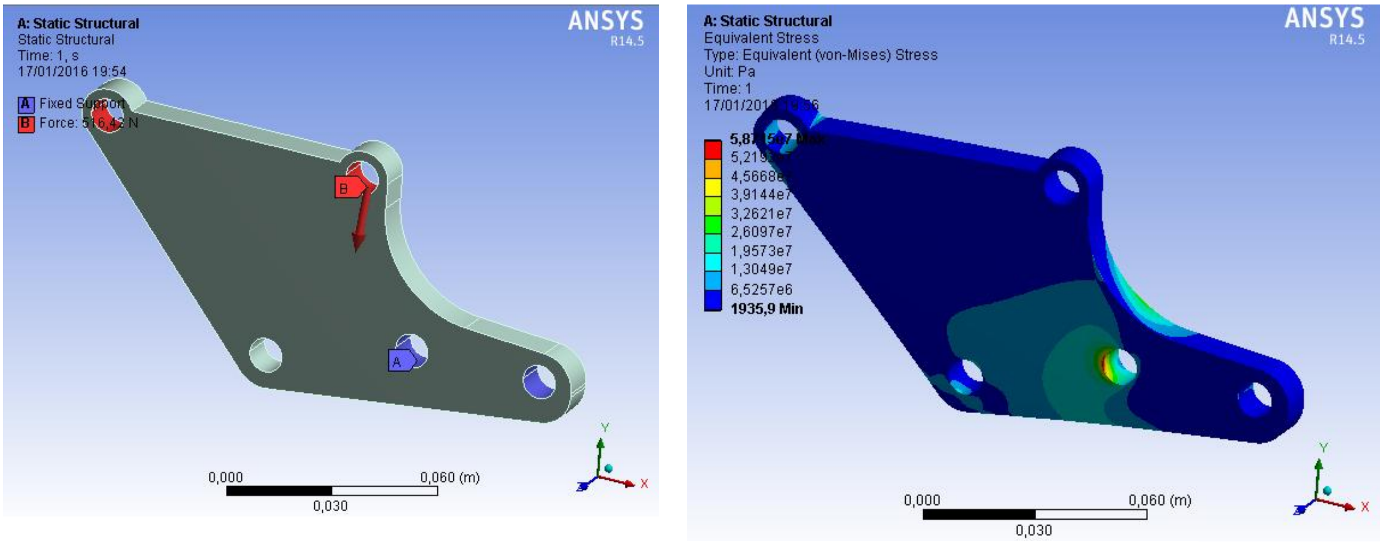

Fig.86 Boundary conditions and stress distribution for the resistance simulation

This time, the safety factor takes a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{215MPa}{58,7MPa} = 3,67$$

Finally, the last simulation that is going to be shown in this project is the one that emulates the union between the swing arm and the HUB motor. The sheet that holds the wheel shaft has to be capable of receiving the highest torque of the motor (28Nm) without failing:

