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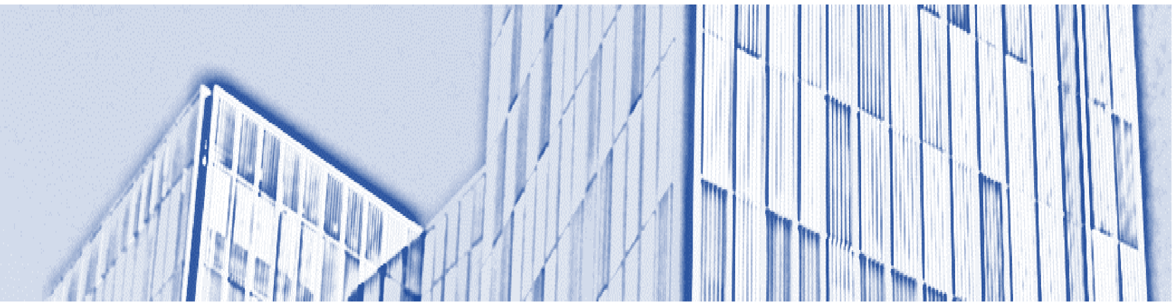
TREBALL FI DE GRAU

Grau en Enginyeria Mecànica

TENSION STUDY OF A CARBON FIBER BOGIE FRAME



Volum I

Memòria

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Abstract

The bogie is one of the essential components of what constitutes a train. It allows the train to run on the train tracks, supports the weight of the car-body, passengers and withstands the forces that appear when; in motion, accelerating and decelerating, alongside ensuring the ride is as comfortable as possible for the passenger. Throughout the years, the bogie has undertaken many design changes – starting from freight transport, to highspeed passenger trains, to light rail city trains, and so on. These designs make it so that the bogie specializes in a certain task, such as making it more efficient, environmentally friendly, or cost effective. All these factors are important when designing a bogie.

The focus of this thesis is the study of the forces that appear in the frame of the bogie when in use, as well as how a fiber reinforced composite material would compare to the standardized structural steel S235 version for the bogie frame. In the railway industry, there is currently an initiative to reduce the amount of railway transport CO2 emissions by 55% by the year 2030, following a zero-emission target in the year 2050, which may be achieved with the use of composite materials, especially in the bigger and heavier parts of the bogie. Recycled carbon fiber is the trusted composite material for the frame, and with it you can achieve higher cost-weight viability without forfeiting structural strength or flexibility, making it more sustainable and saving millions of euros in the process.

For the development of this literature, I used a 3D design software; Solidworks, an Analysis FEM software; ANSYS, and Excel, to do the calculations as well as the illustration listed below.

Keywords: bogie frame, Von Mises, Fiat bogie frame, ANSYS, SolidWorks, stress-strain analysis.

Resumen

El bogie es uno de los componentes esenciales que constituye un tren. Permite que el tren vaya en las vías, sostiene el peso del coche, de los pasajeros, resiste las fuerzas que aparecen cuando: en movimiento, acelerando y frenando mientras asegurando que el pasajero este cómodo durante el viaje. A lo largo de los años, el bogie se modifica varias veces – desde el transporte de mercancías, los trenes de alta velocidad, los "trenes ligeros", entre otros. Estos diseños están hechos para que el tren se especialice en una tasca en concreto o mejorarlo de alguna manera como puede ser: ser más eficiente, conseguir producir menos emisiones, o reducir el coste en total. Todos estos factores son importantes cuando se diseña un bogie

El enfoque central de este TFE es el estudio de las fuerzas que aparecen en la estructura mientras esta en uso, además de cómo se compara fibra de carbono con el acero estructura S235 como material primario de la estructura. En la industria ferroviaria hay una iniciativa de reducir las emisiones de CO_2 hasta un 55% para el año 2030, y en el año 2050 el objetivo es aumentarlo a cero emisiones; cosa que se puede conseguir con la fibra de carbono, en especial con las partes grandes y pesadas del bogie. La fibra de carbono reciclada es el material que se ha escogido estudiar para la estructura del bogie, ya que, con él, se puede conseguir una viabilidad de coste-peso sin renunciar la fuerza estructural del bogie o flexibilidad, haciéndolo sostenible y un buen candidato como remplazo del acero estructural S235.

En este trabajo se ha utilizado: SolidWorks, un software de diseño 3D, ANSYS, un software diseñado para hacer simulaciones y Excel, para realizar los cálculos numéricos y producir las ilustraciones.

Palabras clave: Estructura del bogie, Von-Mises, estructura Fiat bogie, ANSYS, SolidWorks, analisis tensión-deformación.

Resum

El bogie és un dels components essencials que constitueix un tren. Permet que el tren circuli en les vies, sosté el pes del cotxe, dels passatgers, resisteix les forces que apareixen quan: en moviment, accelerant i frenant, assegurant que el passatger estigui còmode durant el viatge.

Al llarg dels anys, el bogie es modifica diverses vegades - des del transport de mercaderies, passant per els trens d'alta velocitat, els "trens lleugers", entre d’altres. Aquests dissenys estan fets perquè el tren s'especialitzi en una tasca en concret o millorar-lo de alguna manera com pot ser: ser més eficient, aconseguir produir menys emissions, o reduir el cost en total del tren. Tots aquests factors són importants quan es dissenya un bogie.

L'enfocament central d'aquest TFE és l'estudi de les forces que apareixen en l'estructura mentre està en ús; a més a més de com es compara la fibra de carboni, amb l'acer estructural S235 com a material primari de l'estructura. En la indústria ferroviària hi ha una iniciativa de reduir les emissions de CO_2 fins a un 55% en l'any 2030, i l'any 2050 l'objectiu és aconseguir arriba a zero emissions; cosa que es pot assolir amb la fibra de carboni, especialment amb les parts grans i pesades del bogie. La fibra de carboni és el material que s'ha escollit estudiar per a l'estructura del bogie, ja que, amb ell es pot aconseguir una viabilitat de cost-pes sense renunciar la força estructural del bogie o flexibilitat, fent-ho sostenible i un bon candidat com reemplaçament de l'acer estructural S235.

En aquest treball s'ha utilitzat: SolidWorks, un programari de disseny 3D, ANSYS, un programari dissenyat per fer simulacions, i Excel per realitzar els càlculs i les il·lustracions.

Paraules clau: Estructura del bogie, Von-Misses, estructura Fiat bogie, ANSYS, SolidWorks, anàlisi tensió-deformació.

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First and foremost I would like to thank my family and friends for their shower of support, love, caring and sacrifices for educating me and preparing me for my future; with a special focus to my brother-in-law for his guidance and help with respect to the research aspect. Another person I would like to express my gratitude is my brother for his friendship, empathy, and his great sense of humor that made this less challenging.

I would like to express my deep and most sincere gratitude to my research supervisor Sanchez Egea, J. Antonio; professor in the Mechanical Engineering department of the Polytechnical University of Catalonia. His dynamism, vision, sincerity, and motivation has deeply inspired me. He has taught me the methodology to carry out the research and to present the research work as clearly as possible. I am delighted and honored to work under his guidance, and extremely grateful for his time and patience.

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Vocabulary

Some words would need to be detailed before the read of this thesis:

a. *Bogie:*
   Def. - A bogie is a rolling structure on which the railway wagons and locomotives rest, allowing the train structure to run on tracks, ensuring the passengers' comfort and safety (for passenger trains).

b. *Jacob bogie:*
   Def. - Jacobs bogies are a type of bogies that instead of being under a piece of rolling stock, Jacob's bogies are placed between two wagons. These bogies are common in articulated trucks.

c. *Track Gauge:*
   Def. – Track gauge is the distance between the train's wheels. Each country has their very own track gauge. Most railways in Europe use the standard gauge of 1.435 mm.

d. *Freight:*
   Def. – These are goods transported either by trains, aircrafts, trucks, or boats. The correct name for trains for this category is freight trains.

e. *Car body:*
   Def. – A car body for a train is the structure that is connected to the bogie when in use. It is where the passenger is located throughout its transport.

f. *Locomotive:*
   Def. – A locomotive is a self-propelled vehicle that runs on rails and is used for moving railroad cars. It is located on one of the two ends of the trains to tuck the train from point A to point B.

g. *Von-Misses stress:*
   Def. – Von-Misses stress is a criterion used with the intent to determine if a material will yield or fracture. The Von-Misses yield criterion states that, if the Von-Misses stress of a material under load is equal or greater than the yield limit of the same material under simple tension then the material will yield.

h. *Unidirectional:*

Def. – Involving a single direction. Related to the fibers in the CFRP, the fibers that make the composite are all orientated in one direction.

i. *Carbon fibers:*

Def. – Material containing of thin, powerful crystalline strands of carbon, used as a reinforcing material. Using a strong resin, you could create a complex structure of just this material alone.

Abbreviations:

Table 1. Table of abbreviations and meanings

Abbreviations	Meaning
UITP	International Association of Public Transport
RENFE	La Red Nacional de los Ferrocarriles Españoles
ICE	Inter City Express
CFRP	Carbon fiber reinforced polymer
W or WEC	Woven epoxy carbon Prepreg
C	Core
UD	Unidirectional
CAD	Computer Assited Design
FAE	Finite Element Analyst

1. Introduction:

We all have seen and used trains at one point in our lives, but how many of you stopped and analyzed what really is a train? In Layman terms, trains are composed of a series of connected wagons that run on tracks using bogies to power and help them maneuver freight or passenger from point A to a destination B. These machines make a huge difference in our lives, and historically are one of the first human-made vehicles ever. Throughout the years, there have been countless different models for the same category of train, all pursuing a common interest – an improved train.

There are many ways of perfecting a train, changing its dimensions so that it fits better with its niche, perfecting the fuel's efficiency to consume less, making the train fully electric to make it environmentally friendly, and so on – but in this work we are taking another route. We are going to change the material of the frame of the bogie.

1.1 Objective:

The main objective of this thesis is to study the frames behavior in different load cases. The material that composes the Fiat Y0235S (the selected bogie) is structure steel S235, and it will be swapped for carbon fiber reinforced polymer with the intention to reach a conclusion if whether it is worth changing the material.

It is also noteworthy to answer the following:

a. Understand the different styles of trains that there are, and their key differences
b. Have a mental overview of where the future in the train sector is heading.
c. Comprehend the importance of composite materials and inspire more users to switch to products constructed using composite materials.
d. Analyze the distinct cases that a bogie is under accordingly and explain the implications of switching materials.
e. Elaborate a case study as to why the composite frame is the correct direction for the innovative sector of any train company.

1.2 Scope:

The scope of this thesis is to consider and alternative material applicable to the bogie frame by studying the tensions that appear in the frame when in motion, breaking, in a curve, unloading, and other load cases. An interesting addition to this thesis could be studying the different companies that could make this frame possible, as well as studying the fabrication process that it would require alongside an accurate cost expenses study.

1.3 Methodology:

To comply with the objective of this study, the following questions must be answered

Table 2. list of methodology routes that I took to answer the objective questions in the subchapter.1.1

Subject	Question	Methodology
Characterization of the different trains.	What are the trains that have legal jurisdiction in cities?	Research analysis of city transport.
	Which trains are related to the transport of passengers, and which trains are related to the transport of freight?	Research analysis concerning the utility of the different trains.
Effects on reducing material's weight and their implications.	What are the disadvantages and advantages of the composite material?	Compare the necessity of reducing the CO_2 emissions and compare the mechanical behavior to that of the structure steel S235.
	What are the technical impacts that implementing said composite would have over the bogie frame?	Analysis of the results gathered from the design and simulation software ANSYS.
	What is the economic impact?	Analysis about how the energy/weight savings and their impacts would be.
Different technologies	What are the materials used in the making of the composite frame?	Research and classification of the main mechanical properties that the composites selected has, description of how they work and their utilization in the software ANSYS.
Analysis of investment	Which are the main drivers and expenses surrounding the reduction of the weight of the bogie frame?	Research the cost of high-speed trains so that we could compare it with the composite alternative.
	What is the necessary investment and what would be the consequences?	Analyze the results and compare them with the tools used for the production of the bogie frame.

1.4 Interest:

Like mentioned before, the train (including the bogie) has gone through many design variations throughout the years, changing the design to specialize in a certain field of work or making it more efficient in a particular way. Knowing this and observing that there is a ***need*** for a 55% reduction in train emissions by the year 2030, and by the year 2050 have a ***zero-emission*** target, I have taken it upon myself to help it be possible [1, 2]. Adding my little grain of salt to this movement.

Another interest that is fueling this thesis is the possibility of dedicating myself to this career path. As a mechanical engineer, I believe I have the capabilities to take projects of this sort and make a difference in society by innovating, designing, and studying the different alternatives to progress what surrounds us.

1.5 Complications:

Several challenges had to be overcomed to complete this thesis, starting with the unavailability of the geometrical dimensions for bogie frames. The railway companies have no legal obligation to upload any dimensions of the bogie frame produced by them, and as such, it makes it very complicated to model the frames accurately.

Due to the COVID-19 pandemic crisis, there have been many restrictions to guarantee our safety. One of which is the limitation of the use of the laboratory in the Polytechnical University of Catalonia. This restriction made me incapable of studying fatigue behavior for the composite material used in this study. In addition, there is no software that allows the analysis via CAD program, making the laboratory tests essential to study the fatigue behavior of the composite. Consequently, it makes it clear that the only way is to study the frame analytically. Thus, using simulation software allows the analysis for the exceptional cases (with the help of finite element analysis) and discards the composite materials' fatigue failure.

The norms and regulations for the productions of composite objects are very strict, making it harder and more expensive to produce a composite alternative for the day-to-day objects. Hopefully, as the composite sector is better understood, the financial investment is reduced, promoting the use of composite materials.

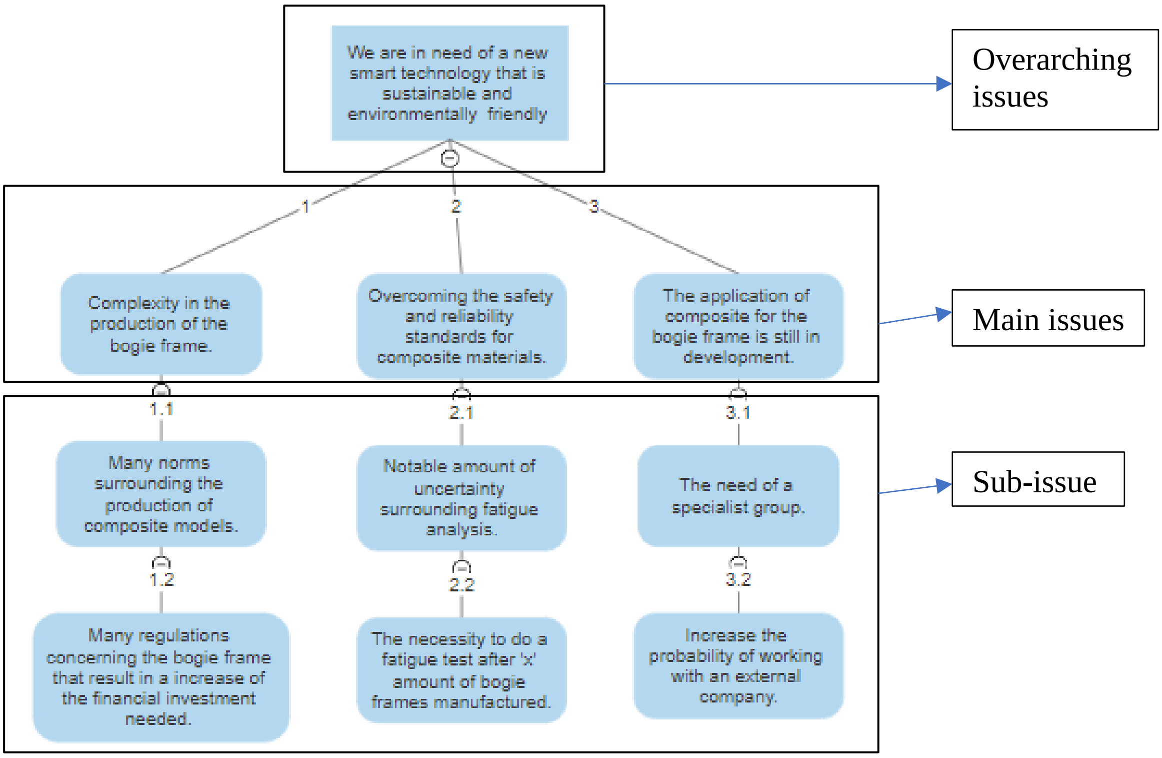


Illustration 1. Issue tree.

2. Overview of a train:

There are many different types of trains and many different specializations to them. Consequently, it is convenient to have an overview of the different types of trains to comprehend the selection of the bogie frame.

- **What is a train:**

A train is a rail vehicle composed by multiple connected units (wagons) that is used to transport passengers or cargo (sometimes also called “goods”). The motive power of a train is called a locomotive or engine and it is usually hanging on the frame of the bogie, but sometimes they can be in the vehicle body itself. Each railroad car can have one or more locomotive.

The word train originates from the old French word *trahiner* that derives from the Latin word *trahere* that means “to pull”. Nowadays, two common types of locomotives are used to pull the trains, the *diesel engine* and the *electric engine*. Although the steam engine historically dominated the scenery when it came to locomotive power [3].

The passenger trains are composed of passenger wagons designed for comfort and in the late 20th century, the use of high-speed passenger trains started to expand rapidly. Apart from that, the term “light-rail” is used for train that are modern tram-like systems and applicable to vehicles in the spectrum between train-tram. A freight train (another word for cargo train) is a train that uses freight cars to transport goods in them, essentially any train that is not used to transport passengers in them.

Regarding what connects the various wagons, there exists an essential part that is called bogie, the main topic of this thesis. The bogie is one of the most important structure of the whole train, due to the fact it oversees the comfort, the maneuverability of the train, dictates how much load can be applied, composes a large percentage of the overall weight of the train, helps maintain the state of the tracks, connects wagons and so on, making it indispensable.

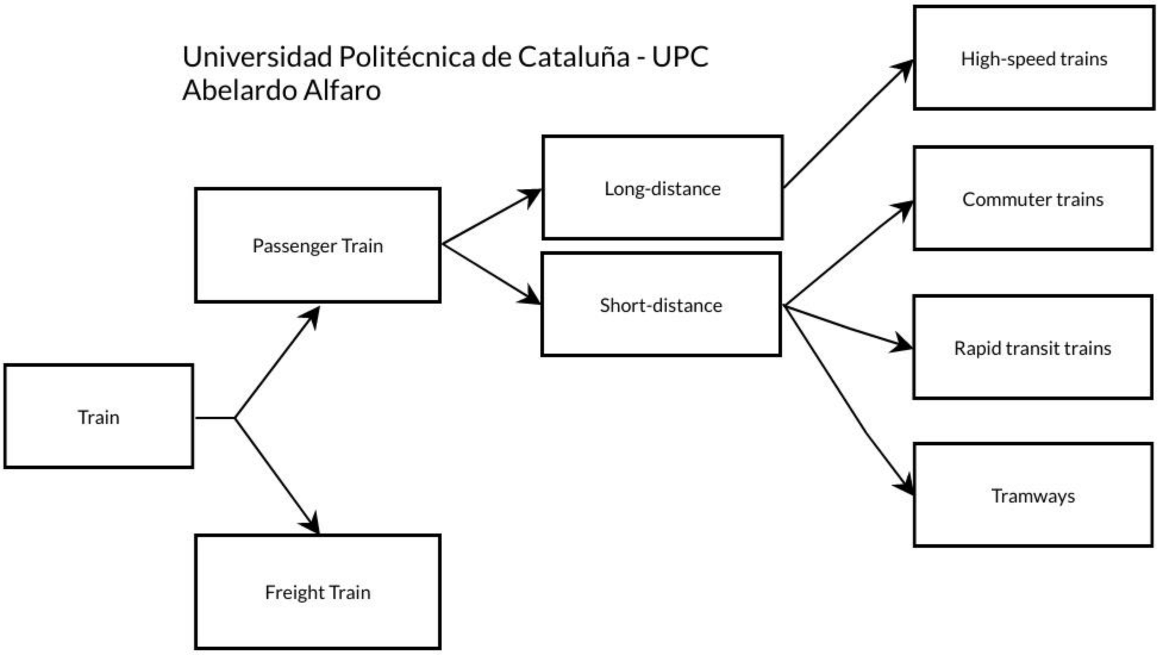


Illustration 2. Tree diagram of the different types of trains

2.1 Passenger trains:

The sole purpose of a passenger train is to transport as many people as possible over long and short distances in the most comfortable way. It can be self-powered multiple units or a combination of one locomotive with one or more unpowered wagons known as coaches. The passenger trains travel between stations and are in a fixed schedule, overrunning the schedule of the cargo trains. In the upcoming sections, we will explain the main type of passenger trains, see in the *illustration 2*.

2.1.1 Long-distance trains:

Long-distance passenger trains are used to travel between cities, regions, or several countries at a time. They may have on board sleeping beds, restaurant, and work area.

- **High-speed trains:**

Since the high-speed trains are used mainly for long-distance and growing evermore in the last couple of years, giving special attention to this train style. The market for high-speed trains has been growing extensively throughout the years, such is that the average European high-speed train count is 17 trains per country in 2012 [4]. To have a little bit of insight, the European country with the most high-speed trains is the United Kingdom. They count with well over 30 high-speed trains.

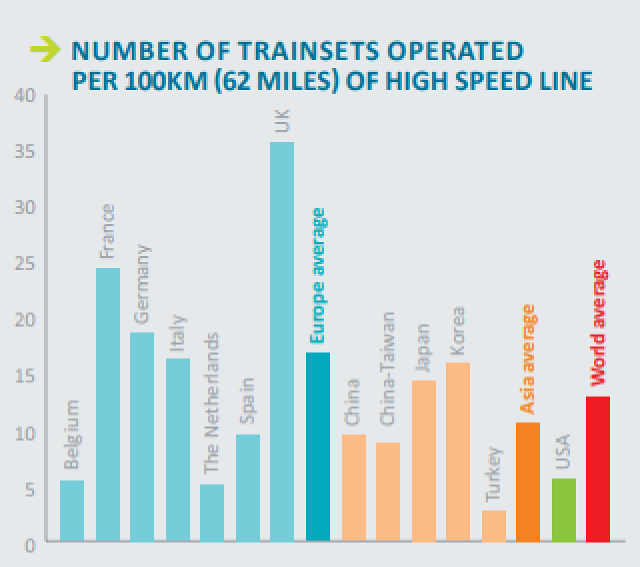


Figure 1. Number of high-speed trains per country [4].

In 2012, more than **2,770** high speed trainsets (able to operate at least at 200km/h (125mph)) were in operation across the world:

Asia	1,087
Europe	1,670
North America	20
TOTAL	**2,777**

Figure 2. The total number of high-speed trains in the world the year [4].

The total amount of fast transited trains is impressive. It is calculated by adding all the Asian, European, and North American high-speed trains, and it resulted in a staggering 2770 trains – however, this amount is expected to grow even more in the upcoming years. In 2025, the total expected sum of high-speed trains is forecasted to add up to nearly 6000 high-speed trains between Europe and other countries.

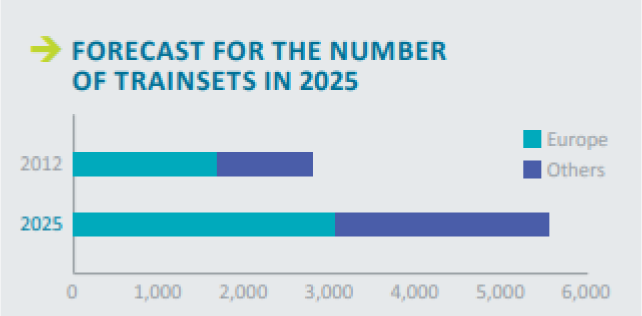


Figure 3. Forecast for a total number of high-speed trains in 2025 [4].

When considering the time needed for creating a new high-speed train, you must consider the different tests and procedures that the prototype goes through to meet the European standards and requirements. The time needed for a new design of a high-speed rolling stock unit is in the range of 3 to 5 years for new technical development, as well for the design and test portion.

- **Velocity of a high-speed train:**

The fastest train ever recorded was the French TGV, which achieved 574.8 km/h under test conditions, although its average speed is in the range of 300-320 km/h, likewise, is the speed for the Spanish train AVE (Alta Velocidad Española), and the German ICE

(Inter-City Express). For a train to be considered a high-speed train, it must run above the 200 km/h threshold [5].

Figure 4. Spanish High-speed train AVE [6].

Tilting technology allows the train to take corners at high velocity, to maneuver at such high speeds around the corners. This tilting technology is a dynamic form of superelevation that allows the trains to pivot, guaranteeing better maneuverability and more comfort for the passenger. This technology could be found not only in long-distance trains but also in short-distance trains.

- **The proficiency of the High-speed train:**

Many reasons consolidate the high-speed trains as the go-to train for long distance passenger transport, one main reason is the energy efficiency that the high-speed train has. If we were to plot the number of people that a vehicle can carry with 1 kwh, the high-speed train would rise on top. It will count with a staggering 170 people, way over the 20 people that the aerial counterpart carries, and the 54 and 39 that the bus and car can carry subsequently [4].

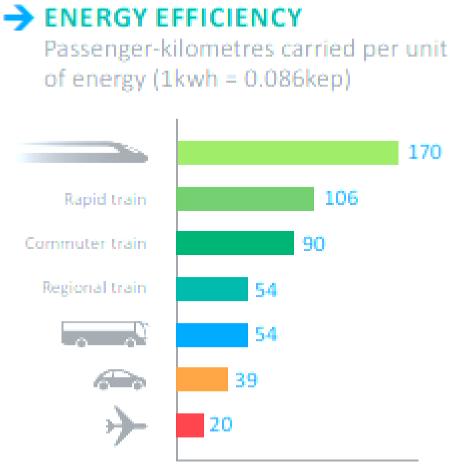


Figure 5. Energy effectiveness comparison between the most used means of transport [4].

Another way of measuring the impact is by comparing the amount of kilogram of CO_2 that the high-speed train generates per 100 passengers or 100 kilometers, against the most utilized means of transport today. Surprisingly, the high-speed train comes out on top once again, and by a large margin. This result is promising since the statistic is only going to get better with time, each time lowering the carbon footprint of the passenger on board the high-speed train. It is also perfecting the proficiency making train travel more eco-friendly, and better for the environment in general.

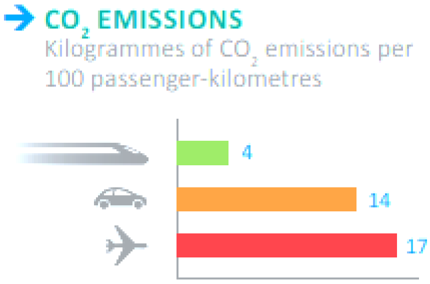


Figure 6. CO2 emissions between the train, car, and airplane [4].

Furthermore, due to the passenger capacity of the high-speed trains (around 666 passengers), the surface of land that would be needed to transport passengers is significantly low. If you were to lay out the facts to camper with that of the highway's lanes, you can easily observe the advantages of the high-speed train concerning land use.

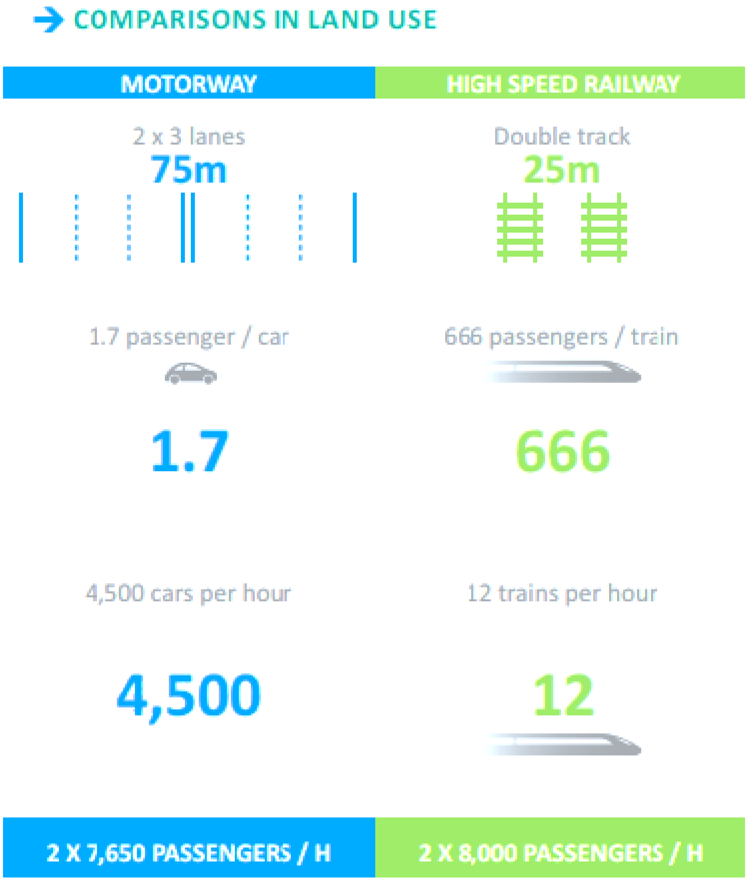


Figure 7. Comparison of land use between the train and the highway [4].