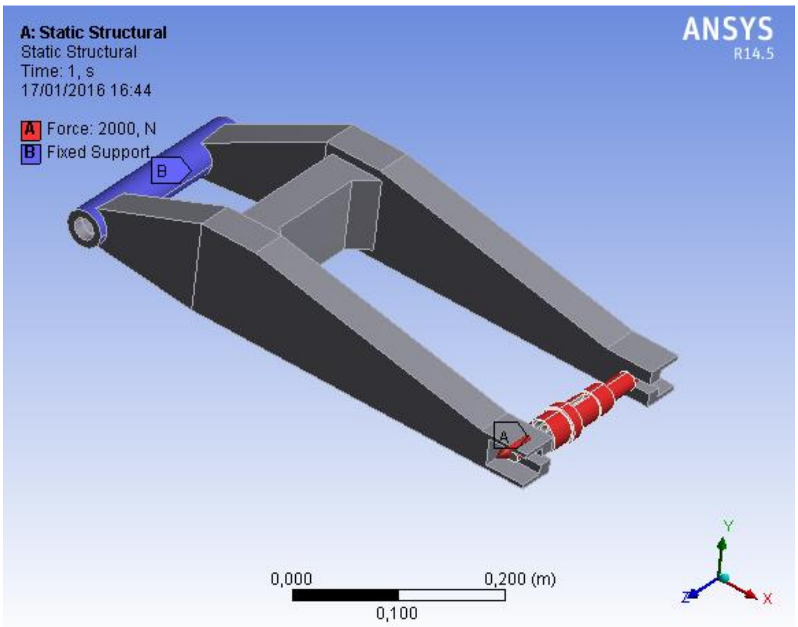

Fig.87 Boundary conditions for the resistance simulation of the swingarm

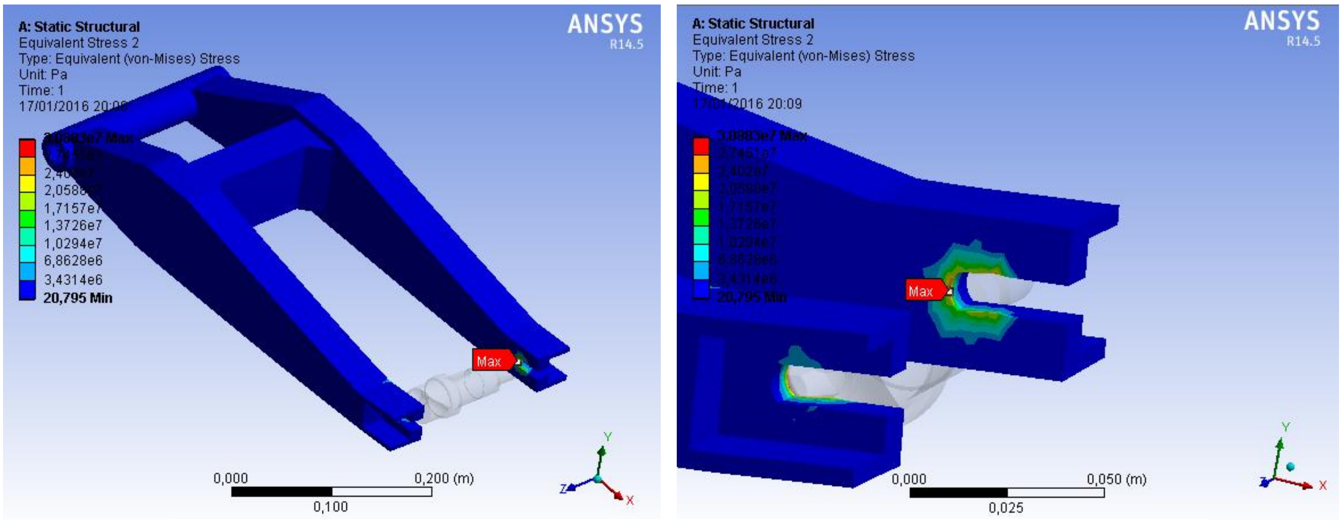

Fig.88 Stress distribution of the resistance simulation following Von-Mises criteria

The safety coefficient for this simulation takes a value of:

$$\gamma = \frac{\sigma_y}{\sigma_{max}} = \frac{145MPa}{30,9MPa} = 4,70$$

8. Fabrication process

In this chapter is shown how the fabrication of the main parts of the chassis is going to be done. These main parts are the frame, the powertrain cradle, the subchassis and the swing arm. The main idea is to clarify how the geometry is going to be physically carried out, from raw materials to the final result.

8.1. Frame

One of the objectives when designing the frame was obtaining a final structure as simple as possible in order to have a really easy fabrication process. As it will be seen, the objective has been reached. The basic structure of the frame is formed by two big aluminum beams that go from the steering head to the swing arm. These beams, as a matter of fact, are formed by two pieces of a commercial rectangular profile welded in angle that then connect with a solid piece of aluminum. The dimensions of the profile are 40mmx120mm with a thickness of 4mm. The solid piece comes from a rectangular piece with a thickness of 20mm that has been cut with EDM (electrical discharge machining) and has been drilled to place the different shafts. To connect both parts, that have different thickness, there is a milled piece that fits into the rectangular profile and into the solid piece.