Having all of this in mind, it is obvious why the high-speed train is the best train for long-distance travel. In many categories, the high-speed train would come on top and it will only just keep getting better as the years pass.

2.1.2 Short distance trains:

Short distance passenger trains are those that travel relatively small distances when in use. We can classify them into 3 broad categories, 1st commuter trains, 2nd rapid transit, and 3rd tramways.

- **Commuter trains:**

Most cities have what are called commuter trains. These are trains of shorter distances that travel between metropolitan areas and connect the city center with adjacent commuter towns. As such, their purpose is to cope with the traffic demands of the metropolis. These trains are designed to have maximum comfort yet also allowing a large number of people to travel in them. This comfort is obtained by having people seated and standing in the car, as well as areas reserved for wheelchairs, bicycles, and elderly people.

The commuter trains can run on both diesel-electric engines or electric. At Catalonia, RENFE (La Red Nacional de los Ferrocarriles Españoles) was created on the 24th of January in 1941. RENFE is the main commuter train that circulates connecting cities and towns alike.

Figure 8. RENFE - Spanish commuter train [41]

- **Rapid rail transit:**

The UITP or the International Association of Public Transport [7] classifies the rapid rail as urban passenger transport. These trains have different names worldwide, such as "Metro", "Subway", "Tube", or "Underground", and they operate within the cities.

Figure 9. Spanish Rapid transit train - Metro Barcelona [8].

The rapid transit category is frequently confused with the light rail (tram-like trains) due to its similarities. An easy way to differentiate light rail from rapid transit trains is by pointing out that the latter is separated from any other type of traffic. In other words, the light rail systems may share tracks with other types of trains or have level crossings (where other vehicles cross the railroad), a rapid transit system operates exclusively on tracks that are exclusive for the metro, with no access on the tracks for pedestrians and other traffic.

All metro systems have more than 1 line, and each line is considered a route - the train that belongs to this line must stop at all the stations, and like most metros have several lines; to distinguish them, they use colors, names, and numbering are used.

These lines repeatedly intersect with one another, making the conductors' coordination essential (more modern rapid transit systems have fully automated trains, hoping it will lead to fewer errors and more punctuality). There are times where the cities allow a line to run through the city center, crossing two branches in the suburbs, which allows a higher service frequency.

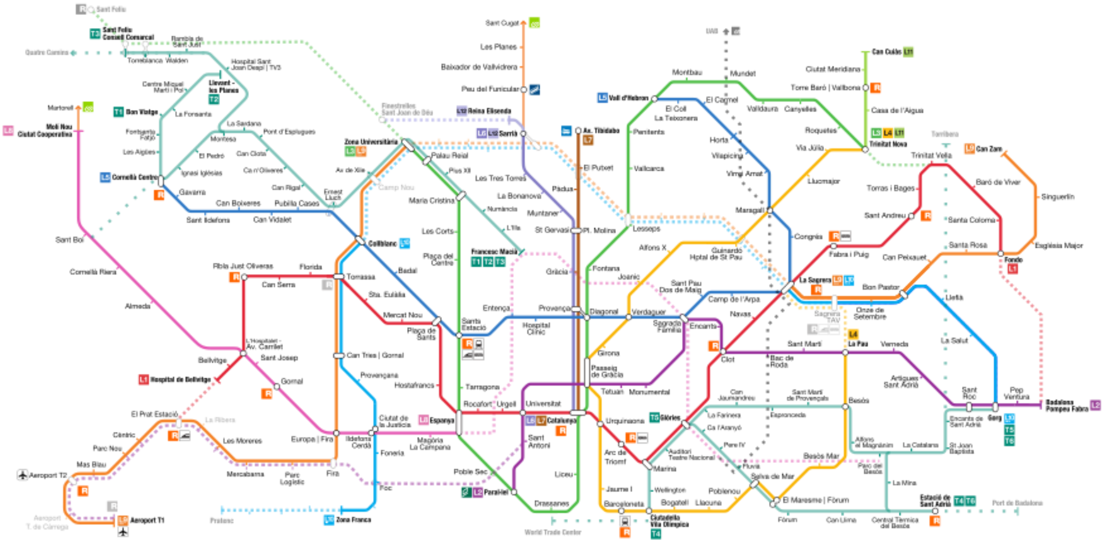


Figure 10. Metro line in Barcelona [8].

The number of passengers that a line has is important, and it is obtained by multiplying together the car capacity, train length and service frequency. There is a distinction that should be made between the rapid rail transit, and the heavy rapid transit trains, that being that the latter one might have six to twelve cars, while lighter systems may use only three or four cars. The number of people that can fit in a wagon can vary from 100 to 270 people. This is explained by considering that some people are sitting down, and others are standing up, which gives a higher capacity.

The waiting time for the next train is also important, (that is where the *rapid* part in the name comes from) the usual waiting period for the next subway is 90s. Making the waiting time, many times shorter than any other train system. Like we now know the average frequency of trains, the number of people fitting into a wagon, the number of wagons on a heavy and light rapid transit train, we could calculate the capacity of a line being 36,000-75,000 people per hour. Quick side note, the highest capacity is *80,000* people per hour by the MTR Corporation in Hong Kong, a truly engineering feat [9].

- **Light Rail:**

The main difference between the light rail (otherwise known as tramway) and the rest of the trains, is that it runs mainly on streets, which means that there are precise and strict laws surrounding the tramway systems.

Figure 11. Tramway train [42].

The regulation of each nation defines the length of a tramway. For example, in Germany, the maximum length that a tram can have is 75m [10]. Although in other countries like, for example, the United States, trolleys are restricted to the local authorities alloying sometimes only a certain type of train to be operating.

2.2 Freight trains:

Rail freight transport is when there is used of railroads and trains to transport cargo.

Figure 12. Freight train [43]

A freight train, cargo train, or goods train is a group of goods wagons dragged by one or more locomotives to transport cargo all, or some of the way between the seller and the intended destination location of a logistic chain.

Under the right circumstances, the freight train is one of the best methods of transport. When talking about the energy consumption of the freight rail, it is considered the most efficient mean of transport. This is due to various factors, mainly being that the friction between the wheelset and the rails is practically cero if we compare it to the cars where the rubber tires encounter a higher level of friction when they meet the asphalt road. This characteristic of having low friction makes it hard for the train to go over certain terrain if there is a slope, and as such, it is needed to level the train track so the train can run. An overall study has confirmed that the freight train on average emits 30% of CO_2 that a vehicle would [11].

Another advantage that freight rail has is that it can be very economical. It is cheapest when the wagon is filled up to the maximum capacity, especially when there are long distances to cover. It is why most goods transported in freight trains are energy products and agriculture commodities that can maximize the entire wagons volume, automobiles and components, construction materials, chemicals, equipment, food, metals, minerals, paper, and pulp. The other percentage of the goods transported in the freight trains consist of consumer goods and other miscellaneous products

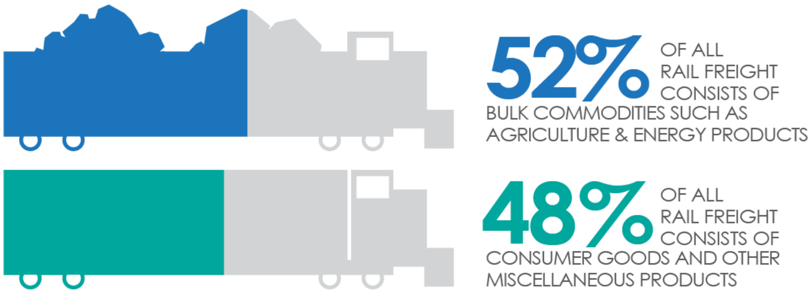


Figure 13. Percentage of goods in the freight trains characterized by the type of product [12]

However, railway shipping is not as flexible as highway shipping, which resulted in much of the freight being hauled by highway trucks. Additionally, the goods by rail involve transshipment costs, especially if the supplier does not have access to a railway
The minimum distance for a freight train to compete with a truck is 400 km to 600 km for theuropean railroad freight system [13]. Thus, the freight train system must change to be more frequent with relatively shorter distances. This can be achieved by implementing more destinations. An intermodal line train making intermediate stops along its route is a feasible solution as it covers more relations and a larger market area than conventional two-terminal intermodal solutions.

Figure 14. The freight rail network in the U.S [14].

3. The European railway industry:

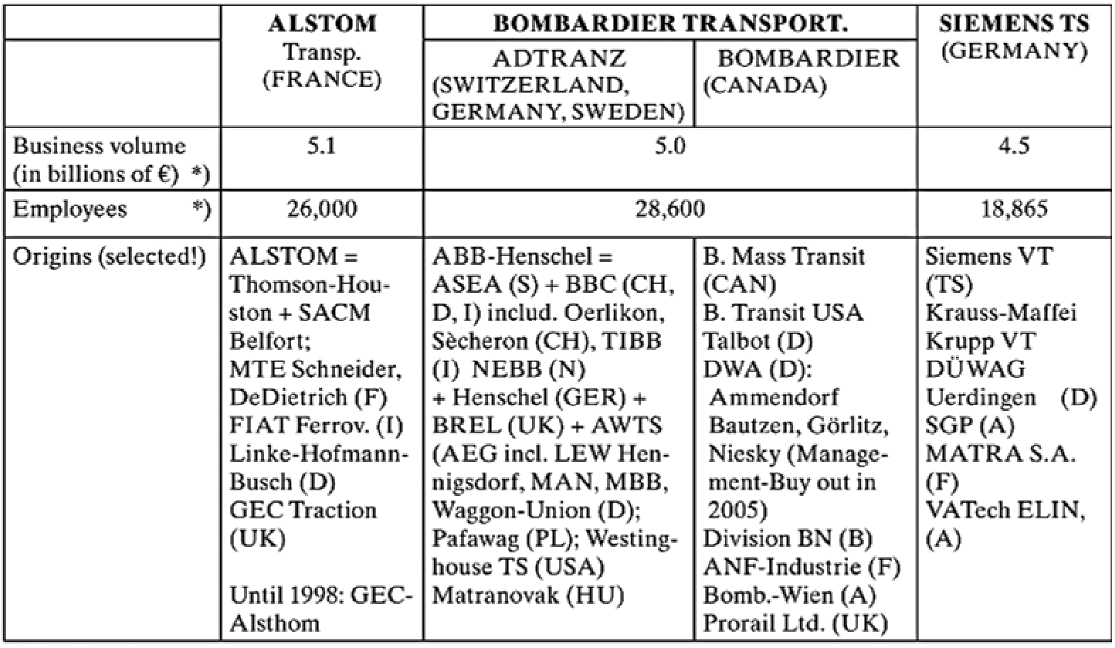
Knowing the distinction between the main suppliers for the European railway industry is significant when analyzing a frame bogie. Why you may ask? If need be, you would put the interest of that said company to orient you in the selection of the material that composes the frame. In this chapter, you will comprehend, in a broader aspect, which are the main companies that take the task of creating the trains and the infrastructure for the railway industry in Europe.

At the end of the 20th century, the European railway industry faced constant changes that led to the reconstruction of the railway organization – that being deregulation, privatization, and so on. This push led to a decrease in order, and therefore the collapse and merges of various companies. The engineering industry responsible for the supply of the mechanical components of the trains (those being Henschel, Krauss-Maffei, Krupp, and SACM) was incorporated into the large-scale electrical transportation division companies like ALSTOM, Siemens ABB, and AEG, now pioneering the technology in this field.

In 2001, Bombardier, which was focusing until then on coaches and aircraft engineering, acquired Adtranz from the Daimler-Chrysler Group, consolidating them as one of the big multinational railway manufacturers in Europe with ALSTOM and Siemens [15].

Following is a list of the top train manufacturers in Europe with some necessary information about them to have a mental structure of the dimensions of these companies.

Table 3. European Traction Unit Manufacturers (2005/06) *[15]*.



	ALSTOM Transp. (FRANCE)	**BOMBARDIER TRANSPORT.**		**SIEMENS TS** (GERMANY)
		ADTRANZ (SWITZERLAND, GERMANY, SWEDEN)	BOMBARDIER (CANADA)	
Business volume (in billions of €) *)	5.1	5.0		4.5
Employees *)	26,000	28,600		18,865
Origins (selected!)	ALSTOM = Thomson-Houston + SACM Belfort; MTE Schneider, DeDietrich (F) FIAT Ferrov. (I) Linke-Hofmann-Busch (D) GEC Traction (UK) Until 1998: GEC-Alsthom	ABB-Henschel = ASEA (S) + BBC (CH, D, I) includ. Oerlikon, Sècheron (CH), TIBB (I) NEBB (N) + Henschel (GER) + BREL (UK) + AWTS (AEG incl. LEW Hennigsdorf, MAN, MBB, Waggon-Union (D); Pafawag (PL); Westinghouse TS (USA) Matranovak (HU)	B. Mass Transit (CAN) B. Transit USA Talbot (D) DWA (D): Ammendorf Bautzen, Görlitz, Niesky (Management-Buy out in 2005) Division BN (B) ANF-Industrie (F) Bomb.-Wien (A) Prorail Ltd. (UK)	Siemens VT (TS) Krauss-Maffei Krupp VT DÜWAG Uerdingen (D) SGP (A) MATRA S.A. (F) VATech ELIN, (A)

In the following pie charts, you will be able to see the summary of the market situation, the entire volume of the railway stock is about 72 billion euros, as for the rolling stock is about 25 billion euros and made up of according the diagrams ahead.

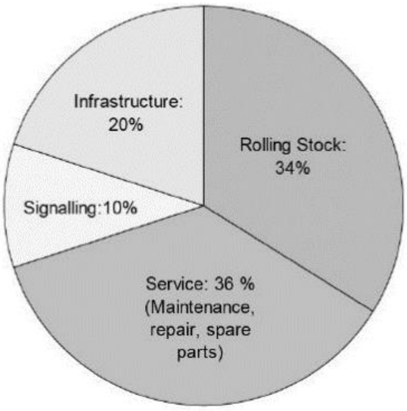


Figure 15. The left-hand pie chart shows the distribution in percentages of the railway stock *[15]*.

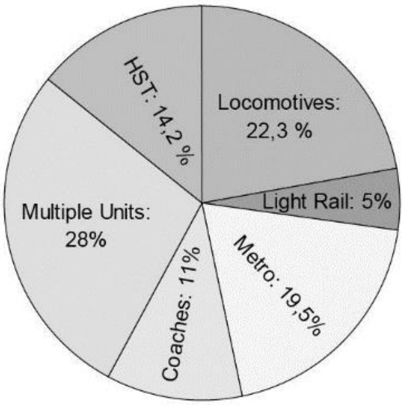


Figure 16. The right-hand pie chart shows the distribution in percentages of the rolling stock *[15]*.

There are many more manufacturers in Europe than those listed before (Siemens, ALSTOM, and Bombardier transport). Those three are just the biggest in Europe and basically produce most of the traction units.

In the following table, you can see other manufacturers that were excerpts but also play a role in the manufacturing of railway units. One honorable mention is TALGO. It is one of Spain's biggest Spanish train manufacturers and is responsible for fabricating the new AVE trains for this upcoming 2021 stated by Europa press [16].

Europe:
AnsaldoBreda, Naples, Italy
Balfour Beatty Rail GmbH – Power Systems, Frankfurt and Munich, Germany
Brush Traction Ltd., Loughborough, UK
Cegielski, Poznan, Poland
Construcciones y Auxiliare de Ferrocarriles S.A (CAF), Beasain and Zaragoza, Spain
ELIN EBG Traction, Vienna, Austria (Siemens)
Ganz Transelectro Traction (formerly Ganz-MAVAG), Budapest, Hungaria
Riga Carriage Building Works, Latvia
Skoda, Prague, with CKD Vagonka, Ostrava, Czech Republic
Stadler Rail Group, Bussnang and Altenrhein/Switzerland; Pankow, Germany
TALGO S.A., Spain
Voith Turbo Lokomotivtechnik GmbH, Kiel
Vossloh SFT (incl. MaK and Kiepe Elektrik, Düsseldorf; acquired the Valencia works for diesel-electric locomotives from ALSTOM in 2004), Germany
Windhoff, Rheine; Schöma, Diepholz, Germany (small locomotives, special vehicles)

Worldwide:
General Electric (GE) Transportation Systems, Erie, Pa., U.S.
General Motors, Electro-Motive Division (EMD), London/Ont., Canada;
formerly also Lagrange, Ill., U.S.A.
Hitachi, Kawasaki, Mitsubishi, Toshiba, Tokyo Denki, Japan
Union Carriage & Waggon Co. (UCW), South Africa
Daewoo, Hyundai, South Korea
Chittaranjan, BHEL, IndiaZhuzhou, PRC

Table 4. Table of manufacturers of railway units *[15]*.

Finally, it is important to know the different organizations and authorities that exist to regulate and standardize the various levels of the rail stock industry and products available: Table 4 lists these authorities that regulate and standardize the rail stock industry.

UIC/IEV	Union Internationale des Chemins de Fer, Paris (International Railway Association)
ERRI	European Railway Research Institute (fm. ORE)
OSShD	Organisazija sotrudnitschestwa shelesnych dorog (Organisation for Cooperation of Railways (East European states, CIS and Iran)
RIC	Regolamento Internazionale delle Carrozze (Accord on the mutual use of passenger and luggage cars in international transport), January 1st, 1950
RIV	Regolamento Internazionale delle Veicoli (Accord on the mutual use of cargo cars in international transport), January 1st, 1958
TSI	Technical Specification on Interoperability. Guideline 96/48/EC of the European Council on Interoperability of the trans-European high-speed railway system, Official Journal of the E.C. No. L 235, September 17th, 1996, p. 6 ff.
UNIFE	Union of European Railway Industries
VDV	Association of German Transport Undertakings, Cologne
VDB	Association of the German Rail Industry, Frankfurt/Main
EBA	Eisenbahn-Bundesamt, Berlin (technical supervision authority)

Table 5. Table of associations, organizations, and authorities that regulate and standardize the rail stock industry *[15]*.

4.The bogie:

Before analyzing the bogie frame forces, you would need to know what the bogie is and what its main components are. The bogie is one of the centerpieces of the train and without it, there would not be any train. All trains have a bogie integrated into them, but they all have differences in them to be better fitted to do a certain task. The essential functions of a bogie are firstly, to carry all the load (from passenger or freight), to convey the forces that appear when accelerating and braking (transmission of traction power from the traction unit to the rail), to steers the carbody smoothly and safely (guidance of the vehicle in lateral dire1ction both on straight and curved tracks), and smooths out the tracks.

Bogies are classified in many types: the total number of axles, the shape of the structure and arrangement of the suspension, and the suspensions' arrangement. Below, you can see some important components of the bogie:

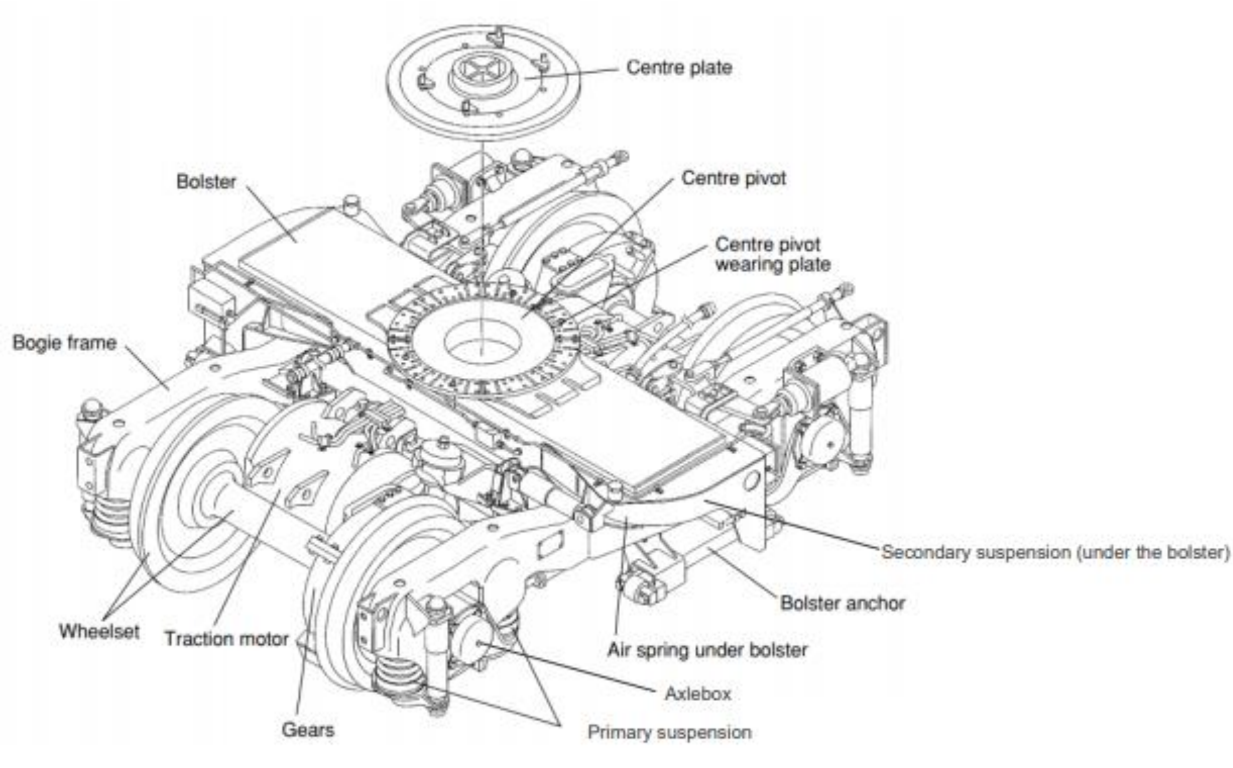


Figure 17. Diagram of a standard modern bogie [17].

a. Number of axles:

As the bogie runs on two steel tracks, the minimum number of wheels needed are two and one axle. These wheels are usually embedded onto the axle. (Fig.17).

The primary categorization is based on the number of axles they possess, as such, bogies then are categorized as single-axle (mono-axle), two-axles (bi-axle), three-axles (tri-axle), and so on.

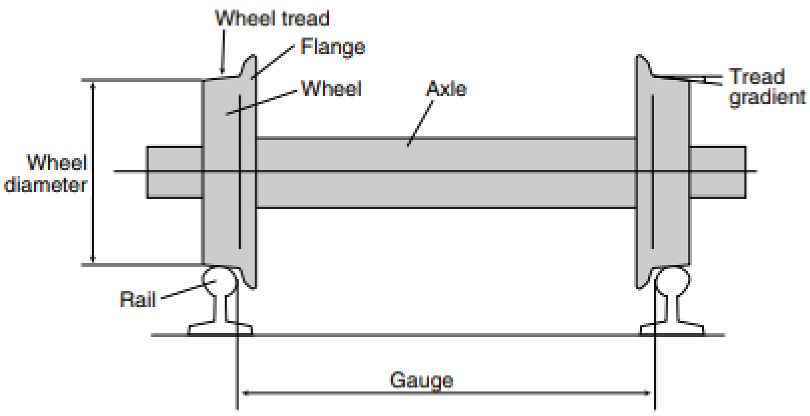


Figure 18. Wheelset made up of the axle and both steel wheels [17].

The bi-axle bogie is the most popular due to its fairly straightforward structure, its benefits of reducing the impacts from the path abnormalities on the carbody and the car suspension point, compared to the single-axle bogie that transfers the blows to the railcar directly.

The tri-axial bogie is more challenging to manufacture, which leads to a decrease in the operating performance and strength of the bogie frame.

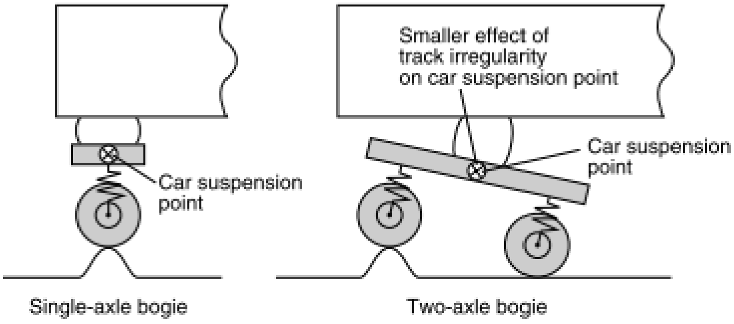


Figure 19. Comparative between the single-axle bogie and the two-axle bogie [17].

b. Non-articulated and articulated bogies:

According to the suspensions present in the bogie, they can be classified into two types, articulated and non-articulated, like shown in Fig.20. There it shows the difference between the articulated and non-articulated bogie. This latter one usually sustains one carbody by itself, and the articulated one helps the front and the rear railcar like you can see in the TGV (French highspeed train), and many suburban Tokyo trains. However, the articulated bogie does have some drawbacks, like the complexity of the structure itself, a large amount of axle load due to one side of the bogie is loaded to support the entire weight of the carbody.

The articulated bogie also has many advantages, like the lower center of gravity, making the train more stable, better ride quality by increasing the comfort, and less noise during the train ride. It is thanks to the seats not being over the bogie frame.

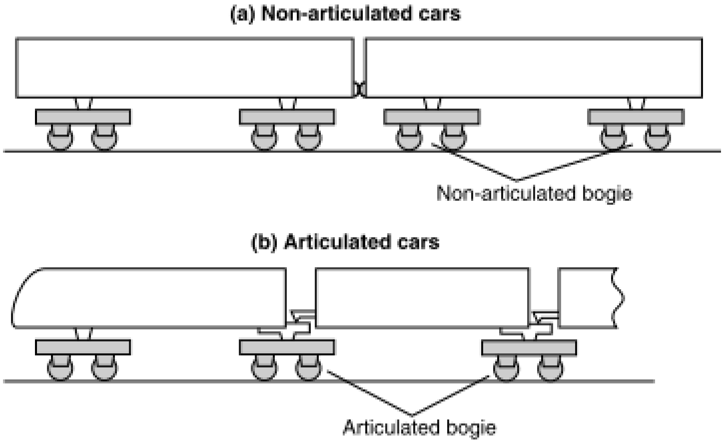


Figure 20. Diagram of the on-articulated cars and the articulated cars [17].

c. Swing hanger bogie and small lateral stiffness bolster spring bogie:

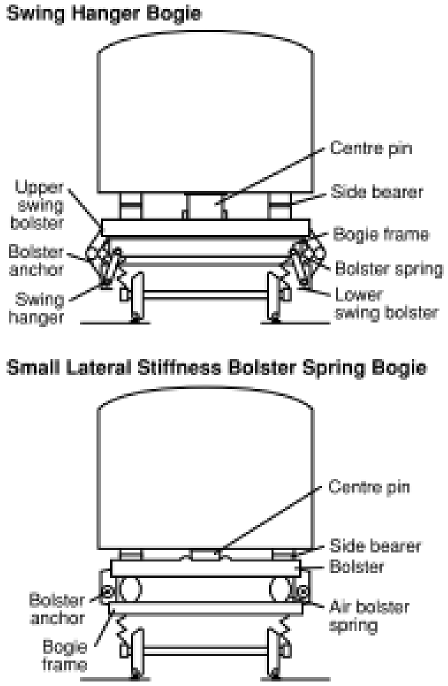


Figure 21. Differences between the swing hanger bogie and the small lateral stiffness bolster spring bogie [17].

The next classification of bogies is the one that takes into consideration the configuration of the suspensions. Firstly, we have the swing hanger bogie and, secondly, we have the comically named, small lateral stiffness bolster spring bogie. The bogie (suspensions) must be able to absorb all the movements that the passengers are perceptive to sense, to guarantee that the passenger receives the best experience while riding, Starting off with the swing hanger bogie, they are designed to support the wagon by using vertical dampers that are connected or linked to a bolster beam that grows out of the frame. This bolster beam has the bolster springs incorporated in it, intending to sustain the vertical effort.

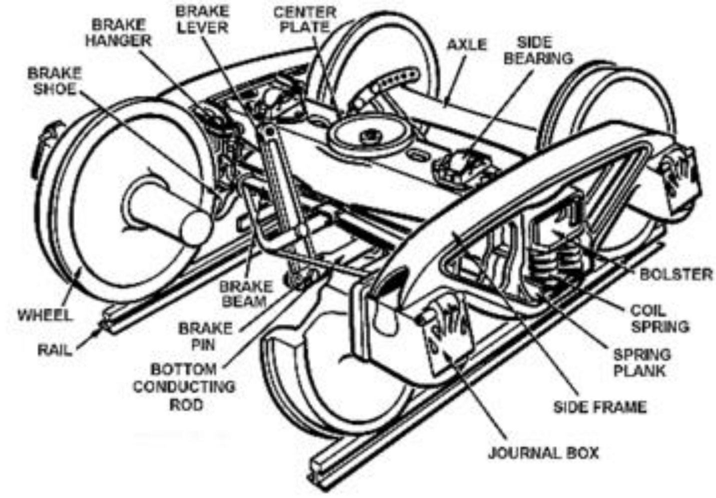


Figure 22. Diagram of a swing hanger bogie [44].