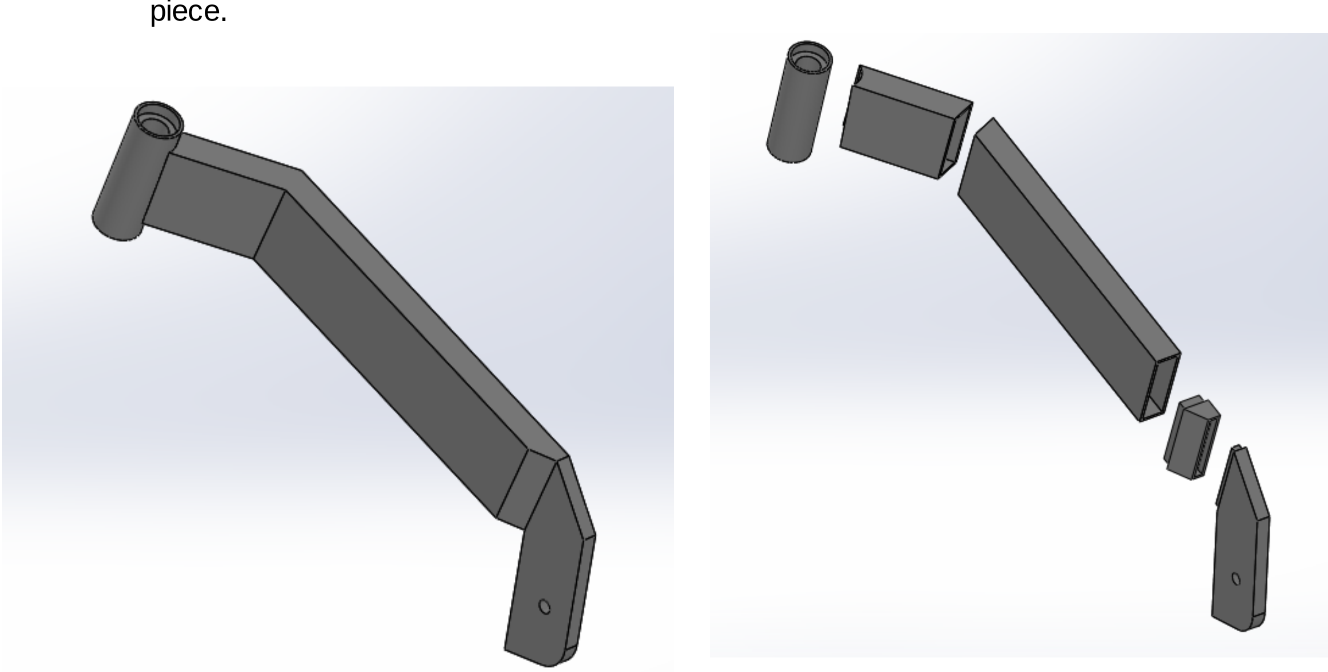

Fig.89 Assembled and disassembled beam of the frame

The steering head is a cylindrical piece that has been lathed to house the fork shaft and the bearings. It's remarkable that the tolerance of the bearing housings must be H7 in order to have the right adjustment.

There are two square profiles that connect both beams. The first one, with 30mm and 3mm of thickness will hold the top of the shock and the second one, with 20mm and 2mm of thickness contains the linkage to the rocker.

The rest of pieces are the appendixes that serve to attach the different components such as the subchassis or the powertrain cradle. These pieces can be mechanized from raw sheets through water jet cutting or EDM depending on the thickness.

The welding is going to be done with TIG and MIG technologies, leaving that decision to the welder because depending on the circumstances, sometimes it is better to use one or another. To guarantee dimensions and tolerances in the welding process, a simple jig will be required; the design and construction of the jig will be left to the welder as well, but supervised before the welding begins to make sure that the critical dimensions will be followed.

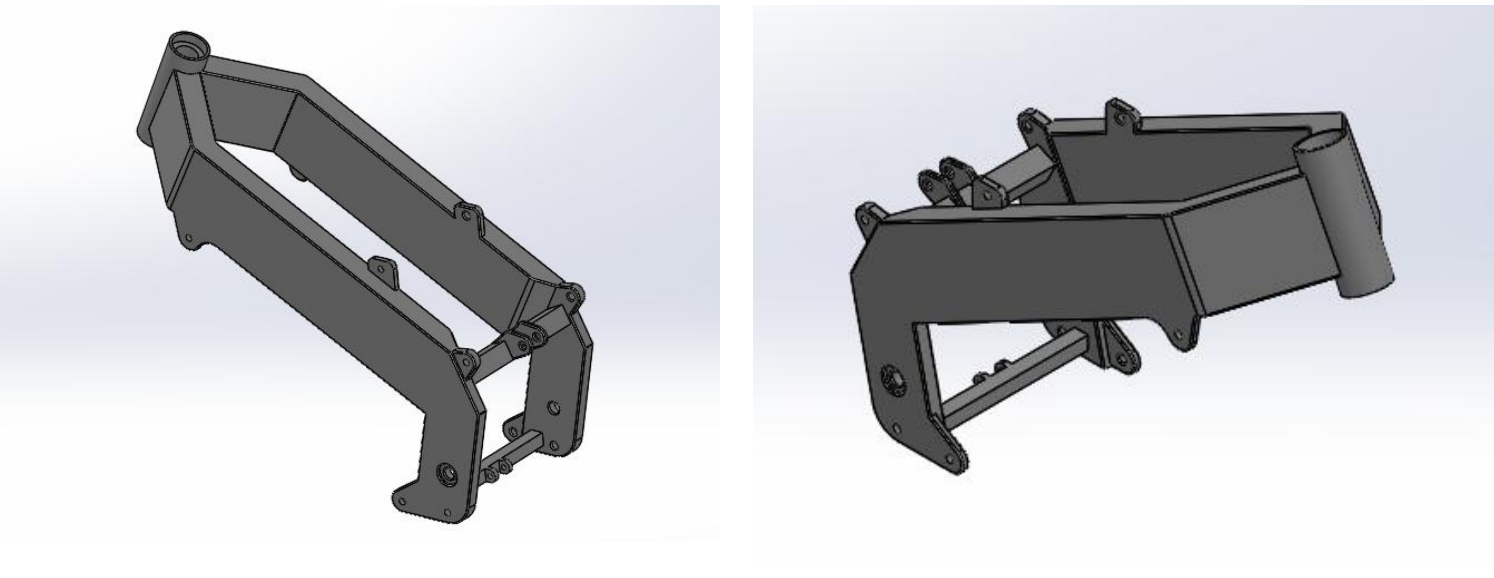

Fig.90 Views of the final result

8.2. Powertrain cradle

The cradle's design involves a very simple fabrication as well. It is simply formed by square aluminum tubes of 20mm with 2mm of thickness that are welded to form the structure. However, in the extremes where it is attached to the frame, small machined parts have been put to improve the attachment and the contact with the steel bar that goes inside. This way, the tubes that arrive to these corners are welded on the milled parts.

Over the bottom structure has been put an aluminum sheet of 3mm of thickness in order to accommodate the components.

The welding criteria are the same as for the frame.