Even though this configuration provides good enough comfort for the rider, its maintenance is difficult due to the complicated structure and the various parts that could wear out over time. In the 60s, air springs were invented. These innovative springs allow minimal lateral stiffness and soon replaced the swing hanger type [18]. It meant a huge decrease in weight in the bogie, but they are complex to manufacture with the downside.

A more in-depth report about springs and damper will be discussed ahead.

d. Bolster and bolsterless bogies:

The characteristic that decided if a bogie should or should not have a bolster is the suspensions on the bogie. The bolster bogie was invented first, allowing it to have the fundamental characteristic of rotation relative to the carbody when taking curves while preserving high rotational resistance during highspeed running in straight sections preventing the wheels from oscillating. Figure 23 shows a representation of a bolstered bogie.

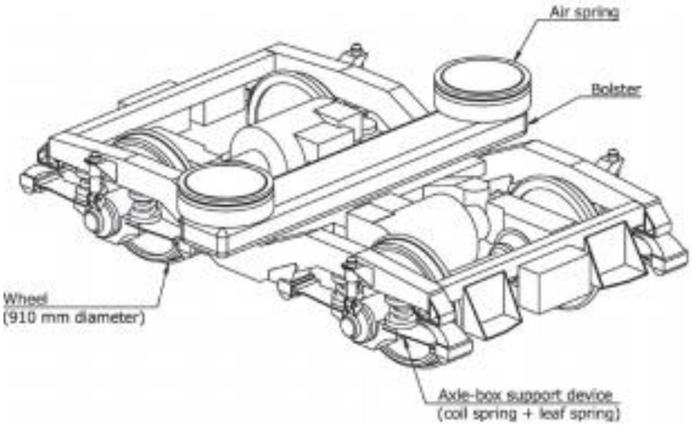


Figure 23. Sketch of a bolster bogie, there is a central bolster crossing the center [45].

In the 80s, bolsterless bogies were invented to perfect the performance by reducing the number of pieces that a bogie needed, ultimately decreasing the weight. Nowadays, the bogies that run on narrower gauges use bolsterless bogies; they allow the rotational displacement that the bolster allowed through the horizontal deformation of the bolster springs (commonly known as secondary suspensions). In Figure 24, it is exhibited a representation of a bolsterless bogie.

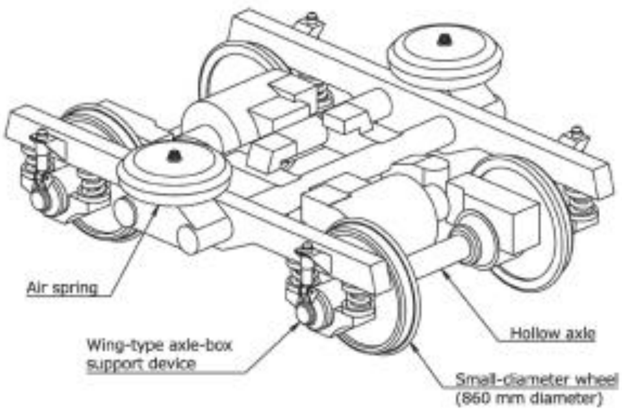


Figure 24. Sketch of a bolsterless bogie, you can observe that there is not a center bolster crossing the center of the bogie, consequently, lowering the center of mass of the carbody and improving the quality of running [45].

4.1 Components of a bogie:

The bogie is one of the centerpieces of the train, which its main role is to support the weight of the carbody, allowing it to run on the track and maximizes the comfort for the passenger. Then, it needs to be composed up of various key parts like the ones you can see in the figure below. In the following subchapter, the different components are going to be explained in more detail, but it should be noted that the elements incorporated vary according to the bogie type.

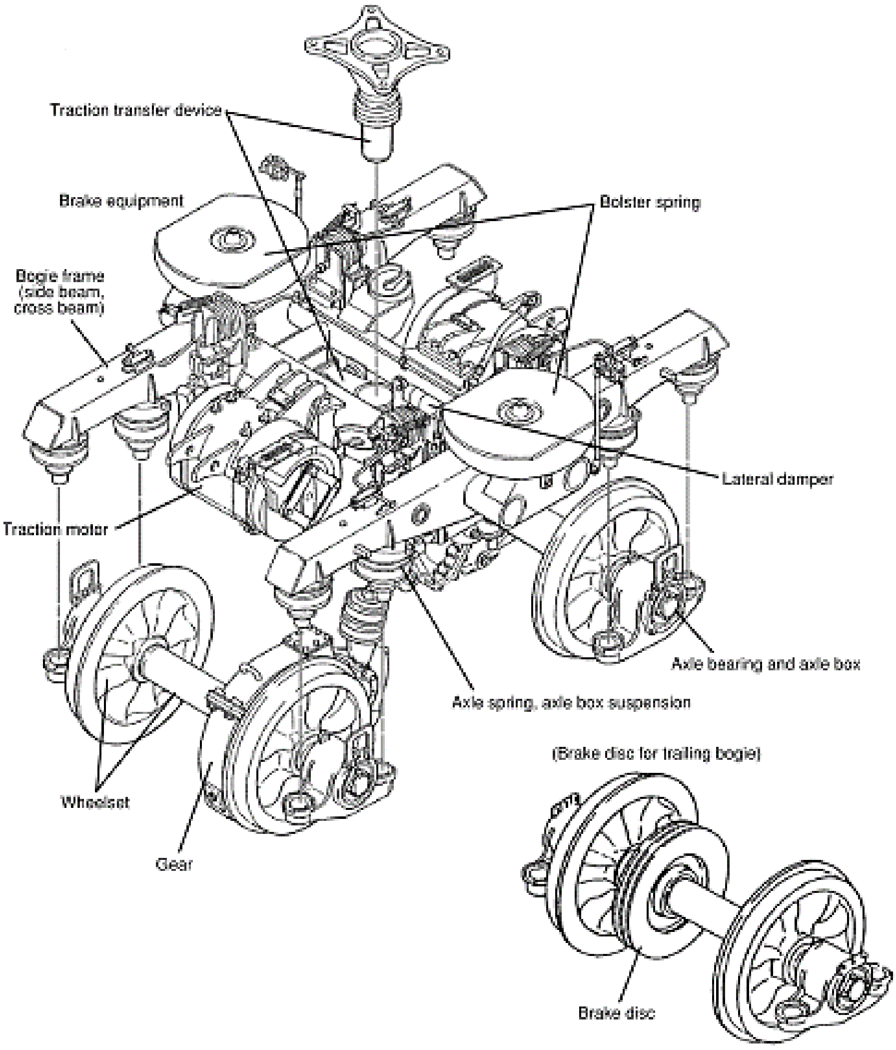


Figure 25. Exploded view of the DT50 bolsterless bogie [17].

4.1.1 Bogie frame

The bogie frame is one of the most important elements to the bogie, wheret there are integrated many of the bogies equipment and it usually is manufactured by welding side beams to two cross beams to create an H shape structure.

When discussing the shapes that a bogie frame can have, we have three types of shapes and all are centered around the shape H

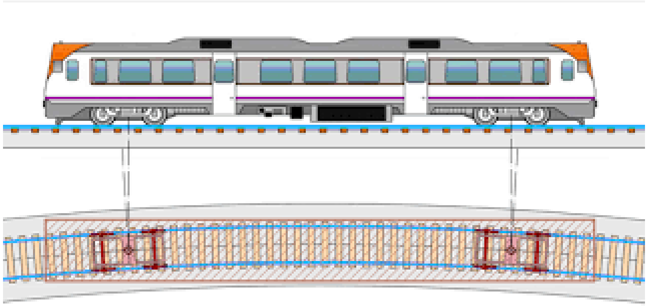


Figure 26.This drawing shows how the train takes curves and how the bogie underneath can move on curved tracks [29].

a) Open H-shape

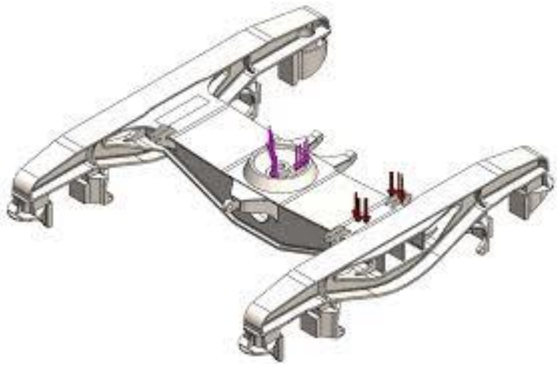


Figure 27. H-shape frame [29].

H shape is the most common frame shape for bogies. It is a light-weight design widely used in high-speed trains, like the ICE 3 – DB, AVE S103 – RENFE. The axle and the wheels are attached to the carbody, the bogie itself is joined by an articulated pivot (that is normally situated in the middle of the bogie) that allows it to have mobility with respect to the railcar and have fewer restrictions while running on curves with the help of the suspension gear, see Figure.27 on the left. The pivot is secured by a plate to not move out of place during the ride.

b) Close H-shape

The close H-shape is an altered version of the open H-shape, which links the extremes of the H with a bolster at each extreme. This alteration provides resistance to torsional forces, but in contrast, it has a higher weight. You can find this style of bogie frame in Alstom's CL 622.

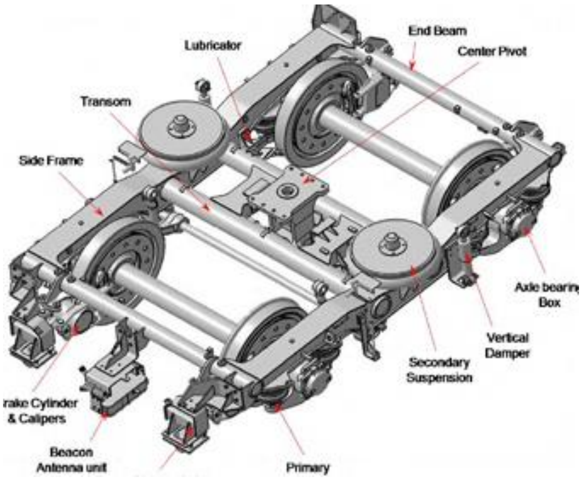


Figure 28. Closed H-shape frame [29].

c) Three-piece

As the name suggests, this bogie is made up of 3 pieces in total, two side frames and one central beam that connects the other lateral beams. The main difference from the open H-shape is that the frame is welded together and considered one solid piece. The central beam that connects the two side frames has a pivot in the middle, connecting it to the carbody just like the open H-shape.

Contrary to the other bogies, this configuration does not have secondary suspensions - this is because the main function for a secondary suspension is to better the quality of the ride for the passenger and since the three-piece bogie is mainly used for freight trains, there is no need for secondary suspensions. This type of structure is mainly used worldwide for freight trains except for Western Europe, and a modern version of this is used nowadays in Great Britain.

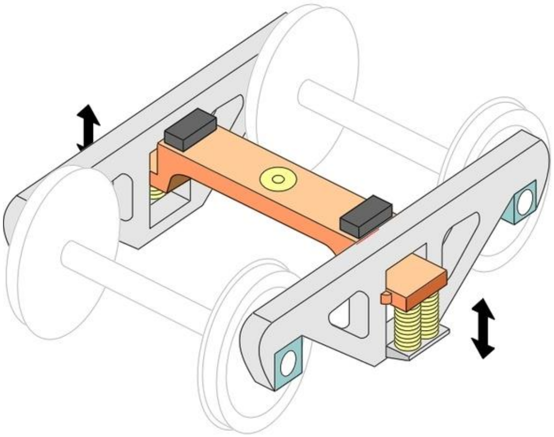


Figure 29. Three-piece bogie frame [46].

4.1.2 Suspension gear:

Another crucial element to the bogie is the suspension gear. The suspension gear is the bolster springs, the yawning resistance dampers, the traction transfer device, and the lateral dampers. All this combined play an important role in supporting the body. The suspension gear system allows the bogie to revolve safely relative to the railcar on curves, reduce the vibrations greatly produced by the bogie on the tracks, and lastly transmits the traction force from the wheelset to the bogie. The bogie counts with primary suspensions and secondary suspensions.

The track has many irregularities, and their interaction with the wheels produces vibrations of many amplitudes and frequencies. Said vibrations might cause damage to several parts of the vehicle unless it is not contained and returned to the track. Figure 30 represents where the primary and secondary suspensions are situated on the bogie frame.

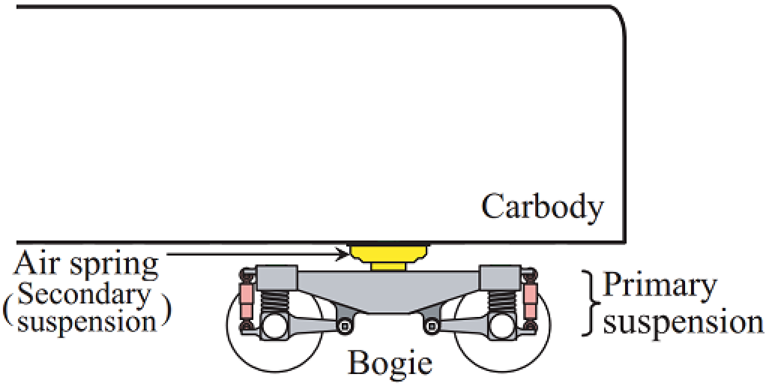


Figure 30. Drawing that shows where the primary and secondary suspensions are located [19].

a. Primary suspensions:

The primary suspensions are located in between the bogie and the wheelset. These suspensions are composed up of springs and dampers. The springs ensure that the train has stable running performance and low track force, which ultimately results in low wear and good behavior while in curves. By incorporating the primary suspensions, the quality of ride and lateral stability is dramatically improved. If the suspensions were not there, the unsprung mass would hit the railroad track due to the imperfections on the tracks and likewise hit the carbody, damaging a lot of the inner components and decreasing the quality of ride for the passenger.

b. Secondary suspensions:

The secondary suspensions are as important as the primary suspensions. Their function is to isolate the carbody from the excitations transferred by the track's irregularities through the wheelsets and bogie. These suspensions are interconnected in between the car and the bogie frame, as shown in Figure.31.

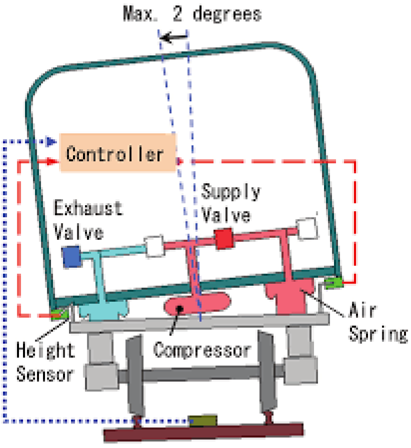


Figure 31. Carbody tilting using air springs [19].

Traditionally the secondary suspensions were springs with dampers like the primary springs, but the more modern rails have switched them with air springs. As previously explained, these air springs are located between the carbody and the bogie and have the job of reducing the accelerations and decelerations sensations. It can also shift the air to one side if there are too many passengers standing or sitting on one side. Finally, it calculates the number of people in the carbody based on how much air is in the airtight springs.

In other words, the main advantages of air springs are that the stiffness can be regulated based on the amount of load or effort it is expected. The advantages of using air springs is that you can control the height of the carbody by adjusting the air in the springs, the substantial horizontal stiffness, less noise is produced, and more vibration isolation.

The disadvantage that the air spring brings to the table is that they are complex and expensive compared to the traditional spring and damper combination. Bellow is a comparative image of both the traditional spring and the air spring Figure.32.

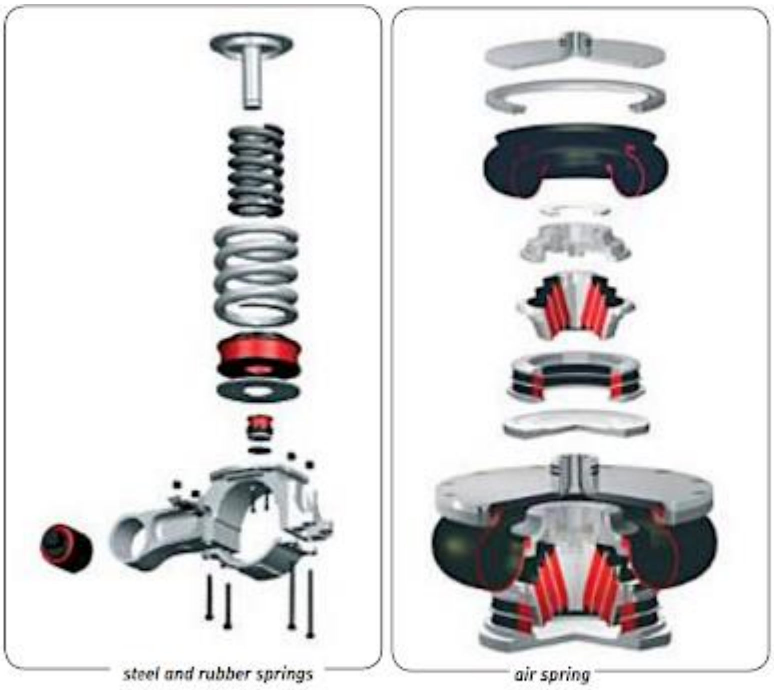


Figure 32. Comparison between the steel spring and the air springs [19].

4.1.3 Breaks

The main function of a braking system is to decrease the velocity of a train. To choose which type of braking system is suitable for the train, you must consider the weight of the train, the axle load, and the maximum speed that the train can reach.

The wheelset of the bogie has many types of brakes integrated into the system. It is provided with an air brake cylinder (for each wheel), parking brakes, a tread brake or a disc brake, which breaks using friction.

a. Tread brakes:

This type of breaks is mostly used in non-tractive units, which use friction to slow down the speed of the train. This friction is being produced by the spinning surface of the wheel and the brake shoe of the tread brake. So, the wheel must be designed in a way that the heat from said friction dissipates and avoids overstress from the thermal heat produced by the rubbing.

The main disadvantage of this system is that the wheel goes through a lot of wear due to the braking shoe, thus over time, this braking system has been replaced for disk brakes in passenger trains. Consequently, these types of brakes are very much present in the freight bogies nowadays thanks to the fact that the freight does not have to break so often.

b. Disk brakes:

The second type of friction brakes commonly used in bogies is the disk brakes - as stated before, this kind of brakes are generally used on passenger trains due to the amount of braking the train must go through.

The axle mounted braking effect is produced by the rubbing between the brake shoe and the brake disc within the braking system, allowing the wheels not to contact the brake shoe and not wearing off the sides of the wheels. When the brake pad is pressed against the brake shoe, the heat that is produced is reduced using cooling fins. The disk brakes are axle mounted brakes and are commonly used due to their simplicity and good braking power, increasing just by adding more discs on the same axle.

Figure 33. Axle mounted disc brakes on a high-speed train [20].

Some disc brakes can also be wheel mounted in a case that the manufacturers want to save up space in the bogie:

Figure 35. Difference between axle mounted and wheel mounted disc brakes *[21]* .

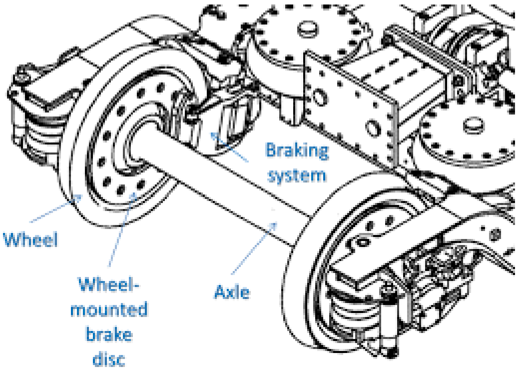


Figure 34. Setup of a wheel mounted disc brake [48].

4.1.4 Tilting mechanism

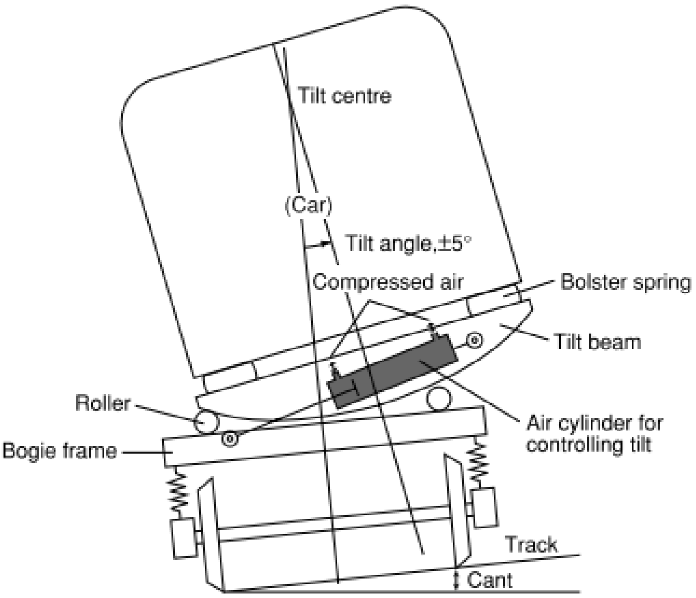


Figure 36. Tilting technology sketch [45].

Centrifugal force is an adversary for trains when in curves, passengers when in this situation are pushed towards the outside of the curve by the centrifugal force, which negatively affects the passenger ride quality. To avoid that, the tilting mechanism is applied specifically to high-speed trains. The tilting of the carbody minimizes the lateral forces acting on the passenger and baggage while in a curve. The physics behind is like what a motorcyclist feels when in a curve, designed to combat the g-forces. The train can be constructed so that the tilting is caused by the inertial forces, called passive tilting, or a more complex design computer controlled powered mechanism with the utilization of airbags - called active titling. Figure 37 shows all the elements that come to play when managing active tilting.

The curvature-dependent body-tilting mechanism, also known as 'Pendolino' (after the first ever successful train with this type of technology at Italy), applies a speed-enhancing system with does not need track guidance to function. The maximum a train can travel is limited on the one hand by the forces present between the wheel and the track (these forces cause wear to the wheels as does to the track itself) and on the other hand, the level of comfort you would like the passenger to feel.

All the equations ahead are from the book: A. Steimel Electric Traction, motive power and Energy Supply, 2008.

$$a_y = \omega^2 * R$$

Equation 1. Centrifugal acceleration

The centrifugal acceleration is related to the travelling speed squared; this appears to disturb the passengers in the cabins moving. Then, it required a super-elevated outer rail of which the maximum value that is permitted is 150 mm in height (ü).

A second elevation of the outer rail of a further üf = 130 mm is applied to improve the comfort of the passengers even more. This is the so-called 'can't deficiency'. Equaling both centrifugal accelerations ``parallel to the rails (where g = 9.81 m/s^2) you get that.

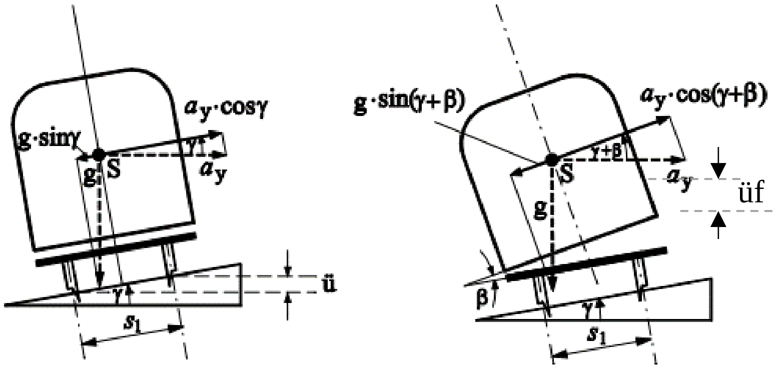


Figure 37. Forces present in car body when through a curve [15].

$$g \cdot sin\gamma = \frac{v^2}{R} \cdot cos\gamma$$

Equation 2.
Equaling both centrifugal accelerations parallel to the rails

Combined with:

$$tan\gamma = \frac{\ddot{u} + \ddot{u}_f}{s_I}$$

Equation 3.
expresses the $tan\gamma$ of the slope in Figure.37

you get that:

$$v = 0{,}7 \cdot {s_l}^{-1} \cdot \sqrt{R \cdot (\ddot{u} + \ddot{u}_f)}$$

Equation 4. Velocity that the train can travel

This reordered and simplified gives:

$$\frac{v}{kph} = \sqrt{\frac{\frac{R}{m}}{11{,}8} \cdot \frac{\ddot{u} \cdot \ddot{u}_f}{mm}} = 4.87\sqrt{\frac{R}{m}}$$

Equation 5. Velocity that the train can travel

This means that the maximum speed for a curve radius of 500 m may not exceed 110 kph (68 mph).

If we give the carbody an additional tilting of an angle β = arc tan$\{\frac{\delta \ddot{u}}{s1}\}$, the admissible speed will be raised (with the same level of comfort):

$$\frac{v_{tilt}}{kph} = \sqrt{\frac{R/m}{11,8} \cdot \left[\frac{\ddot{u} + \ddot{u_f} \; + \; \delta\ddot{u}}{mm}\right]}$$

Equation 6. Velocity that the train can travel if tilting.

For example, a maximum angle of β = 8˚, a super-elevation of 210 mm, then:

$$\frac{v_{tilt}}{kph} = 6.45\sqrt{R/m}$$

Equation 7. Velocity that the train can travel if tilting

Applying the same conditions as before, R=500 m, you may now travel at a speed of v_{tilt} = 145 kph, which increases 30% from the previous calculations. It shows how important a tilting mechanism is. It permits a 30% increase in velocity by just tilting the carbody on curves without sacrificing the comfort of the passenger.

4.1.5 Axle guidance

The steering is the ability to adapt to the radial position on curves, decreasing ten times the wear on both the tracks and train's wheels. The track forces are significantly lowered and, consequently, replacement is reduced considerably in the process. Finally, the noise produced by the rubbing of the wheel and the rails are eliminated partially or totally.

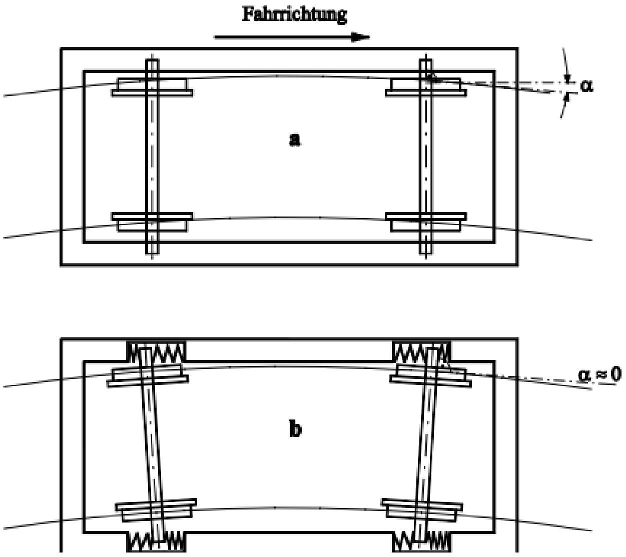


Figure 38. Sketch demonstrating the importance of stiffness [15].

Fig.39 (a) represents a bogie with a stiff wheelset. The frontal wheelset creates a big striking angle (α) between the rails and the wheels of the bogie. This will ultimately lead to wear in the lateral parts of the wheels and, inversely, in the tracks too.

On the other hand, Fig.39 (b) shows a considerable diminishing of the angle α thanks to the self-stirring wheelset. It, in turn, allows the outer-curve wheel to run on a larger curve center allowing it to run faster.

4.2 Miscellaneous bogie designs:

As you previously may have been able to see, there are a lot of pieces to a bogie and a lot of styles to it as well, all associated with a certain train. This subchapter describes some examples of the different design principles for the rolling stock and passenger train used nowadays.

- **High-speed, passenger coach and multiple unit bogie:**

The passenger trains constitute the majority of trains and they are the ones with the most changes done over the years. Each design has its purpose and is specific for a certain region of the world. Each bogie design has small differences, making them preferable for some terrains and circumstances than others.

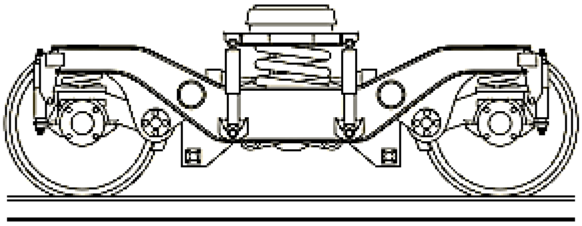


Figure 39. Fiat bogie Y0270S [49]

Fiat bogie Y0270S is important because it is the bogie frame selected to analyzed in this work. It has a bolster on top that sits over a helical spring (secondary suspension), which is substituted for an airbag in modern days. This design was applied for the French bogie Y32, the Italian bogie Fiat Y0270S and the Spanish bogie CAF-GC as well as the Alstom TVG bogies.

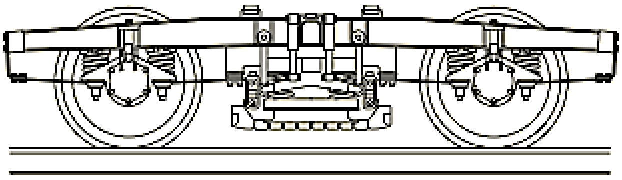


Figure 40. Minden-Deutz bogie MD 36 [49]

Minden-Deutz bogie is a more straightforward design. It has two steel springs on both sides of the axle box that help with the unevenness of the tracks, making this bogie optimal for stability and ride quality.