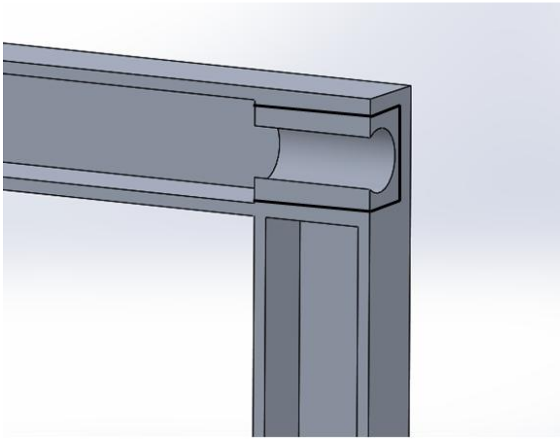

Fig.91 Detail of the machined parts in the corners

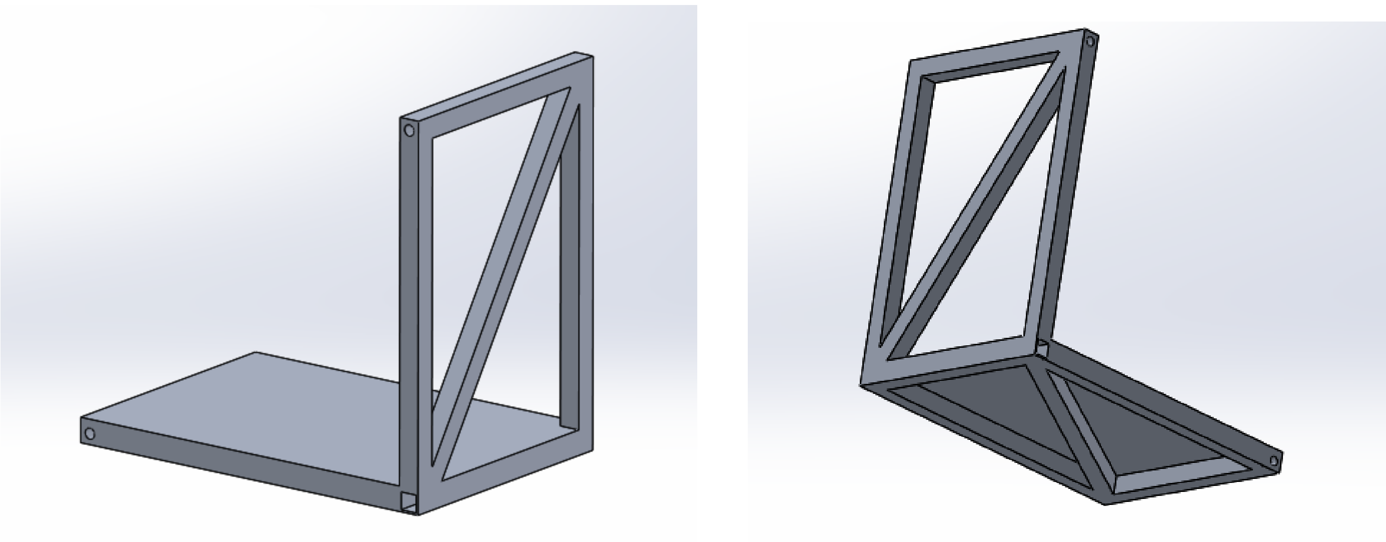

Fig.92 Views of the final result

8.3. Subchassis

The structure of the subchassis is formed by commercial steel square tubes. The 4 basic ones go from the attachment of the frame to the end of the tail, where they meet and are welded. These ones are 15mm wide with a thickness of 2mm and are bended to obtain the desired geometry; it has been checked by the manufacturer that the bending angles defined are possible and will not weaken the tube. Although each tube presents different bends, all of them are placed in the same plane, which makes the process much easier.

Between the main ones, several other tubes are welded to strengthen the structure; these ones are 15mm wide and 1mm thick and are straight. Besides, two sheet pieces with 3mm of thickness are bended and welded to the body. Like it happened with the cradle, small machined parts are introduced in the places of the subchassis that have external attachments: where the body is held in the frame and where the passenger footrest is going to be mounted.

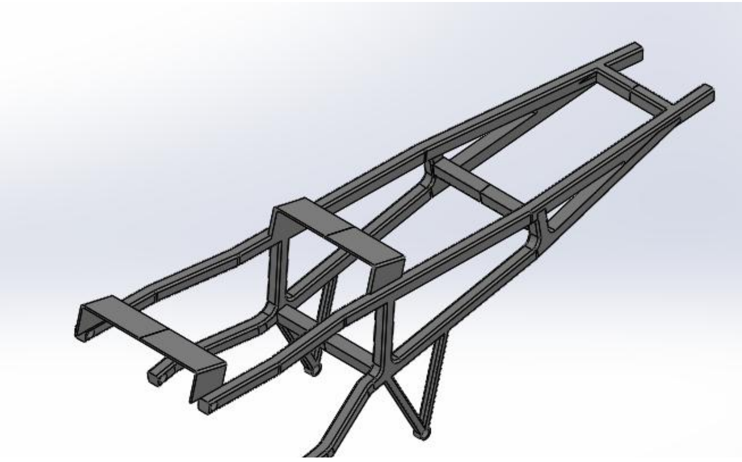

Fig.92 View of the final result

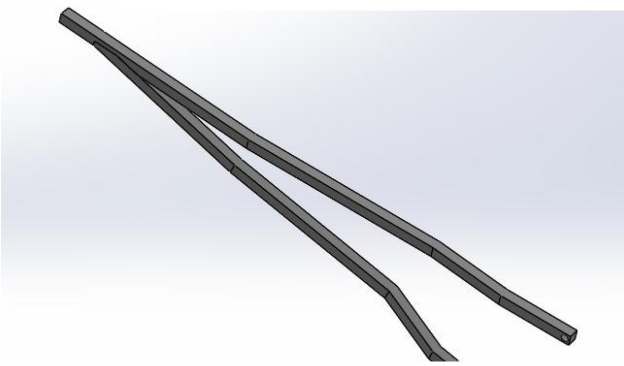

Fig.93 Detail of the bended tubes

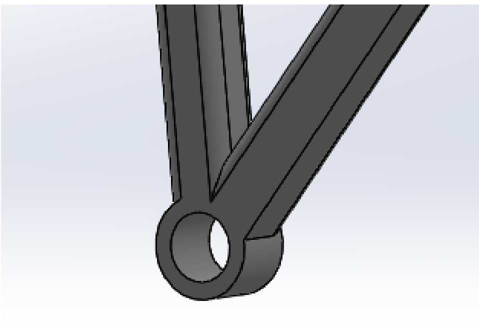

Fig.94 Detail of the machined parts

8.4. Swing arm

The design of the swing arm is based on two main beams, like in the frame. In this case, these beams go from the pivot to the wheel axis and are formed by two pieces of commercial rectangular profiles that have been welded in angle. Then, in the extremes where the wheel is attached, a milled piece is introduced. The commercial tubes have the following dimensions: 100x40mm and 4mm thick; they have been cut longitudinally to obtain the geometry desired and in order to cover the holes, pieces of sheet are welded. The milled piece is able to get into the rectangular profile so as to improve the contact between bodies

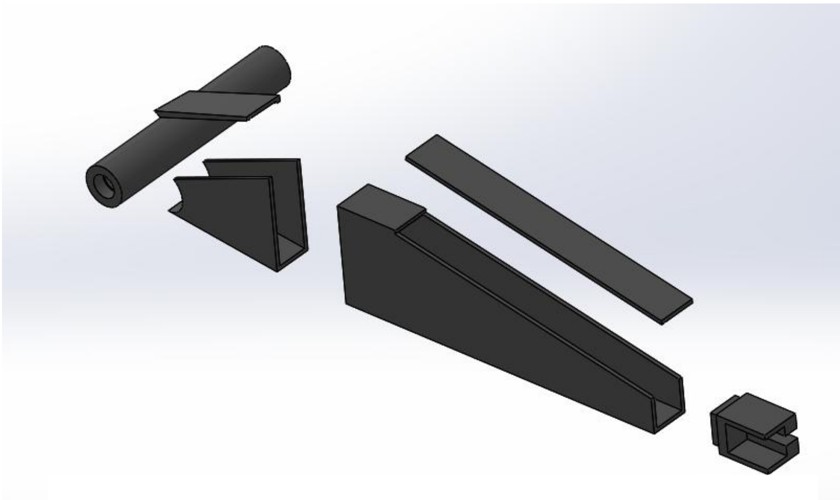

Fig.95 Disassembly of the beam of the swing arm

The swing arm pivot is a cylindrical part that has to be lathed to house the shaft that goes inside and the roller needle bearings. The tolerance for the bearing housing must be H7 as well.

Between both beams, another rectangular tube is welded that measures 80x40mm and 5mm thick. From this tube, two appendixes to hold the suspension rocker are welded. These can be cut through water jet from a raw sheet. Between this tube and the main beams there are two prismatic pieces that can be done with a mill or cut from a solid piece with EDM.

Finally, another machined piece must be welded to the swing arm: the caliper support. It's the most complicated geometry but it entails no particular problem for a CNC mill.

Like with the other parts, the welding techniques used will be TIG and MIG.