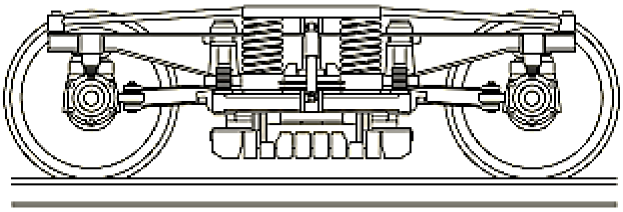


Figure 41. Minden-Deutz MD 52 - used in the German ICE trailer [49]

Minden-Deutz bogie is made to facilitate the maintenance of the axle box, particularly to dismount of the axle box is vertical (easier than the rest) and without any further difficulty. It has two larger secondary suspensions under the bolster and motion dampers around the wheels of the wheelset.

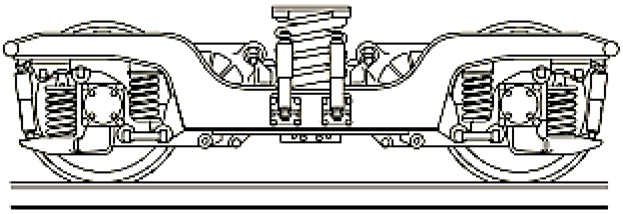


Figure 42. Alstom bogie [49]

Alstom bogie is designed so that the passenger does not feel much of the tracks. It integrates tilting technology and uses two helical steel springs on each side and supports the axle box with another two smaller steel springs and dampers. This design is lighter in weight.

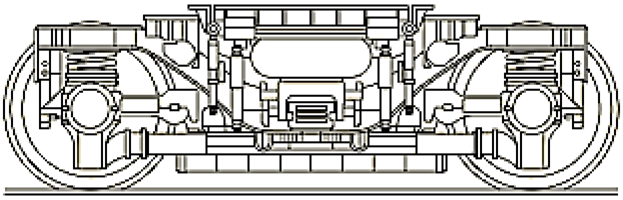


Figure 43. Siemens SF 500 [49]

Siemens bogie is a more modern type. One way to tell is the airbag spring as a secondary suspension system. It has a steel spring on top of the axle box, combined with vertical and horizontal dampers. It has a shallow center of mass, making it very stable and comfortable for the passenger.

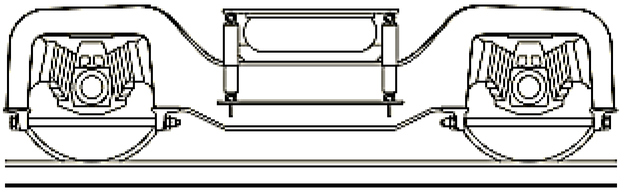


Figure 44. Chevron rubber springs bogie [49]

Chevron bogie has rubber springs allowing it to tilt, act as suspension and guidance, depending on the different circumstances. It has an extensive range of use; it is applicable to multiple mass transit vehicles and the Swedish X2000 high-speed tilting train.

- **Freight cars bogie designs:**

Freight bogie is designed firstly to ensure the stability of the cargo inside and then the comfort of the passengers. The bogie then will have a different type of suspensions called steel spring leaf suspensions over the axle box, just like in the first example.

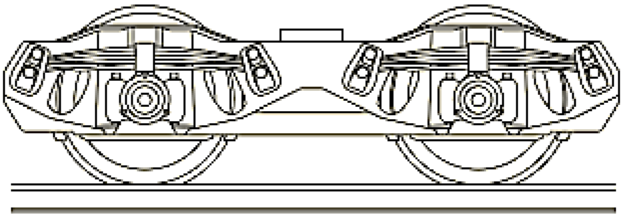


Figure 45. German 665 bogie [49]

This bogie has a parabolic steel leaf suspension on top of the axle box to alleviate the irregularities the tracks may have. The springs act as a guidance mechanism for the wheelset.

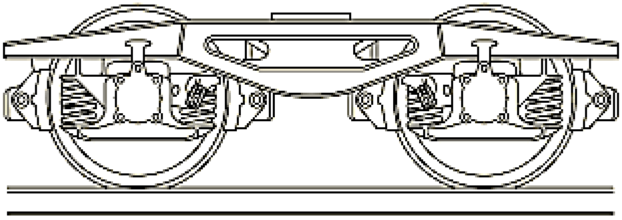


Figure 46. Y25 bogie [49]

In contrast, Y25 bogie does not have the steel leaf suspension over the axle box, but instead has a double steel spring-like the high-speed trains. It does have a vertical and horizontal damper that helps with stability and guidance. This design is a well know one and it can be manufactured using casting techniques.

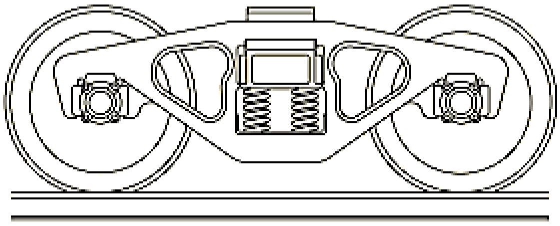


Figure 47. Sealed and greased axle box bearing bogie [49]

Sealed and greased axle box bearing bogie is made in such a way it does not have a primary suspension. It is a very well-known and cheap design to make due to being standardized.

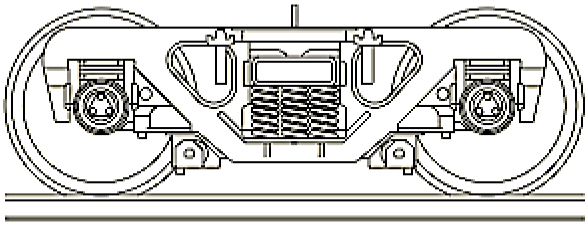


Figure 48. Y25 bogie [49]

Like the axle box before, Y25 bogie is sealed and greased as well; but in contrast, it has a rubber blanket in the primary suspension so that the ride is not as hard on the cargo. The Chinese railway freight industry uses this design.

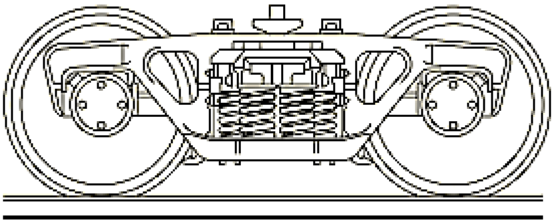


Figure 49. Russian Y25 bogie [49]

Like the Chinese Y25 bogie, Russian Y25 bogie does not have primary suspension. It has integrated a front cover protector in the bearing system, allowing the maintenance to be relatively easy and low cost.

- **Mass transit bogie:**

The mass transit bogies are specially made for metro cars, light rail vehicles, tramways, and suburban trains. The different bogie types can be divided into two main categories, ç standard height floor cars and the low-floor cars, either of which heavily affects the design of the bogie.

- Standard height floor car bogie:

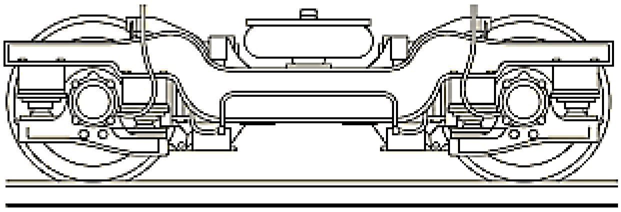


Figure 50. Siemens SF bogie [49]

As you may see, Siemens SF bogie has rubber guidance and springs around the axle box, as well as in the bolsterless connection with the car body (secondary suspension). Several bogie manufacturers apply this design– for example, Siemens SF for bluky and lightweight metros

- Low floor bogie:

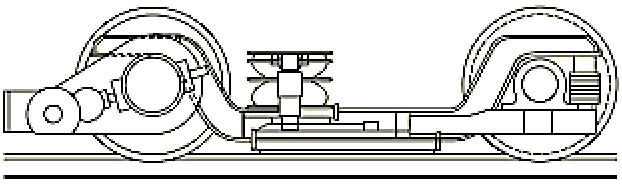


Figure 51. Low-floor bogie created by Bombardier [49]

The low-floor bogie is usually applied for the light rail vehicles and tramcars. The powered wheel pair (left side) is loaded 2/3 and the non-powered around 1/3 of the total bogie load.

4.3 The selected bogie for the analysis:

As stated in the previous subchapter, there are many unique models to the bogie, all linked to the different needs that the bogie has. They all possess small differences that make a world of difference in certain fields of use. It is time to discuss which type of bogie is analyzed in the study and *why*.

The bogie selected for this study is the *Fiat Y0270S* – the frame of the bogie is generally made up of Structural Steel S235 and according to the standards EN1993-1-1:2005, it has a density of 7850 kg/m3, a Young modulus of 210 GPa, and a Poisson's ratio of 0,3. The Fiat Y0270S is mainly used for commuter trains, meaning it is the train category that is used for medium distance travelling. As stated in *chapter 2*, trains are the most environmentally friendly vehicles, with very low fuel consumption. Increasing the efficiency of the train will be hard, but by reducing the weight of the train (e.i., the frame of the bogie), it is manageable.

It is a common interest that the train gets lighter and therefore cheaper. For instance, a lighter train will translate in less CO_2 emissions, and less maintenance on the train and less track maintenance from the impacts of a heavy train against the tracks. Integrating a lighter train in the mix will ultimately mean that the prices of train ticket may go down, as there are less upkeeping done by the government and by the companies themselves.

- **Force transmission:**

Vertical forces come from the carbody to the bogie frame through the secondary suspensions and the track forces (which are also vertical forces) are directly provided by the primary suspensions.

Lateral forces are the forces produced by the carbody (when in a curve) and it is translated to the frame through the secondary suspensions, and as for the lateral forces that the wheelsets have over the frame bogie, they are translated through the primary suspension system.

- **Elements of the bogie:**

It is useful to state some of the elements present in the bogie. Figure.52 displays the location of some of the main pieces of the bogie FIAT Y0270S:

- Wheel diameter: when new 915 mm - when worn 845 mm.
- Suspension elements: the primary suspension consists of a tip rubber pad nested on top of inner and outer springs and dampers.
- Secondary suspension: consist of two nested flexi-coil spring or airbag suspension (for more modern designs), vertical dampers, lateral dampers, and anchor rings.
- Axles: On the bogie, each axle is fitted with two *brake* disks of diameter 640mm and 110 mm in width. An axle bearing is introduced so that the bogie speed is being monitored at all times.

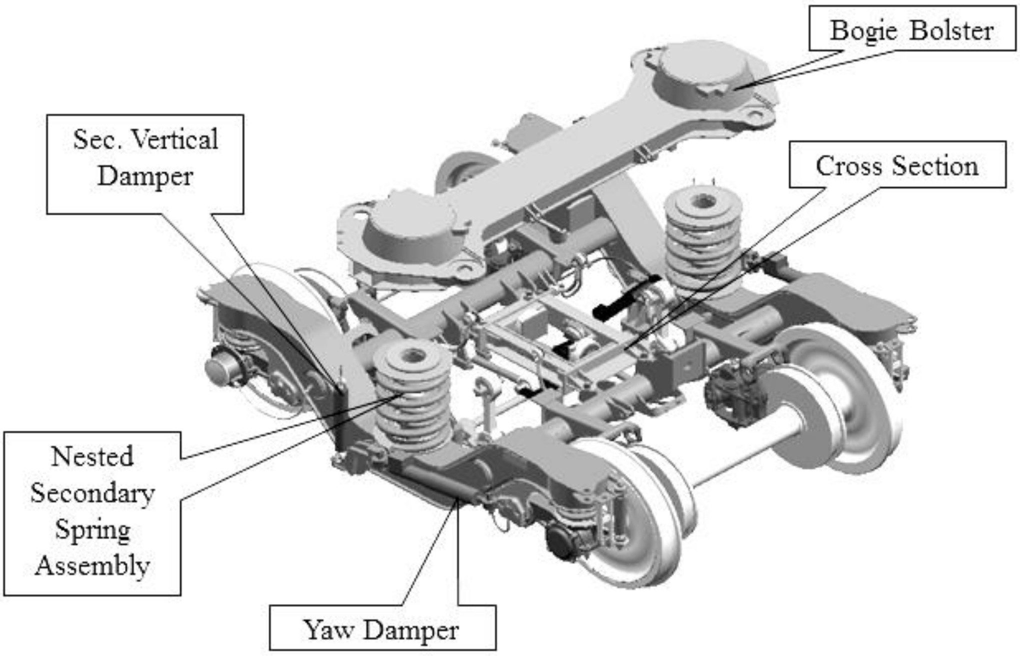


Figure 52. Fiat Y0270S [22]

5. Bogie frame material:

As said earlier, this thesis's main goal is to reduce the weight of the bogie frame without forfeiting the mechanical properties to reduce the CO2 emissions, allowing the train's performance to increase and be more eco-friendly. One method of reducing weight is substituting the original material of Structure Steel S235 to that of a composite material.

For the first part of this study, the bogie frame is made up of structural steel S235 with mechanical properties that, according to EN1993-1-1:2005. It is strong, tough, somewhat elastic and has decent corrosion resistance. The downside to it is that it was heavy, extremely heavy. The density is 7850 kg/m3, a Young modulus of 210 GPa, and a Poisson's ratio of 0,3. It is an issue because the ***frame*** composes >20% of the weight of the carbody. In retrospect, it translates into a considerable cost in maintenance, more fuel needed to move the carbody, less efficiency, less ability to move heavier objects due to it being a heavy element as it is, more emissions of CO_2 and overall more inconveniences. The alternative option is using composite materials. In general, composites are less dense than steel and are relatively equally strong or even stronger. The field of composite materials is gaining potential and is a prominent candidate to substitute many metals we use nowadays.

5.1 Composite Materials:

What is a composite material?

A composite material is composed of two or more materials with distinctive physical and chemical properties that produce a material with a desired characteristic when combined. The components participants in the composite material stay separated and distinct within the individual component. This characteristic distinguishes it from the mixtures or solids solutions.

5.2 Composite material for the bogie frame

The aim is to study the stress behavior of the bogie frame when constructed using a composite material. Nowadays, there have been many studies around the idea of finding the best composite material for the bogie frame, and after going through a pool of options, we chose to go with 3 different plies for the frame. Two different variations of Carbon Fiber Reinforced Polymer (CFRP) and an Aluminum honeycomb structure.

The carbon fiber reinforced polymer (CFRP) is a great alternative because it is a very lightweight material equivalent to the structural steel S235. Thanks to the carbon fiber's adaptability and the ability to vary the number of carbon fibers in the matrix, you can customize the mechanical properties of the CFRP. Thanks to these properties mentioned, there are many variations to the CFRP composites making some variations better than others for certain tasks.

On the other hand, there is a need for another light material and that added thickness to the frame with decent mechanical properties. For that, the honeycomb aluminum structure has been chosen. It is an excellent material to add volume. It gives rigidity to the structure while still having a low amount of material.

As mentioned previously, due to the COVID-19 and the financial restrictions, it makes it impossible to use the laboratory to perform any tests. It has been decided to simulate the mechanical behavior by using ANSYS with regards to the Woven Epoxy Carbon Fiber, the UD Epoxy Carbon Fiber, and the Honeycomb Aluminum structure.

5.3 Woven Epoxy Carbon Prepeg:

Woven Epoxy Carbon Prepeg is a variation for the CFRP and is one of the materials that composes the composite frame. The name Woven Epoxy Carbon Prepeg means that the Carbon chains (carbon-carbon, which have incredibly strong molecular bonds) are in the Epoxy matrix that acts as a resin for the carbon molecules. To create this fabric, you need to wave it, interlacing these matrices from 0º to 90º. The lacing of the fibers produces the mechanical properties characteristic to the WEC.

Woven Epoxy Carbon also has the advantage that it could be draped (this is the capacity to adjust to complex geometry). The area weight and the porosity are controlled by selecting a weaving style, making it a very versatile material and very sought-after. The reason why it is in aerospace aircraft.

Since there exists a range to the mechanical properties for any CFRP, the mechanical properties that were selected are the ones that are available in ANSYS R19.2. The following table displays said mechanical properties associated with the woven epoxy carbon Prepeg:

Table 6. Table of mechanical properties for woven epoxy carbon Prepeg, available in ANSYS R19.2

Density [Kg/M3]								
1420								
Orthotropic Elasticity								
Young's Modulus X Direction [Pa]	Young's Modulus Y Direction [Pa]	Young's Modulus Z Direction [Pa]	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY [Pa]	Shear Modulus YZ [Pa]	Shear Modulus XZ [Pa]
6.134e+010	6.134e+010	6.9e+009	4.E-002	0.3	0.3	1.95e+010	2.7e+009	2.7e+009
Orthotropic Stress Limits								
Tensile X Direction [Pa]	Tensile Y Direction [Pa]	Tensile Z Direction [Pa]	Compressive X Direction [Pa]	Compressive Y Direction [Pa]	Compressive Z Direction [Pa]	Shear XY [Pa]	Shear YZ [Pa]	Shear XZ [Pa]
8.05e+008	8,05e+008	5.E+007	-5.09e+008	-5.09e+008	-1.7e+008	1.25e+008	6.5e+007	6.5e+007

5.4 Recycled Unidirectional Epoxy Carbon Prepeg:

The Recycled Unidirectional Epoxy Carbon Prepeg is the second CFRP variation selected to create the composite frame. A Recycled Unidirectional Epoxy Carbon Prepeg fabric is one where all the carbon fibers are pointing towards one direction, and as the name suggests, it is in an Epoxy resin matrix. The epoxy has the duty of holding the carbon fibers at their place (all pointing in one direction) and represents part of the mechanical behavior of the CFRP.

The advantage of using recycled unidirectional epoxy carbon is that you can orient the fibers to where you need them the most and modify their quantity and porosity. When working with UD's, a very commonly used strategy is layering the UD in 0-degree to 90-degrees plies (not to be mistaken with weaving). This pattern will guarantee you at least a biaxial orientation (two axes), which will give you your primary lines of action.

A recent study has demonstrated that *recycled unidirectional epoxy carbon prepreg* maintains the majority of its mechanical properties after a thermal recycling approach [23]. The study tries a novel thermal recycling process and retrieves the results of the mechanical properties of the recycled unidirectional epoxy carbon, that if compared to other virgin unidirectional epoxy carbon fibers of a similar constitution, you can see there is only a small difference. The Ultimate Tensile Strength decreases 14.26% and the Young Modulus decreases 3.2% . This study has a very promising outcome and will be utilized to simulate the recycled UD epoxy carbon for the composite frame.

Same as before, it is necessary to display in table a format the mechanical properties of the recycled unidirectional epoxy carbon fiber material ahead, so there is a full comprehention of the mechanical behaviour of the composite frame. The mechanical properties for unidirectional epoxy carbon used for the making of this composite frame were the one available in the ANSYS R19.2 database. These mentioned mechanical properties (of the unidirectional carbon fiber) were changed to fit more with the results found in the study mentioned previously (for the recycled unidirectional carbon fiber) [23]. And like said previosely, in the study it has been shown that the Ultimate Tensile Strength decreased by 14.26% and the Young's Modulus decrease around 3.2% after being recycled. With these results, the mechanical properties available in Ansys R19.2 of the unid. carbon fiber will be modified to fit the narrative of simulating a recycled unidirectional epoxy carbon fiber for the composite bogie frame

Table 7 Table of mechanical properties for Recycled Unidirectional Epoxy Carbon Prepeg, available in ANSYS R19.2.

Density [Kg/M3]								
1490								
Orthotropic Elasticity								
Young's Modulus X Direction [Pa]	Young's Modulus Y Direction [Pa]	Young's Modulus Z Direction [Pa]	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY [Pa]	Shear Modulus YZ [Pa]	Shear Modulus XZ [Pa]
1.17e+11	8.3e+09	8.3e+09	0.27	0.4	0.27	4.7e+09	3.1e+09	4.7e+09
Orthotropic Stress Limits								
Tensile X Direction [Pa]	Tensile Y Direction [Pa]	Tensile Z Direction [Pa]	Compressive X Direction [Pa]	Compressive Y Direction [Pa]	Compressive Z Direction [Pa]	Shear XY [Pa]	Shear YZ [Pa]	Shear XZ [Pa]
1.91e+09	2.49e+07	2.49e+07	-1.082e+09	-1e+08	-1e+08	6.E+07	3.2e+07	6.E+07

5.5 Honeycomb aluminum structure:

Honeycomb cores are available in a variety of materials. In our case, the selected material is Aluminum. This material has the advantage that it has high strength and is an extremely lightweight component. They can be modeled in both flat and curved models, making them very adaptable structure.

Despite having good mechanical properties, and relatively low price, aluminum honeycomb has to be used with caution; corrosion is an important factor when considering using aluminum honeycomb. It must not come in contact directly with carbon skin, because it could originate galvanic corrosion. Another disadvantage is that the honeycomb has no memory. If the core is deformed, it has no way of coming back to its original shape. Table 7 displays the mechanical properties that the aluminum honeycomb has in the ANSYS R19.2

Table 8 Table of mechanical properties for Aluminum honeycomb, available in ANSYS R19.2

Density [Kg/M3]								
80								
Orthotropic Elasticity								
Young's Modulus X Direction [Pa]	Young's Modulus Y Direction [Pa]	Young's Modulus Z Direction [Pa]	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY [Pa]	Shear Modulus YZ [Pa]	Shear Modulus XZ [Pa]
1.E+006	1.E+006	2.55e+008	0.49	1.E-003	1.E-003	1	3.7e+007	7.E+007
Orthotropic Stress Limits								
Tensile X Direction [Pa]	Tensile Y Direction [Pa]	Tensile Z Direction [Pa]	Compressive X Direction [Pa]	Compressive Y Direction [Pa]	Compressive Z Direction [Pa]	Shear XY [Pa]	Shear YZ [Pa]	Shear XZ [Pa]
0	0	5.31e+006	0	0	-5.31e+006	0	1.21e+006	2.24e+006

5.6 Fatigue in a composite material:

Virtually all existing materials suffer some degradation of their mechanical properties over time by applying a cyclical load or by consequence of prolonged exposure to specific environmental conditions. Most of the composite elements are also sensitive to fatigue and will be subjected to failure, to a greater or lesser extent.

When a composite laminate is subjected to a cyclical load, two main phenomena can be observed from a structural perspective. The first, the downfall of its rigidity and second, it is breaking into pieces at levels lower than its static strength. This is due to different damage mechanisms that appear at different points in the material (e.i., shear of the laminate, the collapse of the core, wrinkling inside the laminates creating a tension magnifier, and so on). We know that carbon fibers are very insensitive to cyclical loads and, therefore, very well under cyclical fatigue loads, but the problem comes from binder material (epoxy in our case), which does affect a greater extent. So, we will investigate in this important property, as it will greatly affect how the study is carried out.

A laminate is a highly heterogeneous material with great anisotropy, which has a transcendental influence on its behavior, and therefore on the collapse from fatigue. This can be explained because each sheet of the composite has properties that differ from each other depending on the orientation, the binder material, and the uniformity of the composite. This lack of homogeneity gives rise to internal loads between the different components (anisotropy), making this the main cause of deterioration caused by fatigue and possible delamination, fiber fracture, the formation of cracks etc.

When a composite material reinforced with fibers ruptures during a cyclical load, it is considered a progressive process in which different degenerative mechanisms appear to damage the laminate internally. The mechanism that produces fatigue does not resemble the propagation of a single defect, as in metals. Instead, it is a propagation of defects that increase with the number of cycles. It is a problem because most of the studies carried out on the fatigue of the composites are based on prior knowledge of fatigue for metals, despite their different behavior.

Fatigue calculations are carried out by considering several operating parameters: maximum and minimum stress values and the reversion index R (which is just the division between the minimum and maximum tension that appears once applying the force) and its frequency cyclical force. The mean and alternating tension will be obtained and then used to calculate the fatigue parameters (i.e., safety factor, etc.).

Depending on R's values, the nature of the tension is determined. Meaning if it is only a traction study, a compression study or a combination of traction and compression.
After the R’s values are obtained, Wöhler curve can be found.

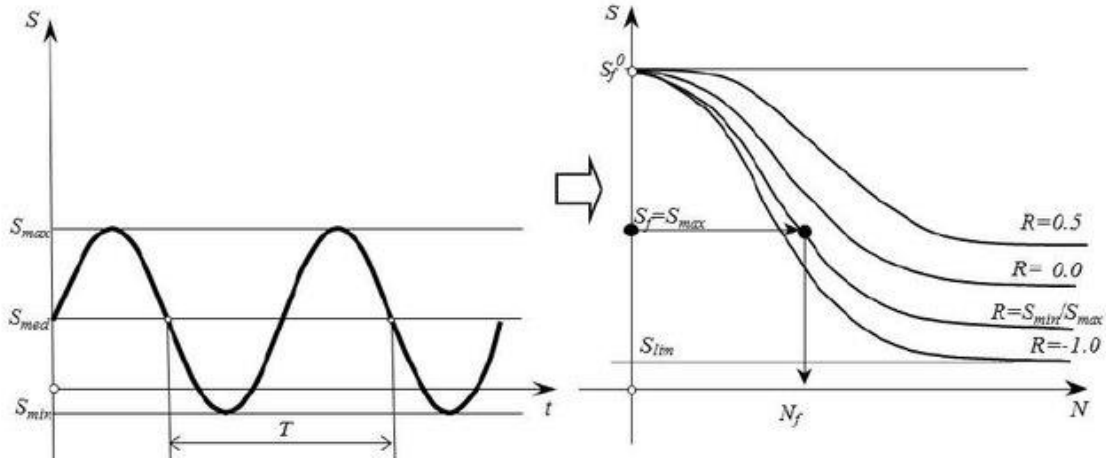


Figure 53. a: Stress evolution at a single point; b: S-N (Wöhler's) Curves [24].

Figure.54 expresses the relationship between resistance values and how they decrease with load cycles and the relationship between the maximum and minimum cyclical stress and the Wohler curve.

The problem resided when we combine the methods that we use for studying fatigue in metals with composite materials (i.e., using Wohlers S-N curves to predict when it will fail, and so on.). For composite, there are ***underlying damages*** that differ depending on what the compound is made up of. The combination of fibers and matrix, distribution and orientation of the reinforcement and the load conditions (if it is in a tensile situation, bending, compression, and so on) do not generalize the experimental results.

In the following figure, you can see S-N curves for a few composite materials, these composites are not all the same (i.e., some are woven, some are UD, some have a 5-degree bias, and so on), and by comparing the different S-N curves, you can notice how sensitive the composites are to certain fatigues.

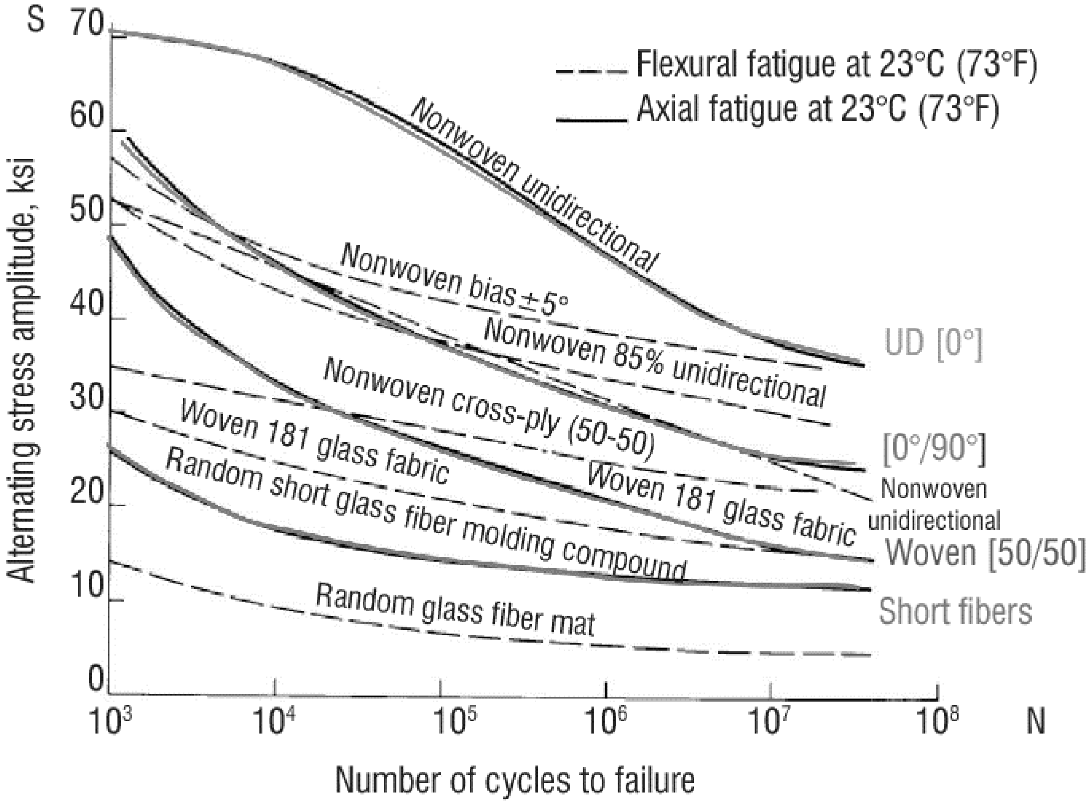


Figure 54. Example of a Wohler curve for composite materials, different R's and life expectancies. [25].

In the last decades, many efforts are being made to understand fatigue on composites, but as it is still a modern material and in continuous evolution, the tests result from the fatigue simulations remain hidden in the companies dedicated to this sector. Each configuration will have a curve and behavior that is specifically only for that matrix/configuration; even if there were a study publicly done with the same materials and ply configuration that we chose (which is highly unlikely), the geometry of the model would not have the same, making the results to that study inapplicable to my case.

To carry out a fatigue test on the bogie frame, we would need to make an exhaustive test using cyclical loads over a bogie frame, and with the results predict a behavior depending on an immense number of variables, which would not be reliable if not done each step perfectly. The objective of this study is to analyze the performance of the bogie under different loads. These loads should consider failure due to fatigue and extreme or exceptional load situations. However, the impossibility of entering a laboratory due to COVID-19 restrictions and the financial limitation that this project withholds makes the fatigue analysis aspect not feasible. Consequently, it makes it clear that the only way is to study the frame analytically. Thus, using simulation software allows the analysis for the exceptional cases (with the help of finite element analysis) and discards the composite materials' fatigue failure.

5.7 Advantages and disadvantages of the CFRP & Aluminum honeycombs:

- **Advantages:**

Governments spend millions of euros on track repairs and maintenances, and part of the money is charged to the companies proportionally to the amount of wear that a bogie design causes on the railroad tracks. Any type of advancement in the field of maintenance is welcome from an economic point of view. It precisely is another reason why CFRP is an excellent choice for the bogie frame. Reducing the bogie frame's weight, that is 20% of the train's total weight. It reduces the wear or damage on the railroad tracks and suspensions, ultimately reducing maintenance costs for both the bogie and the government that maintains the tracks it runs on.

The overall weight is the primary cause of track damage, notably when trains transit or when the dynamic forces appear as the trains enter a curve. The bogie configuration is about 20% of the carbody total weight, so reducing its weight is the obvious solution to reducing the harm done on the rail tracks. A study is done on the damages on rail tracks done by the bogie highlights that it mainly comes from axle loads, yaw stiffness and un-sprung mass [26].

By adding the CFRP in the mix, it can achieve:

1. A weight reduction.
2. A new design for the bogie as you can use the flexibility of the bogie.
3. Less CO_2 emissions as the lightweight frames translate into less fuel consumption.
4. More eco-friendly trains. As science advances, we understand better the science and implications behind using recycled CFRP, hopefully achieving a 100% recycled bogie frame.

One exciting aspect of using a mixed composite for the frame is that you are limited to your imagination. It can combine all the composite that there are available and construct that of what you need, like combining different plies, orienting them differently with respect to one another, redesigning the geometrical shape of the bogie or reducing components that will no longer be needed, and so on. There are virtually thousands of variations that a model could be built using composites, and the research shows it.

- **Disadvantages:**

The primary reason that the Carbon fiber reinforced polymer is not being used widely around the world is that it is a relatively expensive material. Manufacturers like ELG are now implementing recycled carbon fiber (originating from the aerospace industry) and are redesigning new manufacturing processes to lower the global price without risking the quality of the structure [27]. An association of companies (consortium) of RSSB, ELG Carbon Fiber, Magma Structures, Alstom UK, the University of Birmingham (Sensors and Composites Group) and the University of Huddersfield have agreed on a new method

[28]. As the consortium embodies the industrial supply chain (in the UK), it will commercialize the technology soon.

Another disadvantage of this mix of composites has; it is at the core of the aluminum honeycomb that does not have elastic deformation. It means that there is a need to design around the honeycomb limitations, limiting its application in certain areas of the frame. Usually, the main source of failure in any composite structure is the resin that binds together the plies. There will be a large shear force in the material that would want to break the ply apart; this shear force, if greater than the resin, will ultimately produce the model to fail thanks to a propagation of the delamination throughout the model.

All of the above summarizes that the composite models are complex, comparing them to their counterparts, metals; as such, no model can guarantee the coverage of all the aspects of fatigue. We know that composite is very good in fatigue, but we do not know exactly how much confidence. Thus, with this limitation – if we were to produce this composite frame, we would need to ensure that all the frames that was produce met the safety and reliability standards. The strategy designers that use composite material are to over-design the model so that fatigue is impossible.

- **Summary of benefits:**

    - Reduce the weight of bogie.
    - Reduce maintenance cost and access charges.
    - Simplify and redesign the bogie frame.
    - Reduce maintenance of the tracks and bogie components.
    - Reduce global warming.
    - Use of recycled elements, which is better for the environment.
    - Progress in a potentially important field.
    - The ability to pioneer in the field,

Comparing the advantages and disadvantages gives perspective. It is useful to know what is expected and help you formalize a strategic route on how to avoid as many different inconveniences as possible. Although using composite might have negatives, the positives (as to my take) outweigh the negatives. Converting what we see around us into something more sustainable, lighter, smarter, and more advanced is something we should all strive for regardless of the complexities that may be up ahead. *Nothing meaningful is easy - Aim high.*

6. Technique specification:

The scope is to appropriately describe the forces that appear in the bogie frame during its intended life period. For the correct development of the process, it is convenient to have a clear structure of the important points touched upon.

The end goal for this is to make sure that the bogie overcomes all of the conditions that it will be subjected to during the different adverse states. There is a need for a 3D Design (with Solidworks) of the selected bogie frame Fiat Y0270S, afterward validating the bogie frame against the acceptance criteria established in the rule EN 13749:2011.

6.1 Analysis methods and acceptance criteria:

For the methodology, it is necessary to demonstrate that the bogie can withstand the deflections, the permanent deformation and the different load cases or fracture of the structure as a whole or of any individual element. All loads applied on the bogie will have a level of uncertainty that will have to be assumed during the analysis. This uncertainty arises from the fact that no public sheet of specification or elements of any bogie is available online. Companies that manufacture bogies can legally have nondisclosure about certain critical elements considered their intellectual property and are not legally obligated to upload the specification.

Thus, this is a very realistic and uncomfortable challenge that we will have to overcome to properly analyze the bogie frame to the best of my capabilities. For this, we will assume some of the values that will be necessary within a reasonably educated guess. In the EN 13749:2011, some values are available within a stated range. So it will be chosen the exact middle value of both extremes to proceed with the calculations.

7. Forces present in the bogie:

The aim is to describe the loads that the bogie experiences throughout its service. Additionally, it shall give you a satisfactory idea of the behavior of the bogie according to the design and rule EN 13749:2011 and EN 15663:2018

It is necessary to properly describe some of the symbolisms that will appear in the following chapter and their unites so that there is a complete understanding of the different superscripts that will ahead.

All the tables in the following chapter come from EN 13749:2011.
Forces:

Forces (N)	Position	Symbol
		Static
Vertical	Load Applied To Bogie	F_z
	Force On Sideframe 1	F_{z1}
	Force On Sideframe 2	F_{z2}
Transverse	Load Applied To The Bogie	F_y
	Force On Axle 1	F_{y1}
	Force On Axle 2	F_{y2}
	Force At (Vehicle Body) C Of G	F_{yc}
Longitudinal	Force At Each Wheel	F_{x1}

Table 9. Forces present in the different loads

Masses:

Mass (kg)	Symbol
Vehicle Mass In Running Order	M_V
Vehicle Body	m_1
Bogie Mass Without Any Secondary Spring Masses	m^+
Bogie Primary Spring Mass	m_2
Exceptional Payloads	P_1
Normal Services Payloads	P_2

Table 10. Masses

Other symbols and units:

Other	Symbol	Unit
Acceleration Due To Gravity	g	9,81 m/s^2
Stress	σ	N/mm^2
Determined Stress	σ_c	N/mm^2
Material Proof Or Yield Stress	R_{eH}	N/mm^2
Material 0,2% Proof Stress	$R_{p0,2}$	N/mm^2
Material Ultimate Stress	R_m	N/mm^2
Factor Of Safety	S_1	
Car Body Surface Area	A_w	m^2
Number Of Bogies Per Carbody	nb	
Number Of Axles Per Bogie	ne	

Table 11. Symbols and unit

Coordinate system:

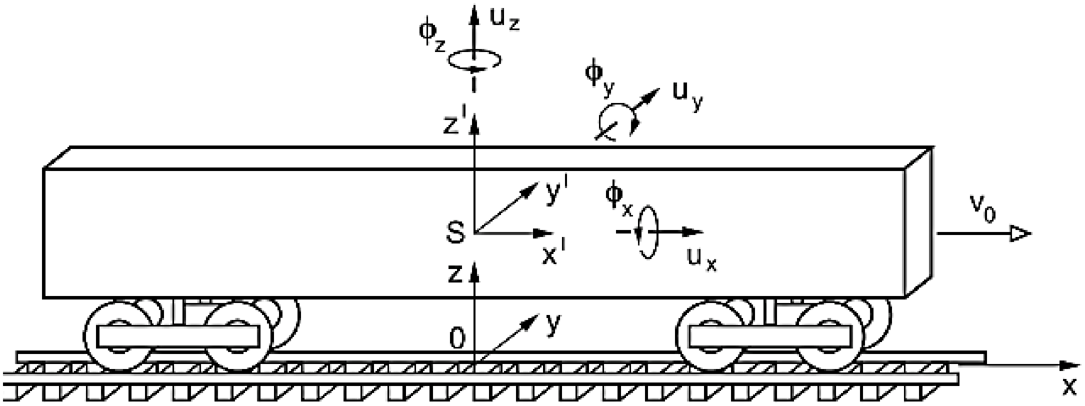


Figure 55. Co-ordinate system and nomenclature of motion, for study purposes [50].

The previous figure relates to the motions that a train is capable of doing in three axes reference. It will help explain the various terminologies that will be used later on.

u_z vertical motion, the linear direction of the travel.
u_y lateral motion, linear parallel to the plane of the track and perpendicular to the direction of the track.
u_x longitudinal motion, linear perpendicular to the plane of the track.
ϕ_z yawing, rotation about the vertical axis,
ϕ_y pitching, rotation about the transversal axis.
ϕ_x rolling, rotation about the longitudinal axis.

7.1 Load cases:

The bogie experiences many different types of loads. These loads fall into two different types of groups, namely external and internal.

External loads are those that are the results from

- Running on the tracks (e.g., vertical forces due to what the bogie is carrying, the transversal forces on curves or when going across crossings, twisting the bogie as a result of the bogie going through a twisted track)
- Starts or stops and associated vehicles accelerations
- Loading or unloading cycles of the vehicles
- Lifting and jacking

Internal load cases are due to the mounted components that are in the bogie (say perhaps the dampers, the brakes, the motor, the inertial forces caused by the masses that are attached to the bogie, and so on)

All the load cases are compromised in three states:

- Static
- Quasi-static
- Dynamic

These three states have many levels to them, but a commonly adopted approach for the design is assessing the structure, divided into two cases.

On the one hand, we have the *static load* representing the extreme load cases in the bogie when in service. These cases are also known as exceptional cases. Thus, a bogie structure should withstand these loads without deflecting or permanently deforming in such a way that would impair its performance after removing the load.

On the other hand, we have the second type compromised in the *fatigue load* case. This case represents those loads that will not produce permanent damage to the bogie if applied once but rather after a prolonged application cycle might start to wear down the bogie. In other words, these are the forces that repeatedly occur in the bogie during regular operation.

7.2 Loads due to the bogie running:

While in use, the bogie is exposed and should survive the following list of forces:

- The weight of the carbody
- The changes in the payload
- Track irregularities
- Taking curves
- Acceleration and breaking
- A sudden change of payload
- Minor derailment

- Buffing impacts
- Extreme environmental condition
- Maintenance stations (lifting and jacking)

In a real scenario, these loads are combined in a really complex manner and it is difficult to represent them in the analysis. To study the different cases stated above, it is represented the different loads in a simplified form for ease of analysis. But in contrast, it is important to ensure that the simplified loads do not underestimate the loads stated above.

The following equations and approaches are described in the regulations of EN 13749:2011.

7.3 Loads that appear in the bogie passenger rolling stock:

In the following subchapter, we will display the equations that are going to be used to calculate the forces that are going to be applied in the FEM model. These are the loads that the bogie will experience through its life cycle; these loads will be divided into *exceptional loads*[1] *and normal service loads*[2] with their respective equations. It is worth mentioning that EN 13749:2011 also clarifies how to calculate the forces present from the weight of the items attached to the frame of the bogie, but we have two distinct elements to analyze and two different situations. We chose a trailer car with no motor that we would need to consider, ultimately simplifying the research calculations.

7.4 Definition of exceptional loads:

All the equations stated ahead are in accordance with the EN 13749:2011. When selecting the bogie's efforts, we had to reduce the number of simulations to finish the project in time. EN 13749:2011 specifies that more than 78 cases are to be looked into when designing a bogie frame. This number arises from the sum of the exceptional service loads (without track twist), the exceptional particular service loads (without track twist), the exceptional service loads (with track twist), the exceptional particular service loads (with track twist), the fatigue service loads (without track twist), the particular fatigue service loads (without track twist), the fatigue service loads (with track twist), the particular fatigue service loads (with track twist), the inertial weight of the items that are attached to the frame (while in service loads and without track twist), the inertial weight of the items that are attached to the frame (while in service loads and with track twist), the inertial weight of the items that are attached to the frame (while in exceptional loads without track twist) and, finally, the inertial weight of the items that are attached to the frame (while in exceptional loads with track twist).

We reduced the number of cases for this study and opted for the primary cases with Exceptional service loads without track twist and the particular service loads without track twist.

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[1] Exceptional loads: representing the loads that occur only in extreme cases.

[2] Normal service loads: representing those that occur in normal service cases.

➢ *Exceptional limit loads*

Vertical loads:

Vertical forces are derived from sprung masses, meaning the force of the weight of the carbody that comes from the interaction applied through the secondary suspensions. The force is applied in both of the side frames. TIt is applicable with the supposition that the vehicle's mass is evenly distributed between the two bogies and the carbody is supported on top of both side frames equally.

$$F_{z1max} = F_{z2max} = \frac{F_{zmax}}{2} = \frac{\frac{k \cdot g}{nb} \cdot (M_v + P_1 - n_b \cdot m^+)}{2} = \frac{\frac{1.4g}{2}(M_v + P_1 - 2 \cdot m^+)}{2}$$

Equation 8. Vertical load

Where:
M_v Vehicle mass in running order
P_1 Exceptional payloads
$\boldsymbol{n_b}$ Number of bogies per carbody = 2
m^+ Bogie mass without any secondary spring masses
k = 1.4
g gravity acceleration = 9,81 m/s^2.

Lateral loads:

These forces are generated while in a curve and transferred to the frame via the dampers.

$$F_{y1} = F_{y2} = \frac{F_{ymax}}{2} = 10^4 + \frac{(M_v + P_1) \cdot g}{3 \cdot n_e \cdot n_b}$$

Equation 9. Lateral load

Where:
M_v Vehicle mass in running order.
P_1 Exceptional payloads.
g Gravity acceleration = 9,81 m/s^2.
n_e Number of axles per bogie.
n_b Number of bogies per carbody.

- *Lateral load on each secondary suspension:*

$$\mathrm{Fy}_{\mathrm{Ss}} = \mathrm{K}_{y_{Ss}} \cdot \mathrm{d}_y$$

Equation 10. Lateral load for each suspension

Where:
$\mathrm{K}_{y_{Ss}}$ Secondary suspension stiffness.
d_y Total displacement.

- *Lateral load on lateral stop:*

$$F_{y_{LSTOP\,(\pm)}} = F_{ymax} - 2F_{y_{Ss}}$$

Equation 11. Lateral load for on each lateral stop

Where:
F_{ymax}Maximum lateral load that the bogie experiences if not for the secondary suspension.
$F_{y_{Ss}}$ The load that each secondary suspension has.

Unloading loads:

This state corresponds to a derailment of the vehicle in operational life, in tare nominal condition.

$$Fz_i(N) = \frac{g}{2 \cdot nb} \cdot (Mv - n_b \cdot m^+)$$

Equation 12. Unloading load

Where:
g Gravity acceleration = 9,81 m/s^2.
n_b Number of bogies per carbody
M_v Vehicle mass in running order
m^+ Bogie mass without any secondary spring masses

Lozenging Loads:

These forces are going to be applied to each of the wheels in the opposite direction. This force appears when the bogie is braking while in a curve.

$$Fxmax\ (N) = F_{X_{whl}} = 0.1\ \cdot (F_{Zmax} + m^+ \cdot g)$$

Equation 13. Lozening load

Where:
m^+ Bogie mass without any secondary spring masses
g Gravity acceleration = 9,81 m/s^2.
F_{Zmax} Vertical load applied to bogie

Longitudinal shunting loads:
This force appears when there is an extremely rapid change in speed. Meaning, when the vehicle is braking. For passenger rolling stock, the mass the gravity sensation is 3 time the normal g, thus:

$$Fx_{WHl} = \frac{Fx}{4}$$

Equation 14. Longitudinal shunting loads on each wheel

Where,

$$Fx\ (N) = 3 \cdot g \cdot (m^+ + m_{beam})$$

Equation 15. Total longitudinal shunting loads

g gravity acceleration = 9,81 m/s^2.

m^+ Bogie mass without any secondary spring masses
m_{beam} Mass of the beam

7.5 Definition of fatigue service loads:

➢ *Fatigue limits:*

Vertical fatigue loads:

$$F_{z1max} = F_{z2max} = \frac{F_{zmax}}{2} = \frac{\frac{k \cdot g}{n_b} \cdot (M_v + 1.2P_2 - nb \cdot m^+)}{2} = \frac{\frac{1 \cdot g}{2} \cdot (M_v + 1.2P_2 - 2 \cdot m^+)}{2}$$

Equation 16. vertical fatigue load.

Where:
M_v Vehicle mass in running order
P_2 Normal service payload
n_b Number of bogies per carbody = 2
m^+ Bogie mass without any secondary spring masses
k = 1
g gravity acceleration = 9,81 m/s^2.

Lateral fatigue loads:
When in normal service mode, this is the standard lateral load expected for the bogie frame.

$$F_{y1} = F_{y2} = \frac{F_y}{2} = \frac{F_z + m^+ g}{8}$$

Equation 17. lateral fatigue load.

Where:
F_z Vertical load present in the normal service of the bogie.
m^+ Mass of the bogie without crossbeam
g Gravity acceleration = 9.81 m/s^2

Longitudinal lozenging forces:

When in normal service mode, this is the standard longitudinal lozenging load expected for the bogie frame.

$$F_{x1} = 0.05 \cdot (F_z + m^+ g)$$

Equation 18. twist fatigue loads.

Where:
F_z Vertical load present in the normal service of the bogie.
m^+ Mass of the bogie without crossbeam.
g gravitational acceleration of gravity = 9.81 m/s^2

7.6 Forces calculation:

To calculate the forces, we need to determine some of the basic dimensions and values of the Fiat Y0270S. The following tables will have a level of uncertainty that arises from the unavailability of a table of content for the Fiat Y0270S. Due to this, an educated guess based on other studies will be made [29, 30, 31].

7.6.1 Forces present in the structure steel S235:

Starting with the structure steel S235 we have the following table of masses and dimensions needed for the calculation process:

Designation	Abbreviations	Units	Trailer car
Vehicle in Tare condition	Mv	kg	28 000
Mass of passengers in exceptional condition (302 people – 70 kg)	P_1		21 140
Mass of passenger in service condition (231 people – 70 kg)	P_2		16 170
Bogie mass without the cross beam	m^+		5 000
Cross beam	m_{beam}		650
Total frame mass	-		5 650
Number of bogies in the car	n_b	-	2
Number of axles in the car	n_e		2
Gravity	g	m/s^2	9.81
Primary suspension – stiffness	$K_{ySp}=K_{xSp}$	kN/m	4 950
	K_{zSp}		1 300
Secondary suspension – stiffness	$K_{ySs}=K_{zSs}$		350
	K_{xSs}		810
Secondary suspension -displacement	Lateral clearance[3]	mm	15
	Lateral stop compression		25
	Total displacement[4]		40

Table 12. Values of the Fiat Y0270S – structural steel S235 according to EN1993-1-1:2005

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[3] The lateral clearance is the relative displacement between the truck frame and the lateral stop before contact.

[4] The total displacement (dy) gives the maximum lateral force.

➢ *Exceptional loads:*

In the appendix I, you will find a visual display of the boundary conditions, including the forces, for all the different load scenarios chosen for this study.

Vertical loads:

$$F_{z1max} = F_{z2max} = \frac{F_{zmax}}{2} = \frac{\frac{1.4g}{2} \cdot (M_v + P_1 - 2 \cdot m^+)}{2} = \frac{1.4g \cdot (28000 + 21140 - 2 \cdot 5000)}{4} = 134387.2\ N \cong 134888\ N$$

Equation 19. Result of the vertical load for the structure steel S235 frame

Lateral loads:

$$F_{y1} = F_{y2} = \frac{F_{ymax}}{2} = 10^4 + \frac{(M_v + P_1) \cdot g}{3 \cdot ne \cdot nb} = 10^4 + \frac{(28000 + 21140) \cdot g}{3 \cdot 2 \cdot 2} = 50172\ N$$

Equation 20. Results of lateral loads without any secondary suspension for the structure steel S235 frame

- *Lateral load on each secondary suspension:*

$$\mathrm{Fy_{Ss}} = \mathrm{KySs} \cdot \mathrm{dy} = 350 \cdot 40 = 14000\ \mathrm{N}$$

Equation 21. Results of the lateral load for each secondary suspension of the structure steel S235 frame

- *Lateral load on lateral stop:*

$$F_{y_{LSTOP\ (\pm)}} = F_{ymax} - 2F_{y_{Ss}} = 2 \cdot 50172 - 2 \cdot 14000 = 72344\ N$$

Equation 22. Results of the lateral loads on the lateral stop for the structure steel S235 frame

Unloading loads:

$$Fz_i(N) = \frac{g}{2 \cdot nb} \cdot (Mv - nb \cdot m^+) = \frac{g}{2 \cdot 2} \cdot (28000 - 2 \cdot 5000) = 44145\ N$$

Equation 23. Result of unloading loads on the structure steel S235 frame

Lozenging Loads:

$$Fxmax\ (N) = F_{X_{whl}} = 0.1 \cdot (F_{Zmax} + m^+ \cdot g) = 0.1 \cdot (2 \cdot 134387 + 2 \cdot 5000) = 31783\ N$$

Equation 24. Result of lozenging loads on the structure steel S235 frame

Longitudinal shunting loads:

$$Fx\ (N) = 3 \cdot g \cdot (m^+ + m_{beam}) = 3 \cdot g \cdot (5000 + 650) = 166280\ N$$

Equation 25. Result of the longitudinal shunting loads on the structure steel S235 frame

➢ *Fatigue loads:*

Vertical fatigue loads:

$$F_{z1max} = F_{z2max} = \frac{F_{zmax}}{2} = \frac{\frac{k \cdot g}{n_b} \cdot (M_v + 1.2P_2 - nb \cdot m^+)}{2}$$
$$= \frac{\frac{1 \cdot g}{2} \cdot (M_v + 1.2P_2 - 2 \cdot m^+)}{2}$$
$$= \frac{g \cdot (28000 + 1.2 \cdot 16170 - 2 \cdot 5000)}{4} = 91734\ N$$

Equation 26.Result of the vertical fatigue load for the structure steel S235 frame

Lateral fatigue loads:

$$F_{y1} = F_{y2} = \frac{F_y}{2} = \frac{F_z + m^+ g}{8} = \frac{2 \cdot 91734 + 5000g}{8} = 29065\ N$$

Equation 27. Result of the lateral fatigue loads for the structural steel S235 frame

Longitudinal lozenging forces:

$$F_{x1} = 0.05 \cdot (F_z + m^+ g) = 0.05 \cdot (\ 2 \cdot 91734 + 5000g) = 11626\ N$$

Equation 28. Twist fatigue loads for the structure steel S235 frame

7.6.2 Forces present in the Composite bogie frame:

Ahead there is a table listing the masses and dimensions of the composite bogie frame. The main differences with the previous table are the weight variation when using the composite chosen as the main material for the frame.

Designation	Abbreviations	Units	Trailer car
Vehicle in Tare condition	Mv	kg	22 824
Mass of passengers in exceptional condition (302 people – 70 kg)	P_1		21 140
Mass of passenger in service condition (231 people – 70 kg)	P_2		16 170
Bogie mass without the cross beam	m^+		465,82
Cross beam	m_{beam}		8,32
Total frame mass	-		474,14
Wheelbase of the bogie	e	mm	2 000
Number of bogies in the car	n_b	-	2
Number of axles in the car	n_e		2
Gravity	g	m/s^2	9.81
Primary suspension – stiffness	K_{ySp}=K_{xSp}	kN/m	4 950
	K_{zSp}		1 300
Secondary suspension – stiffness	K_{ySs}=K_{zSs}		350
	K_{xSs}		810
Secondary suspension - displacement	Lateral clearance[5]	mm	15
	Lateral stop compression		25
	Total displacement[6]		40

Table 13. Values of the Fiat Y0270S – CFRP

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[5] The lateral clearance is the relative displacement between the truck frame and the lateral stop before contact.

[6] The total displacement (dy) gives the maximum lateral force.

➢ *Exceptional loads:*

As for the composite bogie frame, the visual display of the boundary conditions and forces for all the different scenarios are available in the Appendix I.

Vertical loads:

$$F_{z1max} = F_{z2max} = \frac{F_{zmax}}{2} = \frac{\frac{1.4g}{2} \cdot (M_v + P_1 - 2 \cdot m^+)}{2} = \frac{1.4g \cdot (22824{,}1 + 21140 - 2 \cdot 1211)}{4} = 147752{,}1\ N \cong 147753\ N$$

Equation 29. Result of the vertical load for the CFRP frame.

Lateral loads:

$$F_{y1} = F_{y2} = \frac{F_{ymax}}{2} = 10^4 + \frac{(M_v + P_1) \cdot g}{3 \cdot ne \cdot nb} = 10^4 + \frac{(22824{,}1 + 21140) \cdot g}{3 \cdot 2 \cdot 2} = 45940{,}7\ N$$

Equation 30. Results of lateral loads without any secondary suspension for the CFRP frame.

- *Lateral load on each secondary suspension:*

$$\mathrm{Fy_{Ss}} = \mathrm{KySs} \cdot \mathrm{dy} = 350 \cdot 40 = 14000\ \mathrm{N}$$

Equation 31. Results of the lateral load for each secondary suspension for the CFRP frame.

- *Lateral load on lateral stop:*

$$F_{y_{LSTOP\,(\pm)}} = F_{ymax} - 2F_{y_{Ss}} = 2 \cdot 45940{,}7 - 2 \cdot 14000 = 63881{,}4 \cong 63882\ N$$

Equation 32. Results of the lateral loads on the lateral stop for the CFRP frame.

Unloading loads:

$$Fz_i(N) = \frac{g}{2 \cdot nb} \cdot (Mv - nb \cdot m^+) = \frac{g}{2 \cdot 2} \cdot (22824{,}1 - 2 \cdot 465{,}82) = 53691{,}4\ N \cong 53692\ N$$

Equation 33. Result of unloading loads for the CFRP frame.

Lozenging Loads:

$$Fxmax\ (N) = F_{X_{whl}} = 0.1 \cdot (F_{Zmax} + m^+ \cdot g) = 0.1 \cdot (2 \cdot 147752{,}1 + 2 \cdot 465{,}82) = 9645{,}1\ N \cong 9646\ N$$

Equation 34. Result of lozenging loads for the CFRP frame.

Longitudinal shunting loads:

$$Fx\ (N) = 3g \cdot (m^+ + m_{beam}) = 3g \cdot (465{,}82 + 8{,}32) = 14198{,}8\ N \cong 14199$$

Equation 35. Result of the longitudinal shunting loads for the CFRP frame.

8. Solidworks modelling:

Part of the difficulty of this thesis was the lack of dimension values for the bogie frame Y0270S. We went around this issue by downloading a model that had as many similarities as possible with the one we wanted to dedicate my thesis to, and with the measuring tools that Solidworks has (the trusted 3D modelling software we chose to use), we measured and replicated, to the best of my capability, the 3D model.

Solidworks is a very powerful 3D modelling software that many engineering companies use; this software allows you to model 3D objects and simulate and create eDrawings afterward. SolidWorks software was very helpful and an essential part of the development of the thesis. We will visually demonstrate the steps that were taken to create and assemble the bogie frame, add the drawings of the bogie frame and the individual parts in the appendix.

8.1 Frame rod:

The parts of the bogie frame were created separately and later assembled into the bogie frame. The first part that was created was the rod that connects both of the beams.