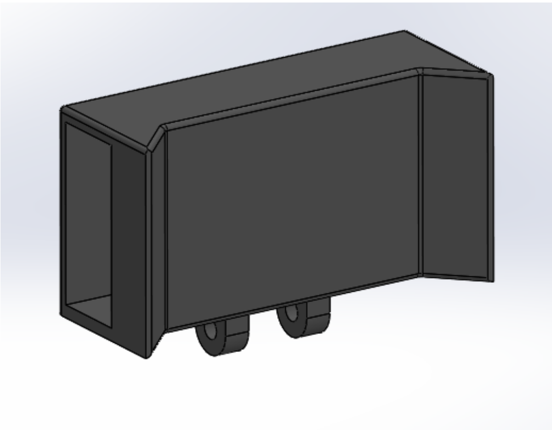

Fig.96 Detail of the central tube

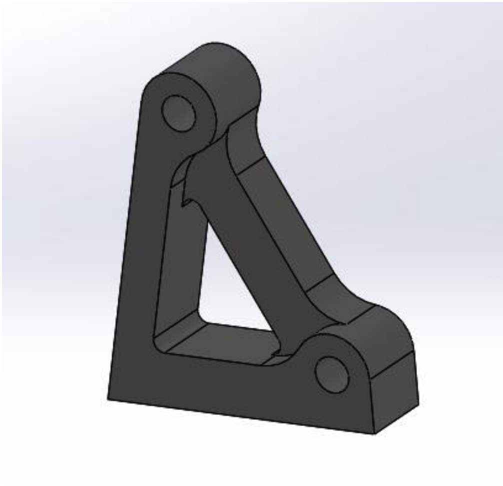

Fig.98 Detail of the caliper support

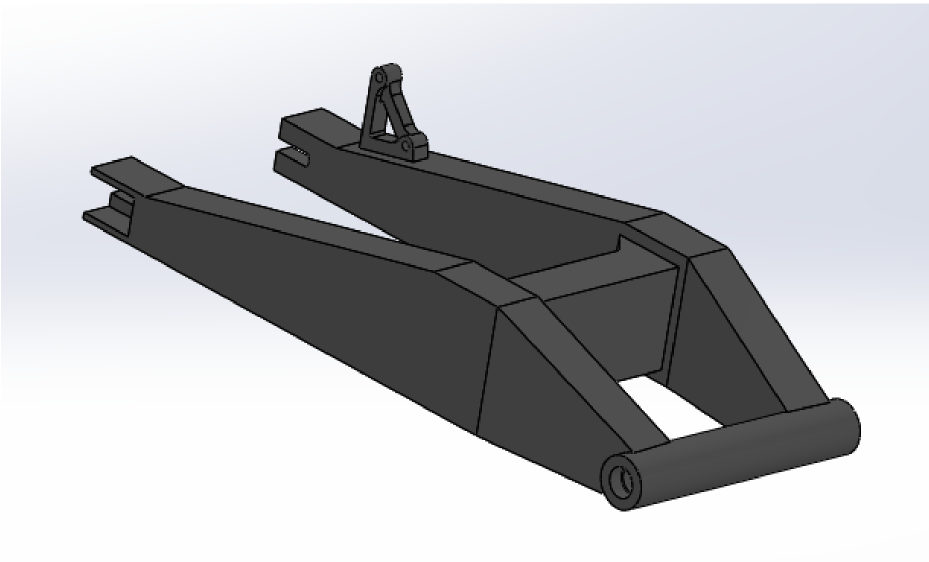

Fig.99 Overview of the final result

9. Budget

The aim of this chapter is presenting an approximated cost of the project and to have a general idea of how the time and the money have been invested between the different parts. Mainly, this budget is formed by two categories: the first one is the cost of development of the project and the second one is the cost of fabrication of the different parts (frame, subchassis and swing arm). The cost of development shows the approximate fee that an engineer could earn after doing this project in a company. The cost of fabrication of the prototype involves all the costs that have taken place during the manufacturing process, from the procurement of the materials, the machining, welding... and also the employee fees. For this last cost, a much approximated overall value has been given by the manufacturing sponsor, without further apportionment, that includes all the workshop expenses.

Considering that this project has a value of 12cr and that every credit involves approximately 25h of work, the total time invested on this project has been 300h. It can be divided into:

	€/h	h	€
Research	40	75	3000
Conceptual design	50	25	1250
FEM analysis	50	100	5000
CAD design	35	75	2625
Documentation	25	25	625
			12500

In addition to this value, the equivalent cost of the license of the programs used must appear:

	€/year	h/year	€/h	h	€
Ansys Workbench 14.5	30000	1000	30	100	3000
Solidworks 2014	15000	1000	15	75	1125
					4125

This makes a total cost of development of 16625€.

The approximate cost of fabrication given by the sponsor is 6000€.

The total budget for the project is 16625+6000= **22625€.**

10. Environmental Impact

Electric mobility is arguably one of the major symbols of the green movement. Probably the reason is that this particular part of the automotive industry has to fight directly against the refineries and fossil fuel producers to survive. Considering all the global interests and the great amount of money that fuel moves, the fact that the electric mobility exists is already a win and shows that the world is beginning to understand the effects of pollution. Every day, the concept of carbon footprint takes more importance in the industry, and companies and also costumers want to make sure that products are not damaging the environment.