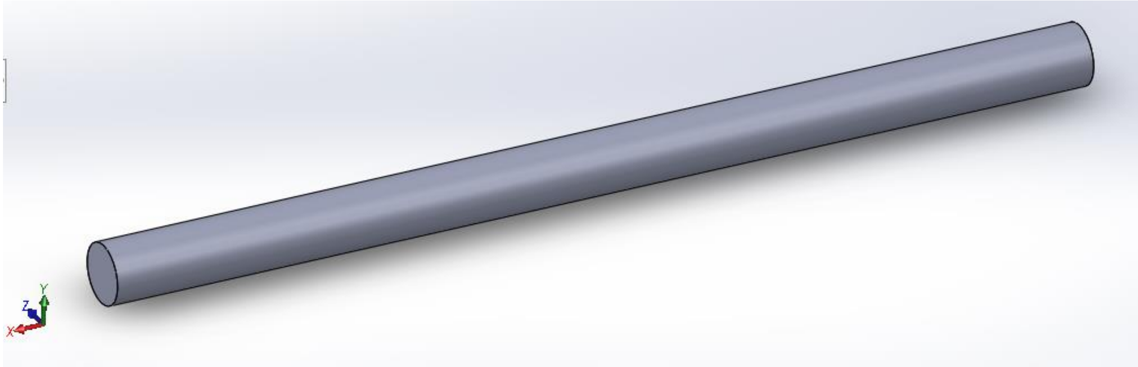


Figure 58. Extruded cylinder

It started by just making an extructed cylinder that later will be the rod's main body.

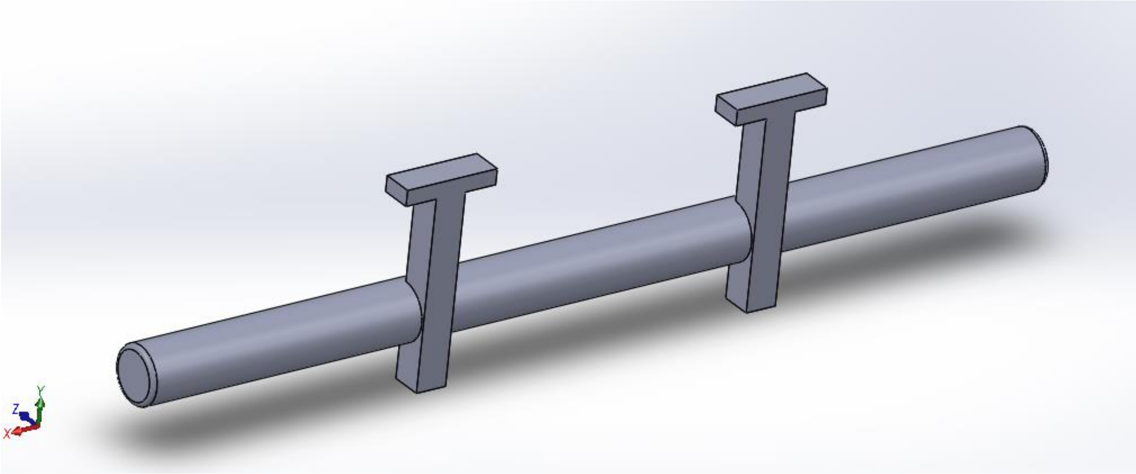


Figure 59. Supports

Later, we modelled the supports where the breaks, some dampers and the motor would have been hanging; and rounded the corners of the cylinder so when assembling it with the beams does not have any sharp edges, avoiding any possible stress concentration.

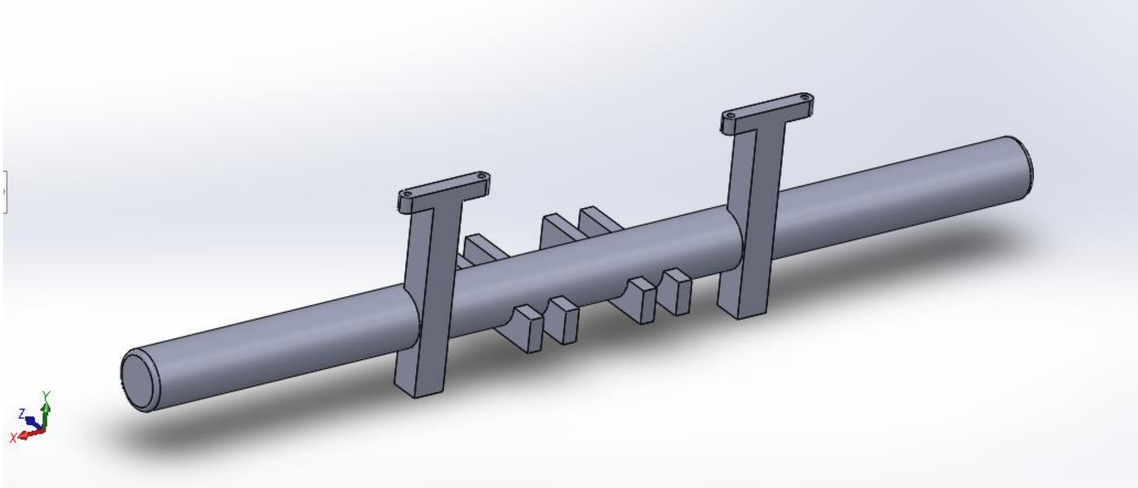


Figure 60. Other supports that will help with the loads.

Afterward, we added some more supports between the previously created ones, which would help carry the hanging pieces (to make it seem realistic). Rounded the edges of the supports and made a hole on them. (this would have been where supposedly the engine is located).

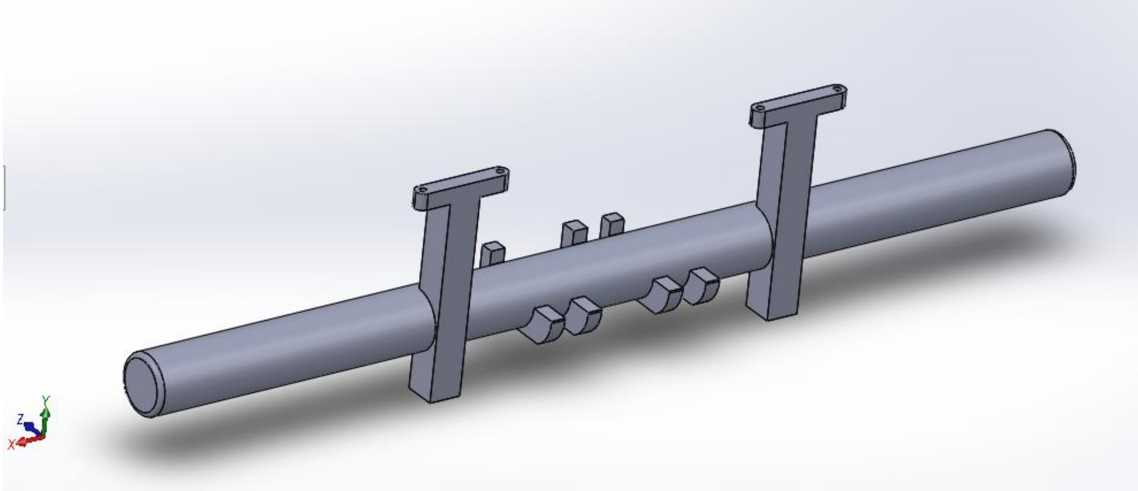


Figure 61. Finishing touches for the rods

Lastly, some finishing touches to the rods so that it resembled more to the photos that there are available online. We tried to make all the pieces as realistic as possible using photos and another bogie frame for reference.

8.2 Beams:

Following the rod, we created the bogie beams. This part was harder to model because we had to take some shortcuts and simplify some parts without making the beam not resemble the real one. The first step we took to create the beam was to create a block that later will be shaped into the beam:

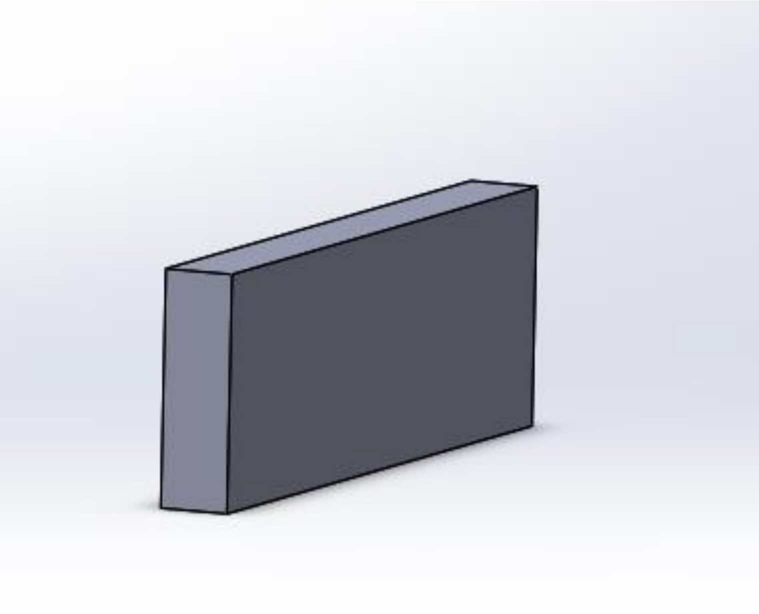


Figure 62. Block that later will for into the beam.

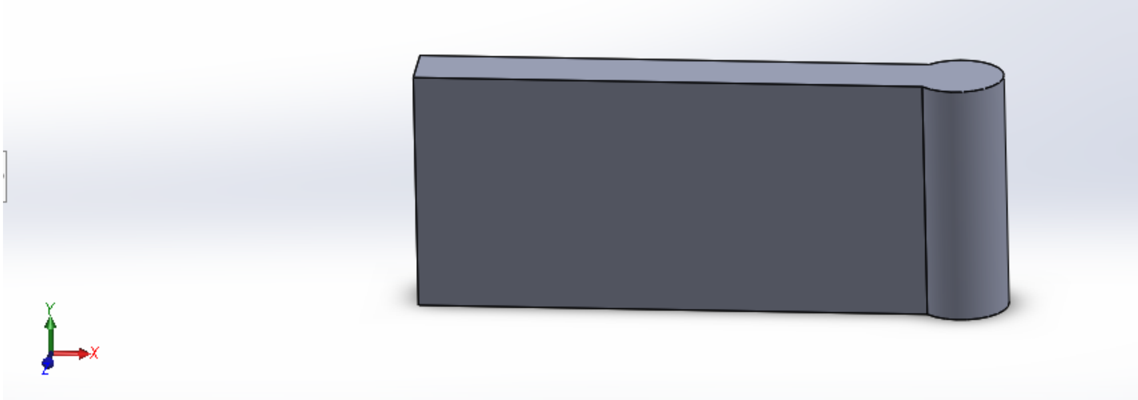


Figure 63. Extruded a round area to the block

Later we extruded a rounded surface to one of the sides of the block:

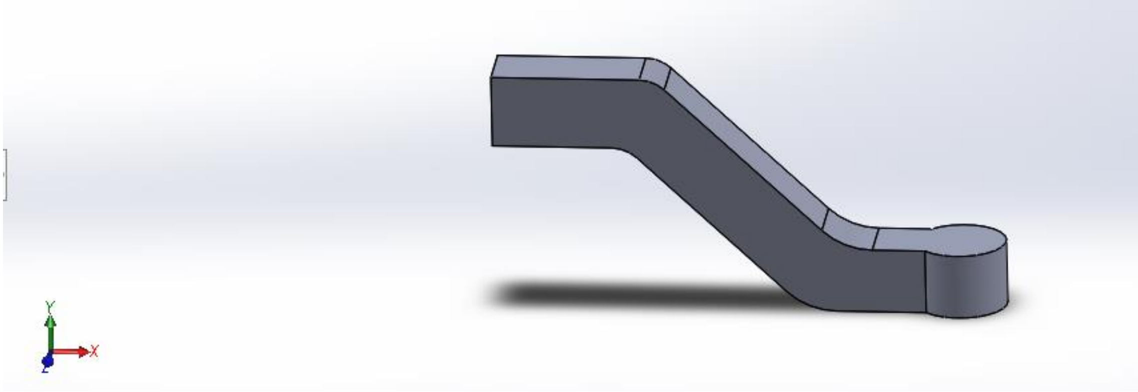


Figure 64. Shaped beamed

From the previous block, we shaped it to be exactly half of the beam, and following the curvature of that, the Y0270S follows:

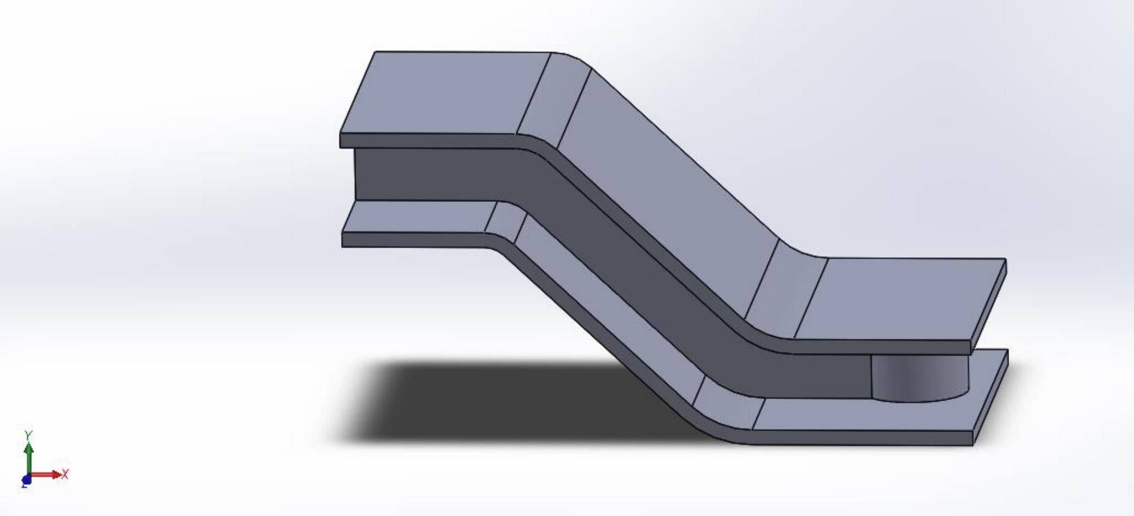


Figure 65. Plates that sit on top and under the beam.

The beam has two “lips” located over the top and under its bottom, making it look more like a beam in a building. These “lips” are later trimmed to fit better the shape of the bogie beams making the change in geometry less exaggerated and better to sustain loads.

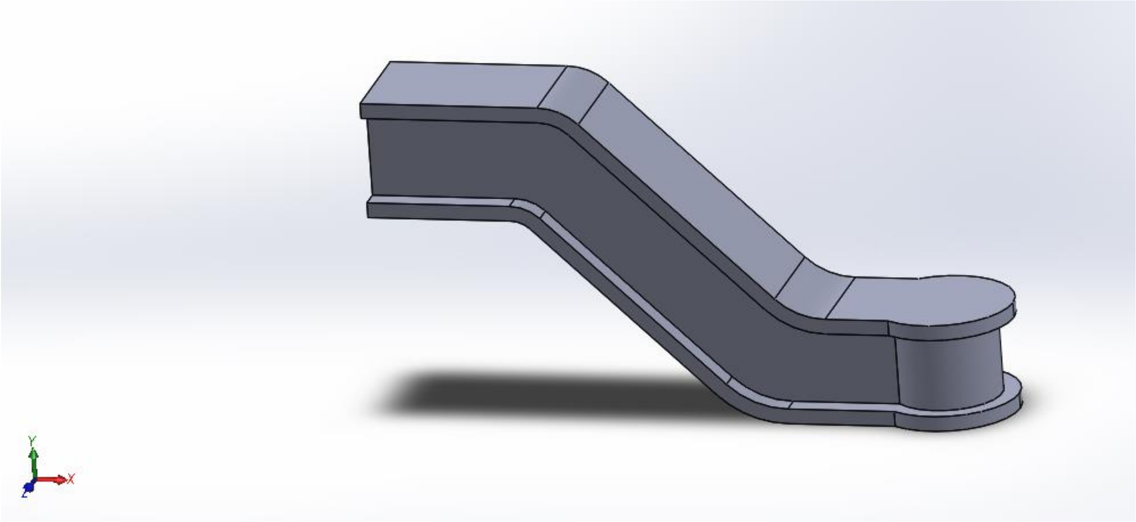


Figure 66. Cut lips.

Dimensioned the parts where the screws would be located (near the end of the beam)

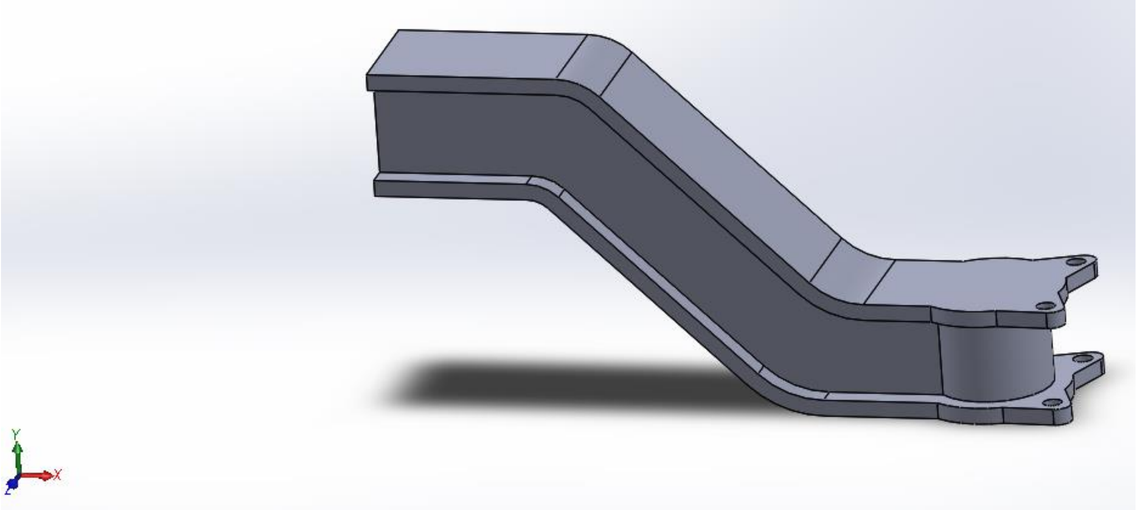


Figure 67. Extruted lips with drilled holes.

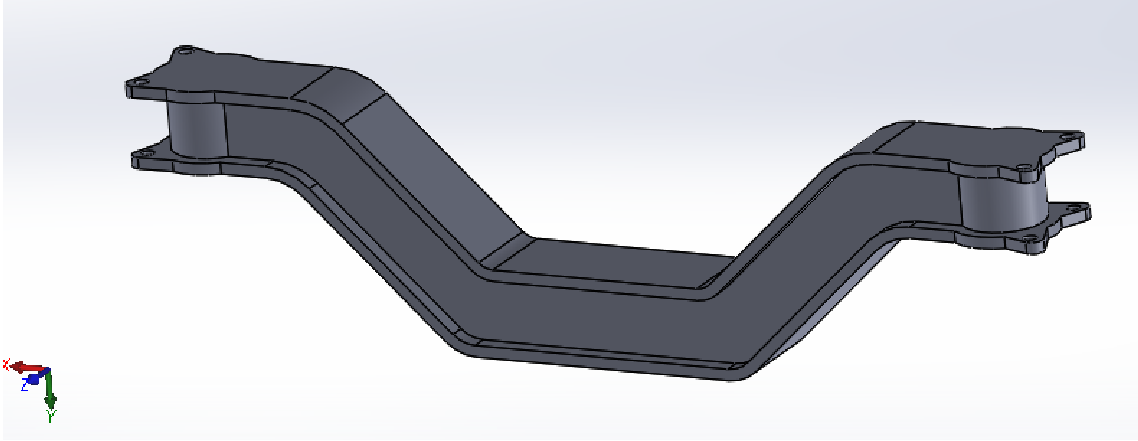


Figure 69. Result product of after using the symmetry tool.

Next, we used the very useful symmetry tool that allowed me to create a symmetrical adjacent body to the face we select. This method of modelling saved me a lot of time and allowed me to be more precise with the model.

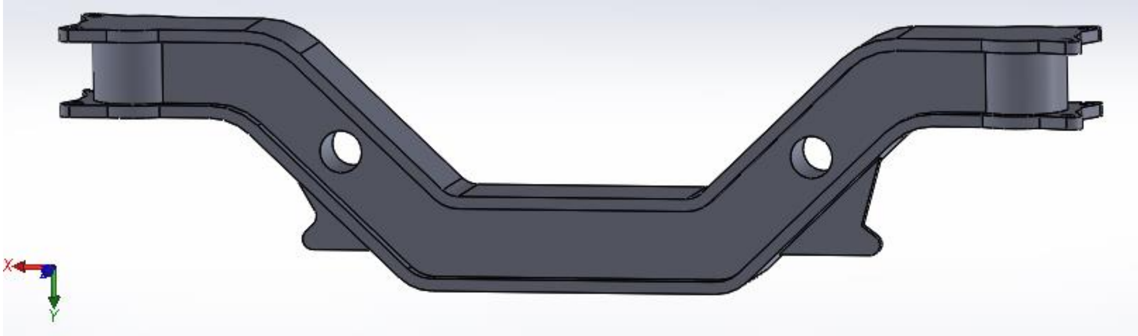


Figure 70. Added the wholes where the rods would be located.

Nearly at the end of the modelling for the beam, holes where the rods would be located when assembledwere constructed.

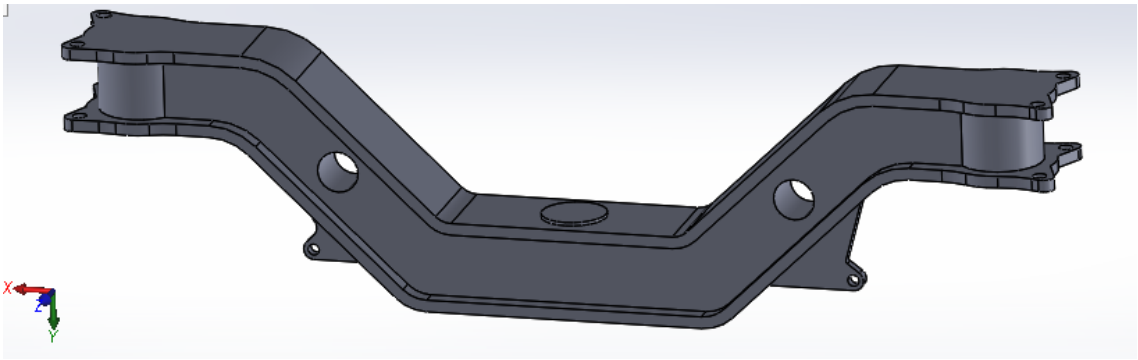


Figure 71. Pad added on top and drilled in holes for the dampers from the brakes to be attached.

It finalized the beam's modelling by drilling holes in the bottom supports where the brakes and wheelset would have been and created a pad where the secondary suspension and the bolster would be located.

8.3 Assembly:

The assembly of the bogie frame was relatively easy:

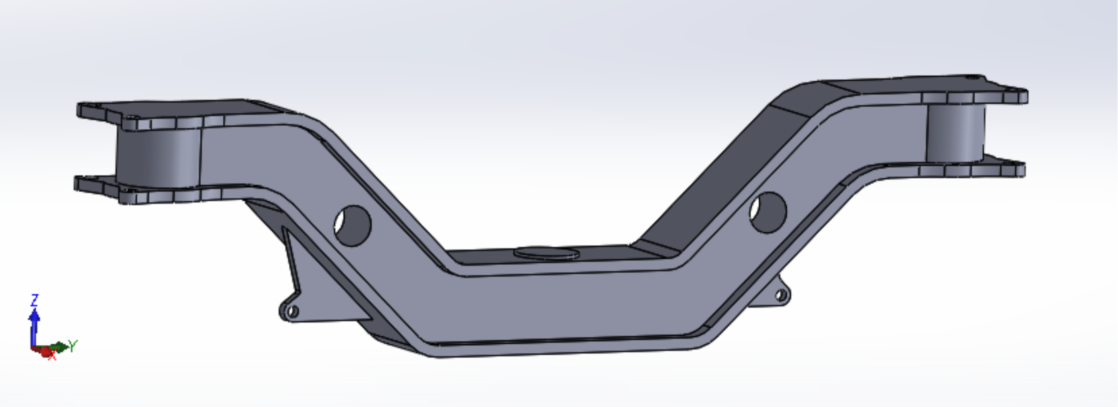


Figure 72. First part to be uploaded for the assembly.

The first part uploaded of the assembly module was one of the beams, making the beams symmetrical made this step easy because it didn't make the assembly harder.

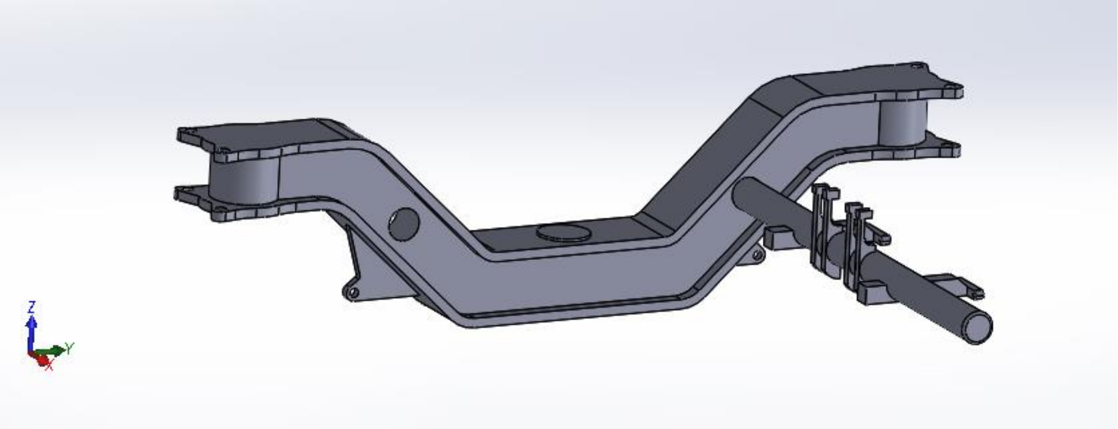


Figure 73. First beam to be inserted.

Later the steps after this were basically inserting the rod in the bogie beams concentrically.

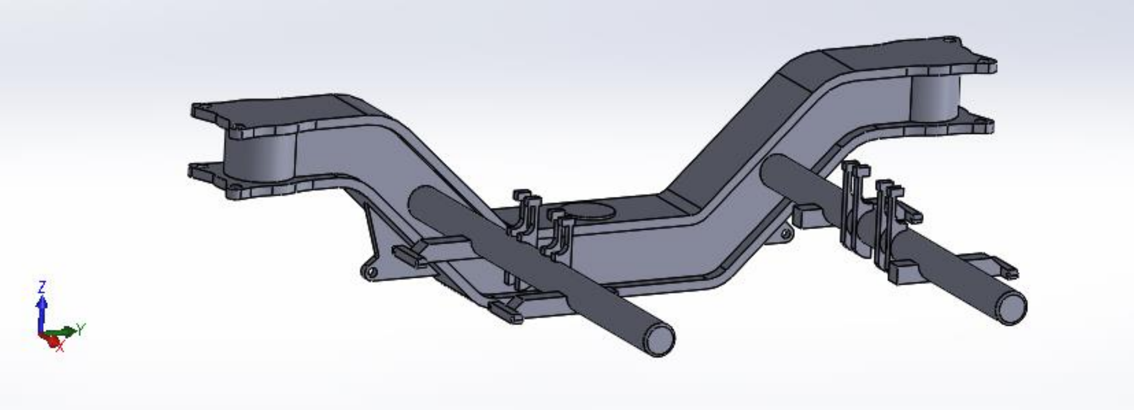


Figure 74. Secon beam inserted.

These rods do not surpass the opposite face of the beam, making the flat side of the cylinders parallel.

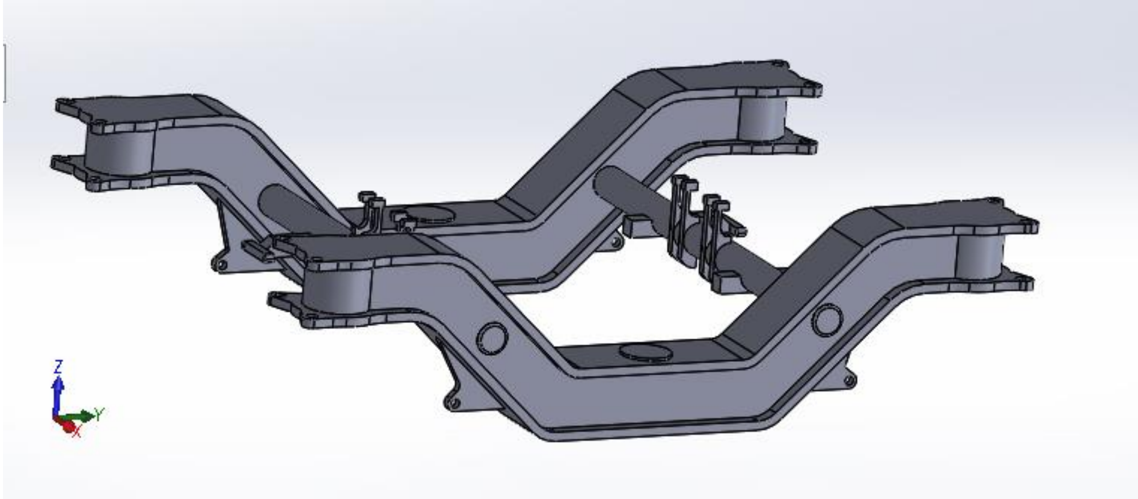


Figure 76 Completed view of the bogie frame completely assembled.