However, nowadays the carbon footprint of an electric motorcycle is not as clean as it seems. Although the motorcycle itself won't pollute during its use, the carbon footprint considers all the emissions throughout the cycle of life of the product and because the electricity used to charge the batteries from the mains comes not only from clean sources, the amount of carbon cannot be considered 0. Adding to this, the electricity used for the fabrication and the later scrapping has to be taken into account. Only if all the possible sources of the electricity of the mains were renewable, or at list not polluting, the value of the carbon footprint could be 0, and for now, this affirmation cannot be done. Anyway, compared to a traditional motorcycle, this value is very small.

Neglecting the effect of the carbon footprint, there is certainly one factor of electric vehicles that has an adverse effect on the environment: batteries. The kind of batteries that uses the most part of electric vehicles nowadays contain hazard materials for the earth and the environment and, most of the times, they cannot be recycled. This constitutes the main downside of electric vehicles referring to the environment keeping and is one of the main reasons for the investigation on the hydrogen cell.

Referring particularly on the building of the chassis, that is what this project is about, it is remarkable how small the environmental impact is. All the materials used for the construction of the chassis are highly recyclable: the aluminum used for the frame and the steel used for the subchassis are examples of it. As a matter of fact, a high percentage of the production of these two materials comes directly from recycled parts. However, it is true that the electrical energy used to build these parts is not small: welding, milling, lathing... are activities that require heavy duty machines and have a high specific consumption of electricity. In addition, the materials used here are not completely raw; that means that in order to obtain the different tubes, sheets or solid parts an important electrical power has been used.

11. Time planning

Time Planning	28 Sep- 11 Oct	12 Oct - 25 Oct	26 Oct - 8 Nov	9 Nov - 22 Nov	23 Nov - 6 Dec	7 Dec - 20 Dec	21 Dec - 3 Jan	4 Jan - 17 Jan
Research	Others	Others	Others					
Boundary conditions		Design						
Basic geometries			Design					
Powertrain conditions and packaging			Design					
First design of the frame				Design				
Stiffness simulations of the frame				FEM simulation	FEM simulation			
Check material (frame)				Fabrication				
Wheels, fork, suspension type					Design			
First design of the swing arm					Design			
First design of the subchassis						Fabrication		
Check material (subchassis)						Fabrication		
Check material (swing arm)						FEM simulation	FEM simulation	
Stiffness simulations of the swing arm						FEM simulation	FEM simulation	
Resistance simulation of the chassis assembly						Design		
Bearings						Design		
Brakes and discs							FEM simulation	FEM simulation
Resistance simulation of the rest of parts							Design	Design
Final design of the frame							Design	Design
Final design of the subchassis							Design	Design
Final design of the swing arm							Design	Design
Writing memory						Others	Others	Others

Design	green
FEM simulation	blue
Fabrication	red
Others	orange

12. Conclusions

The final result of this project has been very favorable, for the objectives that have been put in the beginning have been achieved. Next, a little explanation of the accomplished objectives is done:

The chassis presented meets all the requirements that were asked: it has all the main electronic components and still leaves room for unforeseen changes, it presents the desired geometry and a fairly good approximation to the ergonomics that we're looking for, the mass distribution has been taken in account in the design and the geometry meets the given manufacturing limitations.

The chassis passes all the simulation tests: the numerous resistance simulations of all the parts that have been designed bear out that the chassis will be able to support all the unforeseen critical loads that will suffer the motorcycle during its life. Furthermore, the stiffness simulations of the frame and the swing arm also guarantee handling features of first class. And it has been possible to obtain these properties with a significantly small weight.

The chassis is ready to be manufactured: all the manufacturing process is presented with detail and the spare parts that are needed to form the chassis assembly have been mentioned and specified.

Finally, as a final personal conclusion, I would like to say that I've learned a lot through this project and that it has fulfilled all the expectations. I was looking for a more profound knowledge of the chassis development process when I chose this topic for my project, and without any doubt, it has been like that. Being able to invest so much time on something that really interests me and having prof. Angulo giving advice and marking clearly the guidelines of the process, have made possible to obtain a final result of which I can say I feel very proud. However, it hasn't been easy to carry it out, because it signifies practically all the work that has to be done in the dynamic department of the team during all the year, and this project has been made only in one quatrimester. Looking at the result, though, it has definitely worth it.

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