It is the completed look of the bogie frame modelled after the fiat Y0270S. Some parts were not necessary for the study, but were created nonetheless so that it does not loose similarity to the real model.

To end the 3D modelling chapter, its been decided to add in the end an exploded view of the bogie frame and the physical properties of it. This view allows the person to view where the pieces are located exactly, it is convenient when you have a very complex piece and there are a lot of parts in its assembly. The bogie frame can be considered a mostly rigid body and virtually 1 piece.

To reiterate what has been said at the start of this chapter, in the Appendix I are the technical drawings of the parts and the assembly drawings, witt detail and some geometrical tolerances worth mentioning for manufacturing the bogie frame.

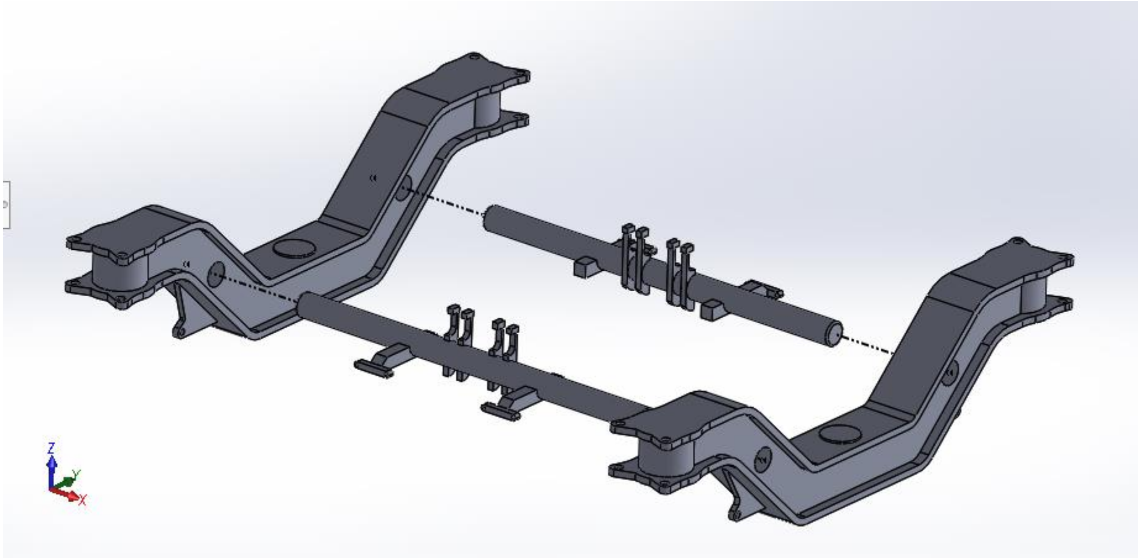
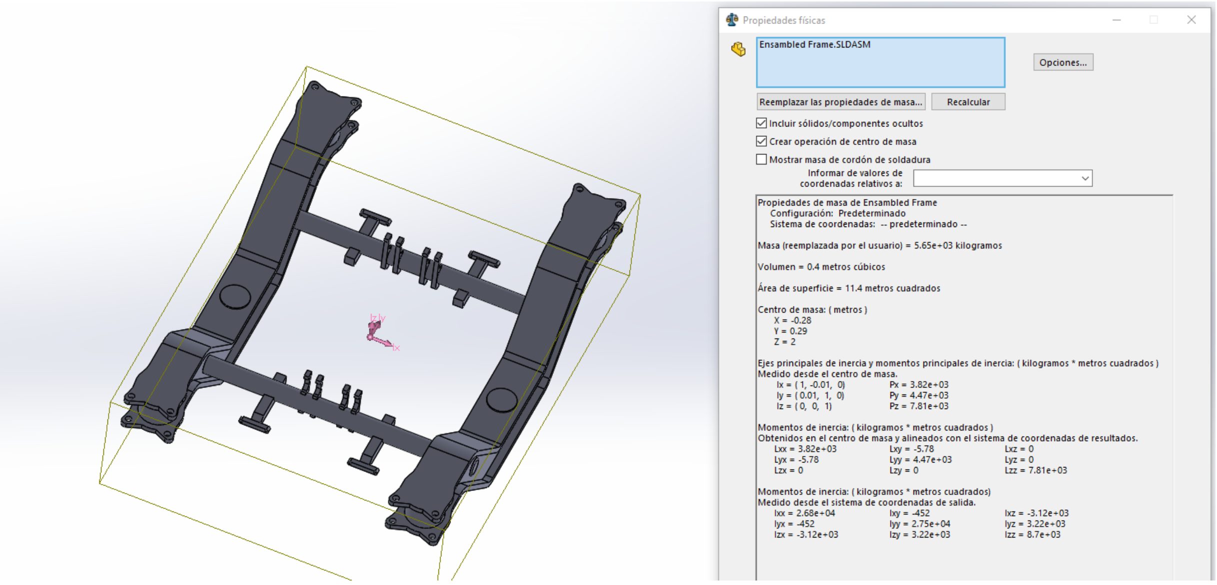


Figure 77. Exploded view of the bogie frame fiat Y0270S



Ensambled Frame.SLDASM

☑ Incluir sólidos/componentes ocultos

☑ Crear operación de centro de masa

☐ Mostrar masa de cordón de soldadura

Informar de valores de coordenadas relativos a:

```
Propiedades de masa de Ensambled Frame
    Configuración:  Predeterminado
    Sistema de coordenadas:  -- predeterminado --

Masa (reemplazada por el usuario) = 5.65e+03 kilogramos

Volumen = 0.4 metros cúbicos

Área de superficie = 11.4 metros cuadrados

Centro de masa: ( metros )
     X = -0.28
     Y = 0.29
     Z = 2

Ejes principales de inercia y momentos principales de inercia: ( kilogramos * metros cuadrados )
Medido desde el centro de masa.
      Ix = ( 1, -0.01,  0)          Px = 3.82e+03
      Iy = ( 0.01,  1,  0)          Py = 4.47e+03
      Iz = ( 0,  0,  1)             Pz = 7.81e+03

Momentos de inercia: ( kilogramos * metros cuadrados )
Obtenidos en el centro de masa y alineados con el sistema de coordenadas de resultados.
     Lxx = 3.82e+03                 Lxy = -5.78                 Lxz = 0
     Lyx = -5.78                    Lyy = 4.47e+03              Lyz = 0
     Lzx = 0                        Lzy = 0                     Lzz = 7.81e+03

Momentos de inercia: ( kilogramos * metros cuadrados)
Medido desde el sistema de coordenadas de salida.
     Ixx = 2.68e+04                 Ixy = -452                  Ixz = -3.12e+03
     Iyx = -452                     Iyy = 2.75e+04              Iyz = 3.22e+03
     Izx = -3.12e+03                Izy = 3.22e+03              Izz = 8.7e+03
```

Figure 78. Physical properties of the bogie frame

9. Ansys Simulations:

For the simulation chapter, we will separate it into two parts, the first part will discuss structural steel S235 and the second part will be about the composite material. (EN1993-1-1:2005)

There are three states that the train will go through during its life cycle: dynamic, quasi dynamic and static state. To correctly simulate these states, they will go through a transformation process into a static state employing boundary conditions and the forces that are calculated in chapter *7.4 - Force calculation*. Before starting the simulation, er will explain a little about the program that was used.

Ansys is a 3D design software that allows simulations that expand into many fields, such as fluid dynamics, aerodynamics, healthcare, mechanical, thermal, and many more. This program is top-rated in the engineering field, thanks to its diversity and uniqueness. Ansys has a selection of material database (including composite materials), making this program the obvious choice to do the CFRP part. This database combined with the previously calculated forces, the restrictions, and the mesh that Ansys can create a thoroughly mechanical study for this thesis. The version of ANSYS that was used in this R19.2

Before going into the different materials, it is first described the characteristics that have in common, the frame. To correctly study the bogie frame, it is necessary to initially do a mesh over the piece. A mesh in Ansys is a geometrical shape that connects throughout the entire object, where points and edges form these shapes. These so-called points are where the shapes connect and are formally called nodes, the edges, in the other hand, are called elements. With a mesh, you can appropriately describe, to a degree, what is happening to an object when put under certain forces. It is accomplished by analyzing the relative movement that the nodes and elements go through after the simulation is over, allowing you to know deformations, fatigue, safety factor, etc.

When properly describing a mesh, you would need to know three aspects: the geometrical shape that the mesh has, the number and size of elements and the number of nodes that have our final model. Later, it is also convenient to refine the mesh in a few areas of the piece, especially those with a very drastic change in geometry. By refining the mesh, you are decreasing the size of the mesh, allowing it to adapt better to the object in hand – giving you a more accurate result. Considering that there are two very different materials, we would need to use two different modules in ANSYS R19.2, forcing me to create two different meshes for this study. We will begin with the mesh of the structure steel S235.

9.1 ANSYS simulation of the Structure Steel S235 bogie frame:

There is a need for the static structure module for the correct simulation of the structure steel S235 bogie frame. In the said module, one of the initial steps is to mesh the frame bogie, as such the subchapter ahead will focus on the meshing of the bogie frame for the structure steel S235.

9.1.1 Meshing the Structure Steel S235 bogie frame:

The mesh of the structural steel S235 will be associated with solid geometry, meaning the initial shape of the mesh will be triangular. In the following figures, you can see how the geometry distinction of ANSYS compared to Soliworks and the frame meshed.

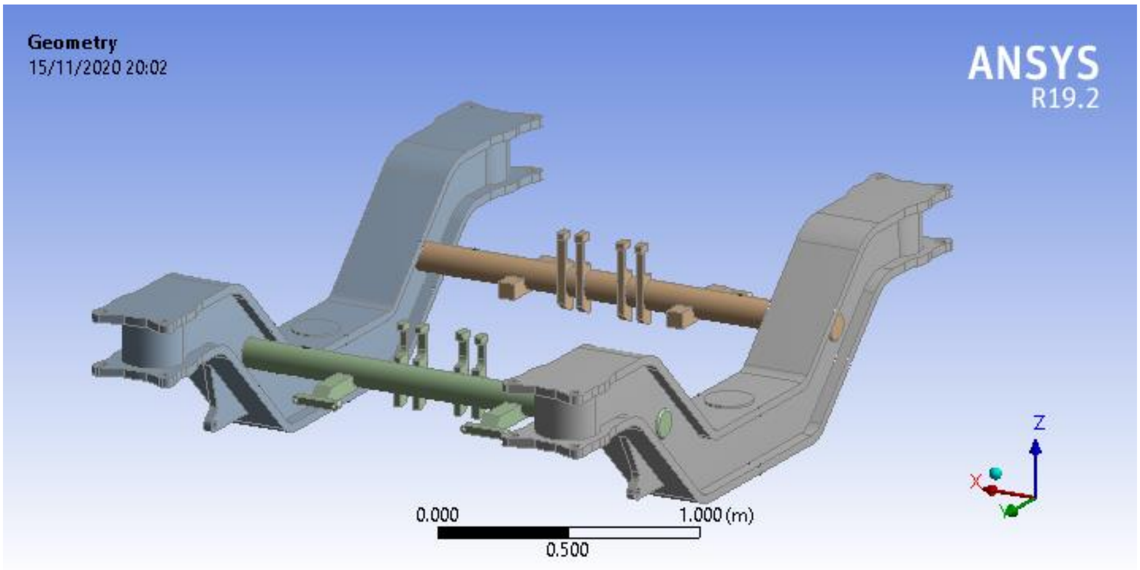
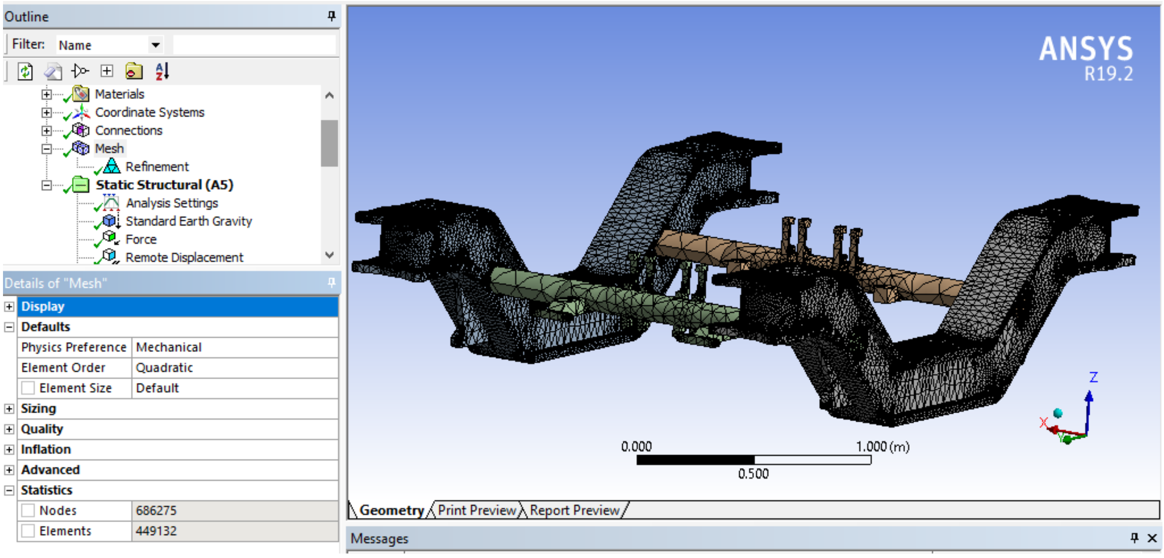


Figure 79. General overview of the bogie frame in the Ansys software.



Details of "Mesh"

Display	
Defaults	
Physics Preference	Mechanical
Element Order	Quadratic
☐ Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
☐ Nodes	686275
☐ Elements	449132

Figure 80. Details of the mesh.

It is necessary to show the characteristic of the mesh to comprehend the model and its quality. In Figure.78, the shape of the components of the mesh is quadratic elements. The number of nodes and elements (on the bottom left corner of the snapshot) is also noted: *nodes: 686275, elements: 449132*. The mesh's element size was taken by default by Ansys to choose the best one for the frame (but it has a value of 0.1m).

Here is a full-size view of the meshed structure steel bogie frame.

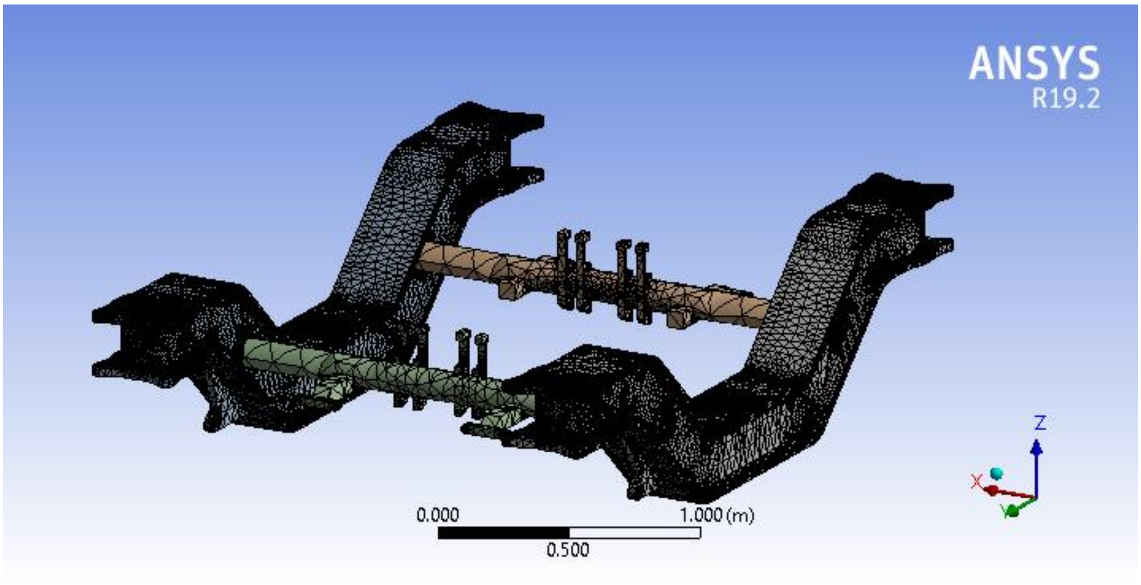


Figure 81. Final product of the generated mesh of the frame.

Figure.78 shows several areas where the mesh is smaller than others because of the sizing where there is a change in geometry (between the rods and the beams). The mesh that Ansys generated by default was not enough. To increase the accuracy of the model, the areas of interest and those parts that the geometry is changing (beam) were refined. In this sense, the results retrieved after the simulation was many times more accurate.

The following figures will show the selected faces that were refined and a more detailed view of areas of interest (i.e., change in geometry, contact regions, drilled holes, and so on).

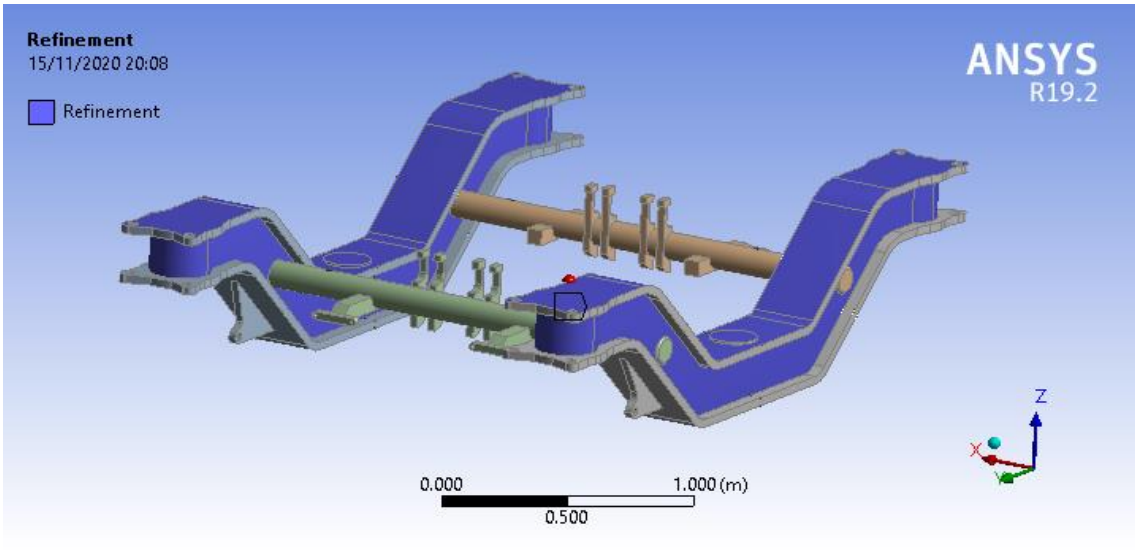


Figure 82. Refined faces [blue].

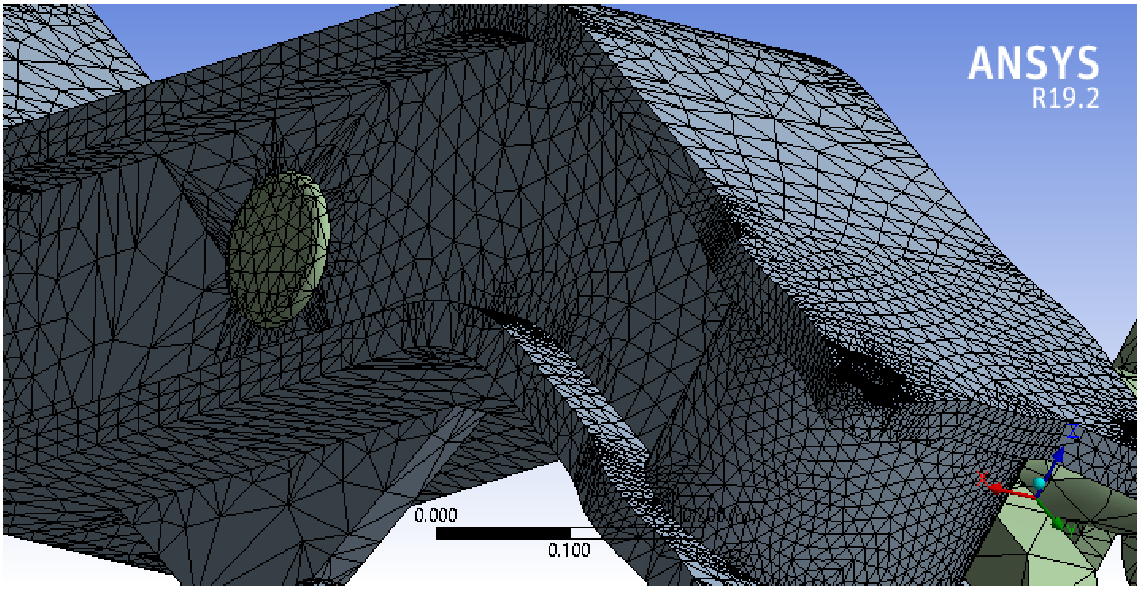


Figure 83. close up of the refined mesh, area 1.

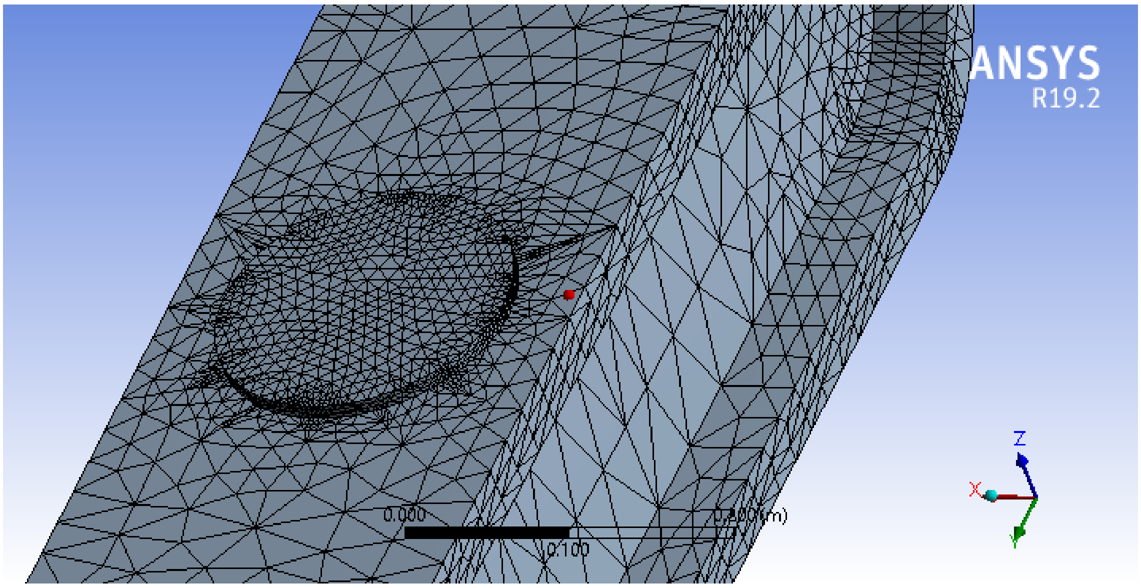


Figure 84. Close up of the refined mesh, Area 2

As seen in chapter 8, the model is an assembly of two rods and two beams. The nodes that are in the contacts regions will ultimately get confused because of their proximity between them, if not merged or specified through the contact tool available in the tree inside *Mechanical*. A node merging was done so that ANSYS does not consider nodes close to each other in the contact region like one node. The total number of nodes merged in the contact regions between the beams and the rods are 105 nodes.

For further clarification, the following two tables summarize the number of nodes per assembly parts (as you can see in table.15) and more additional information so to have a full characterization of the mesh (table. 16).

Table 14. Table decomposing the number of nodes and elements per parts.

Statistics			
Nodes	318,916	333,947	16,706
Elements	210,579	220,493	9,030
Parts	Beam 1	Beam 2	Rod 1&2

Table 15. Additional information of the mesh.

Defaults	
Physics Preference	Mechanical
Element Order	Quadratic
Element Size	0.1 m
Sizing	
Use Adaptive Sizing	Yes
Resolution	Default
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	3.7224 m
Average Surface Area	2.0098e-002 m²
Minimum Edge Length	5.e-004 m
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical
Target Quality	0.95
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Number of Retries	Default
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Statistics	
Nodes	686,275
Elements	449,132

9.2 ANSYS simulation of the compsite bogie frame:

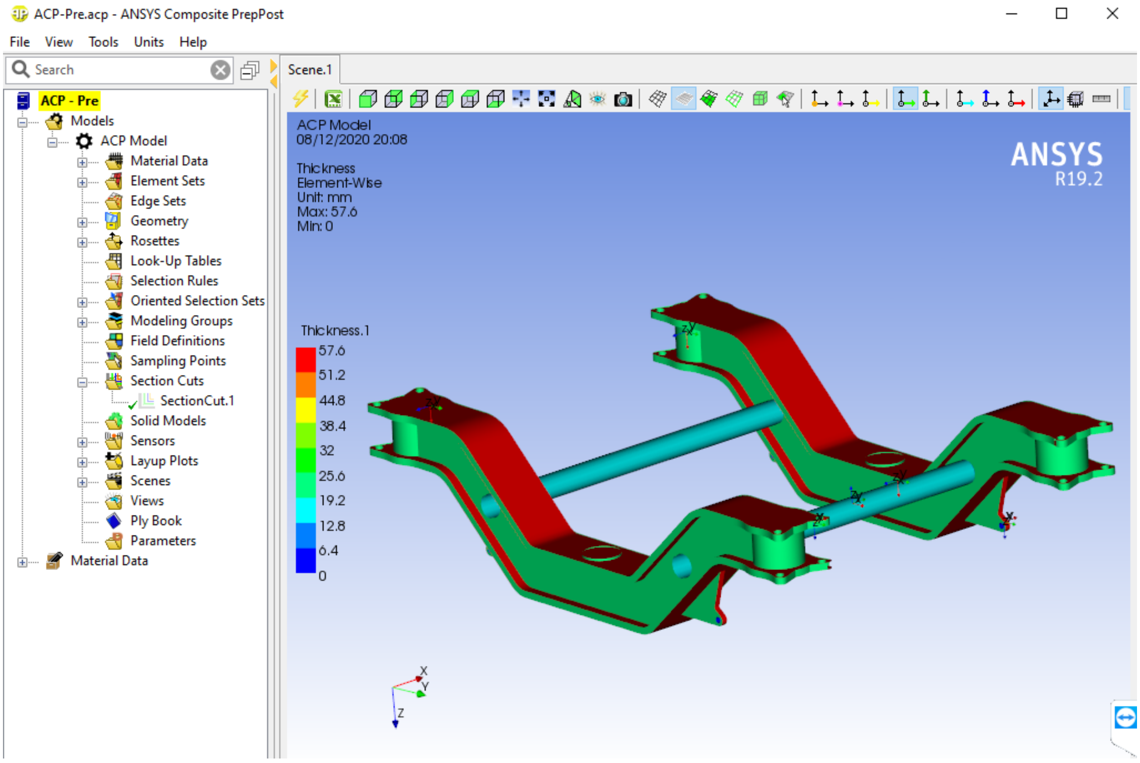
For the simulation of the composite bogie frame, there is a need to take a different route. It is needed to go through the ACP (Pre) module to later link the composite frame to the static structure module, opposed to the first simulation methodology to simulate a composite initially. This extra step is so that you can define (before any analysis) the plies that will be in use for the composite frame.

9.2.1 ACP (Pre) module:

The structure steel S235 was very straight forward: Mesh→contacts analysis→ constraints & boundaries→solution. For the composite material, there is an extra step. The ACP (Pre) module needs to create the layers of composite materials to do the analysis.

The materials used for the composite simulation are woven epoxy carbon fiber, recycled unidirectional (ud) epoxy carbon fiber, and, finally, honeycomb aluminum so that it gives rigidity and shape to the frame. The ACP (Pre) module allows you to create the plies that will be stacked up on the frame.

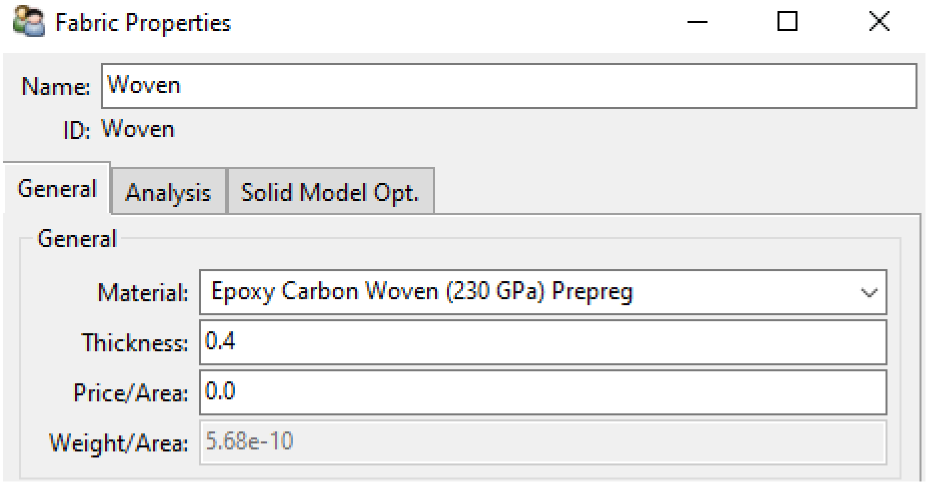
To better understand how the composite frame was built, we need to know which are the fiber's critical orientation so that we can know what the preferred orientation of the ply is. If you orient the fibers in a certain direction, that direction would need to be more resistant. To describe how the ACP (Pre) works, we will be using the figure ahead. In Figure.88, you have a tree of configurations on the screen's left side. This tree will allow you to access all the configurations to create the ply.



ACP Model
08/12/2020 20:08
Thickness
Element-Wise
Unit: mm
Max: 57.6
Min: 0

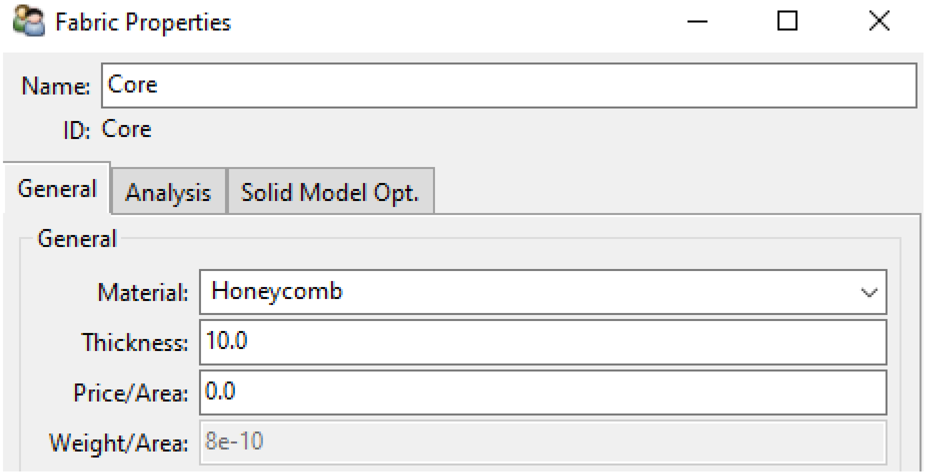
Figure 85. General view of how the ACP (Pre) modules looks like.

The first step to using the ACP (Pre) module is to look at the material that you have at hand available (imported). Once the materials are imported, it is needed to create the fabric uses for the stacks. It is created 3 fabrics for the frame. These fabrics are called Woven, the second one is called Core (which is the honeycomb), and the last one is called UD (unidirectional).



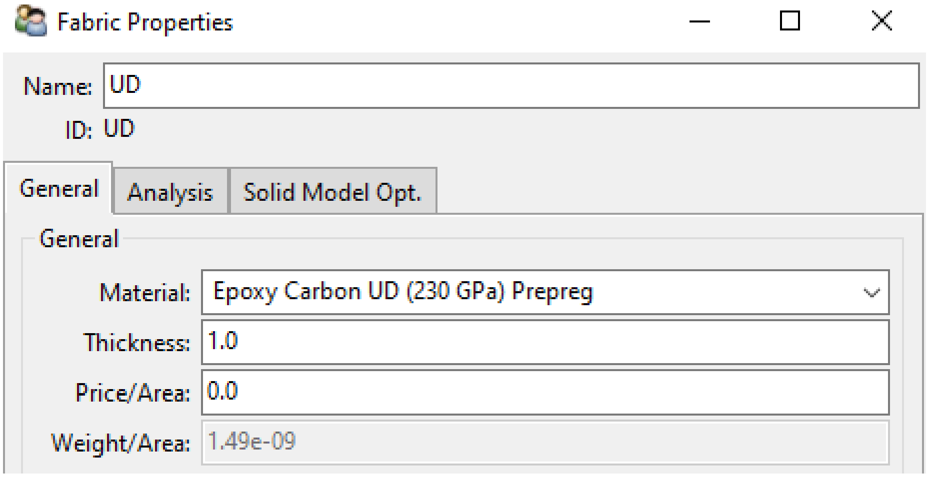
Name: Woven
ID: Woven
Material: Epoxy Carbon Woven (230 GPa) Prepreg
Thickness: 0.4
Price/Area: 0.0
Weight/Area: 5.68e-10

Figure 86. Fabric properties for the woven carbon epoxy.



Name: Core
ID: Core
Material: Honeycomb
Thickness: 10.0
Price/Area: 0.0
Weight/Area: 8e-10

Figure 87. Fabric properties for the honeycomb.



Fabric Properties

Name: UD
ID: UD

General | Analysis | Solid Model Opt.

General

Material: Epoxy Carbon UD (230 GPa) Prepreg
Thickness: 1.0
Price/Area: 0.0
Weight/Area: 1.49e-09

Figure 88. Fabric properties for the UD carbon epoxy.

The ACP (Pre) fabric tool required the thickness of the layers. It is defined 1 mm of thickness for the UD epoxy carbon fabric, 10 mm of thickness for the honeycomb fabric of the Core, and 0.4 mm of thickness for the woven epoxy carbon fabric. One of the options available for the fabrics is the ‘Analysis option’. This option allows you to understand what ain direction are, f it is anisotropic or isotropic the behavior.

Ahead it is attached three diagrams that have the shape of a circle. These circles diagrams represent (in percentage-wise) the maximum mechanical property that the fabric has, e.g. if the UD epoxy carbon has all of the fiber pointing in one direction. It is shown a thin eclipse where a biased of 1 degree, then, it is not taking full advantage of them being all aligned in one direction. Instead, it would be utilizing 25% less of its young modulus, making it easier to break, deform, and so on.

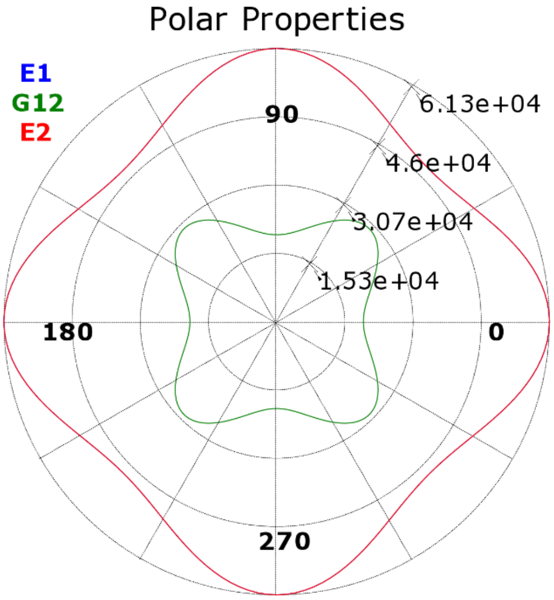


Figure 89. Polar properties diagram for the woven carbon epoxy.

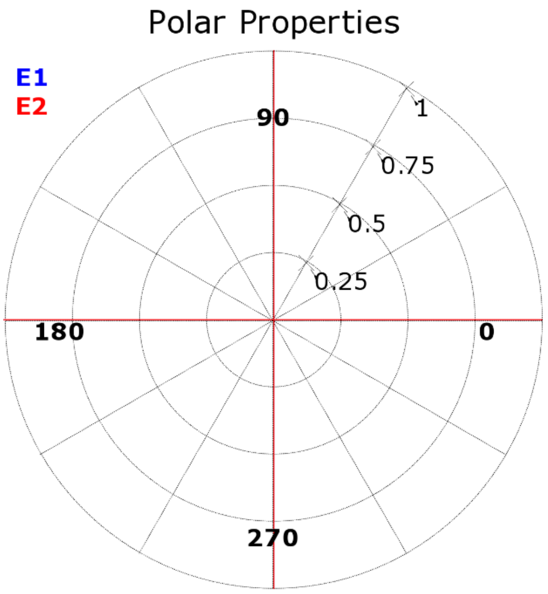


Figure 91. Polar properties diagram for the honeycomb

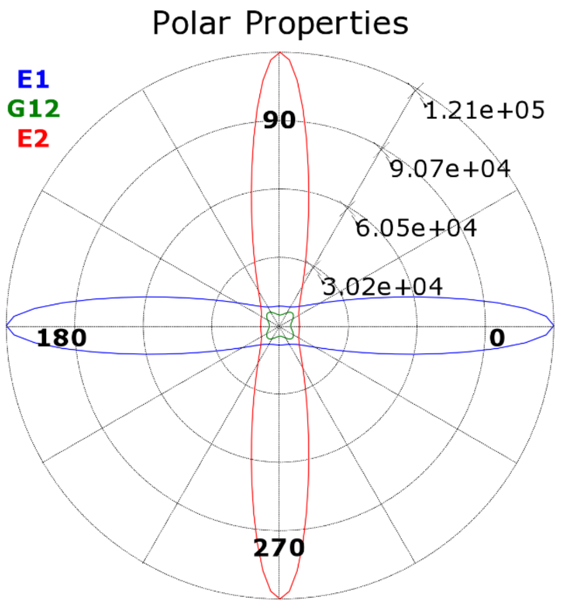


Figure 90. Polar properties diagram for the UD carbon epoxy.

Where,

Orthotropic Young's Modulus:

- E1: in-plane, in fiber direction (fiber direction is corresponding to angle 0 for the ply's definition)
- E2: in-plane, orthogonal to fiber direction
- E3: out of plane direction

Orthotropic Shear Modulus:

- G12: in-plane
- G13: out of plane, in fiber direction
- G23: out of plane, normal to fiber direction

After analyzing the fabric, the next step would be creating the ‘stackup’. This step is basically putting different layers of the fabrics that have been developed prior. For this step, we designed two different stack ups, the first one concerned the woven carbon epoxy that layered over the another the woven carbon epoxy with a 45-degree angle with respect to each other - the second one will be a stackup of the UD carbon epoxy one over the other like the first one and at 90-degrees concerning one another.

Following this last description, the analysis chart for the new stackup has been designed so that along with a thickness diagram, so you know how thick one stack is.

Where,

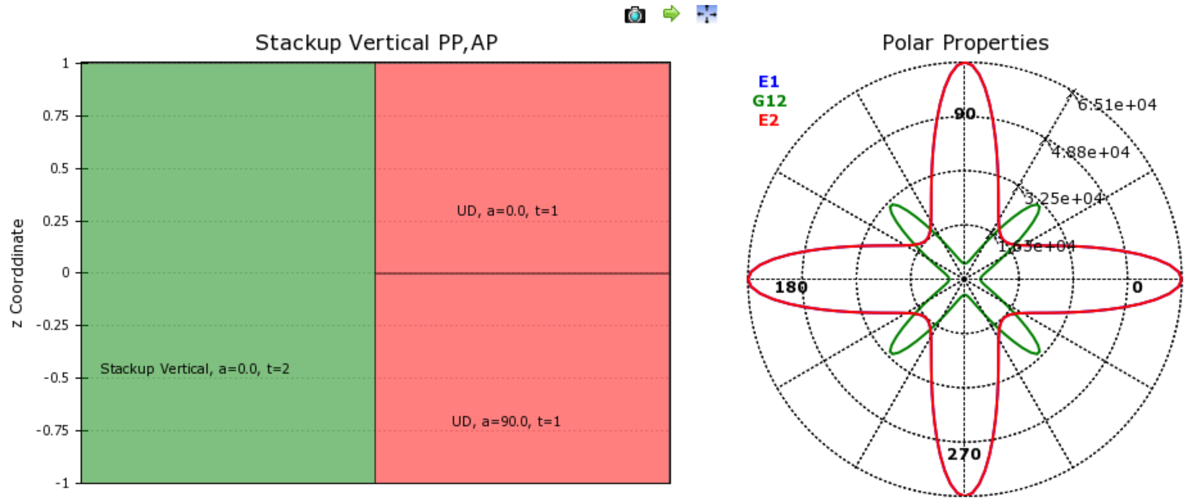


Figure 93. Analysis chart of the woven stack up.

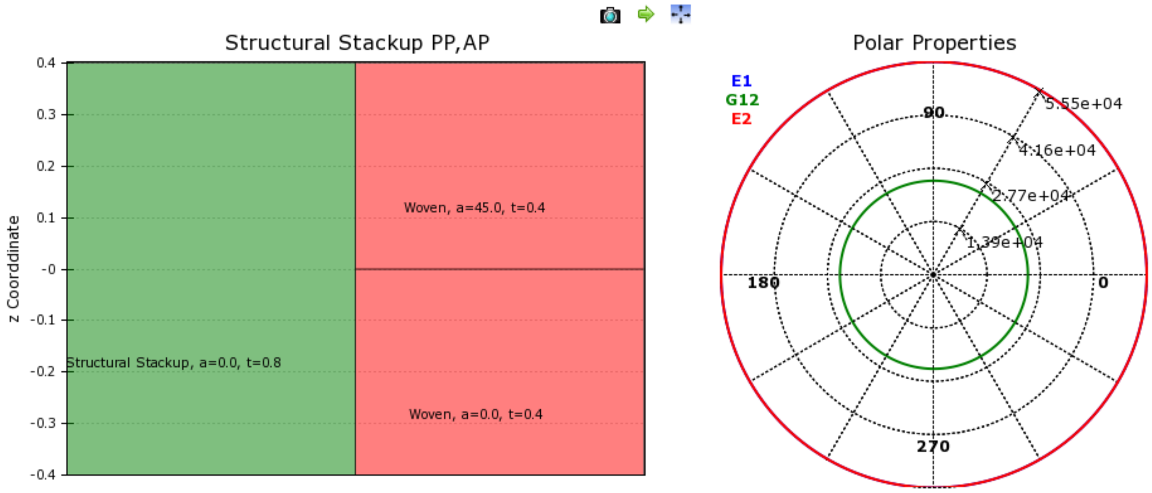


Figure 92. Analysis chart of the stack up UD.

- a = angle [˚]
- t = thickness [mm]

The last step of developing the ply is how you combine the stackup, selecting the fiber orientation, the direction of growth for the ply depending on the desired mechanical properties. The model is divided into various sections, the first selection is the top and bottom faces of the beams, the second selection was both of the rods, the third selection is the sides of the beams, the fourth selection is the vertical cylinders of the model and, finally, the drilled holes down under the beams. The faces were selected this way because we wanted all these selections to have different fiber directions. Later, it is defined and selected the fibers' orientation. All the selected areas have different orientations. Figure 97 exhibits a fiber orientation over the surface of the frame.

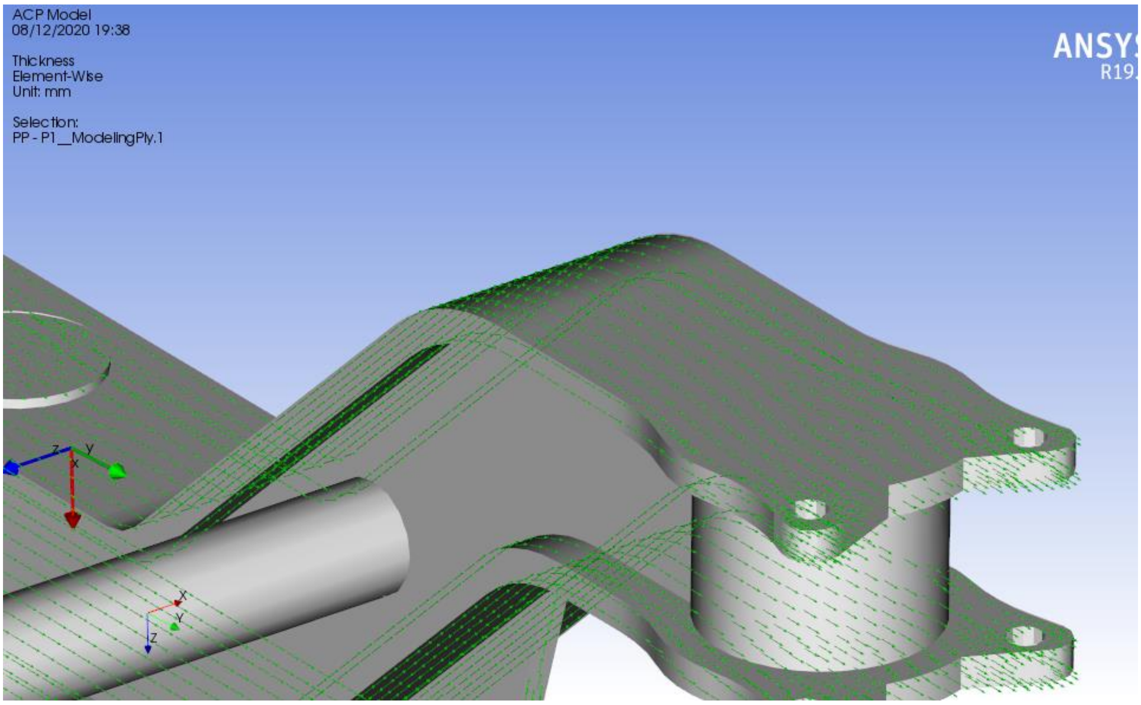


Figure 94. Fiber orientation for the top & bottom faces of the beams.

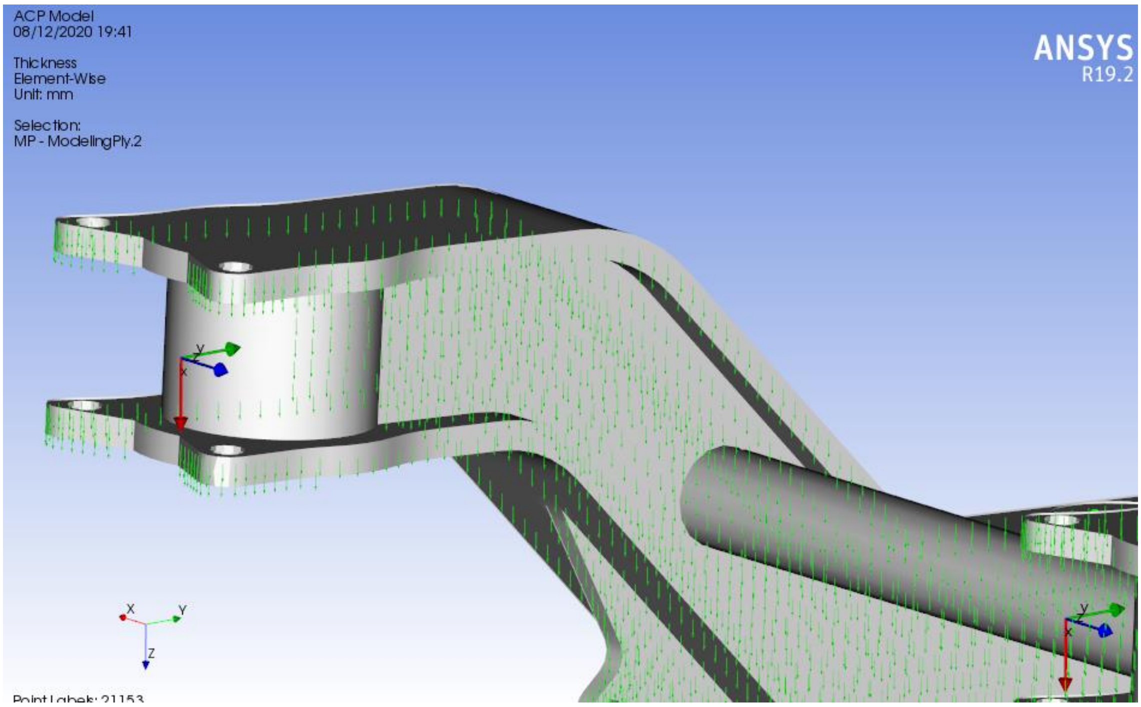


Figure 95. Fiber orientation for the side faces of the beams.

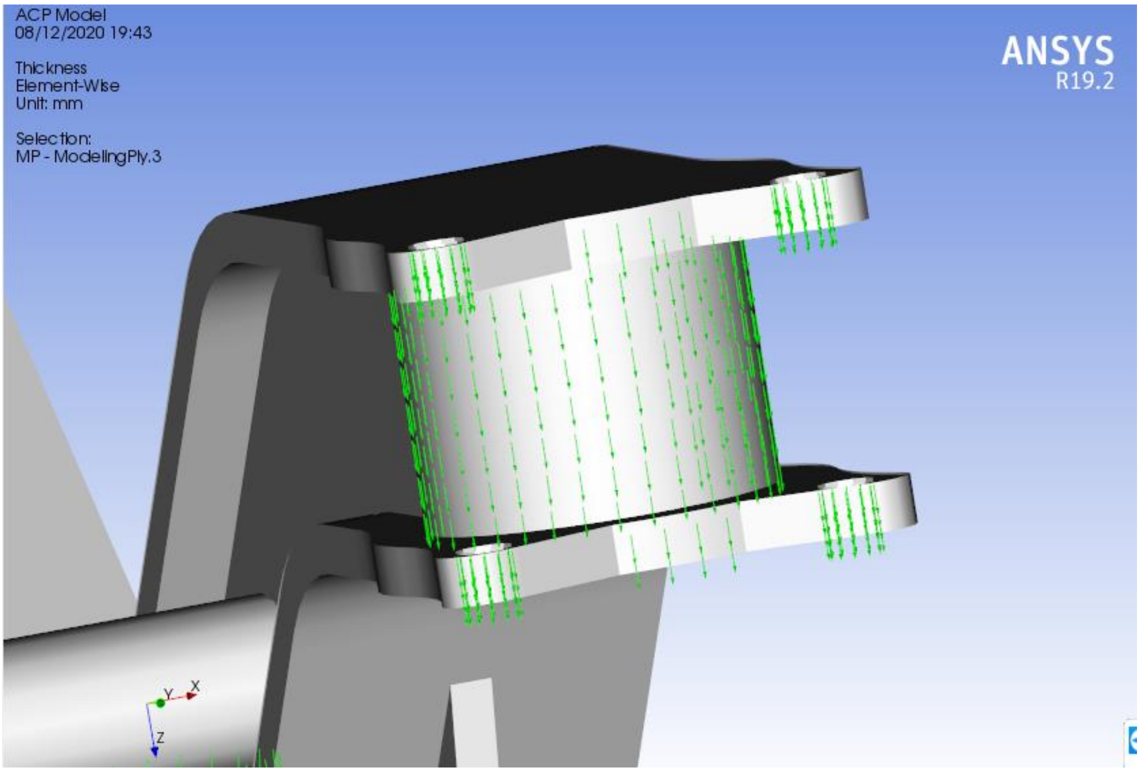


Figure 96. Fiber orientation of the cylinder faces that make up the beams.

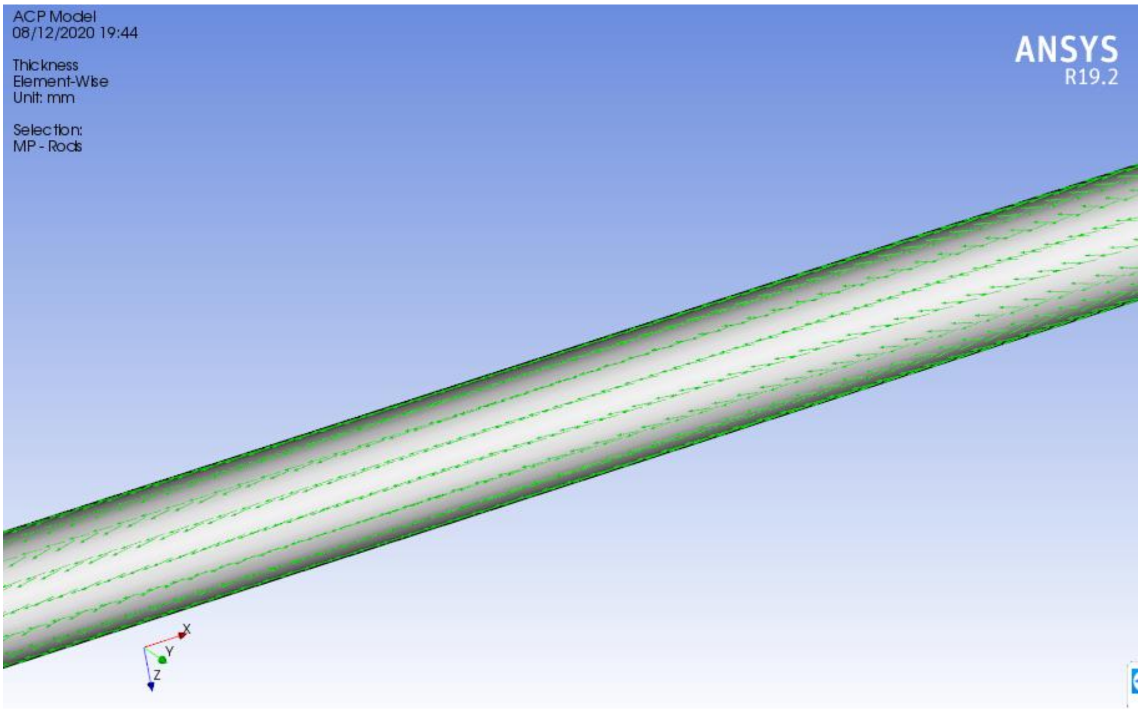


Figure 97. Fiber orientation for the rod in between the beams.

Regarding the geometry, it is decided that the best direction of growth for the entire model would be inwards.

Lastly, it is worth mentioning how the plaies we layered:

- For the top and bottom faces, we layered 14 stacks of the UD carbon epoxy (for a total thickness of 57,6 mm for the top and bottom faces).

- For the sides of the beams, we layered alternating between the woven stackup we created and the core honeycomb (for a total of 2 cores and 3 woven stackup that each contains, that adds up to a 24,8 mm thick wall – W/C/W/C/W).

- The rods follow a similar stack as the side walls (all alternating – W/C/W/C), but they only have 2 cores and 2 woven stacks (for a total thickness of 13.2 mm).

- For the cylinder, we sandwiched a honeycomb core with 2 stacks of woven at each side (for a total sum of 24,8 mm of thickness).

For further clarification, the following figures are section cuts of a beam and a rod and look at this subchapter's initial figure. The different gradients effect of the frame represent the different thickness of the faces.

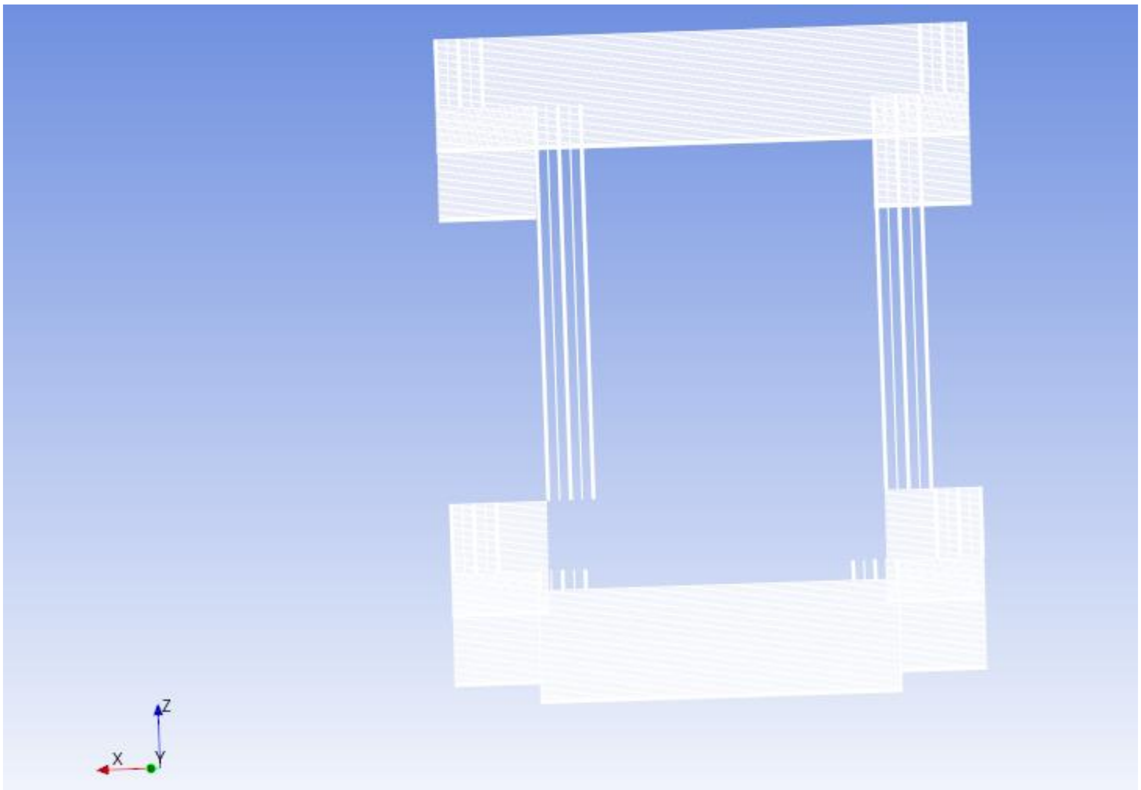


Figure 98. Cross section of a beam from where you can see the stacks of plies

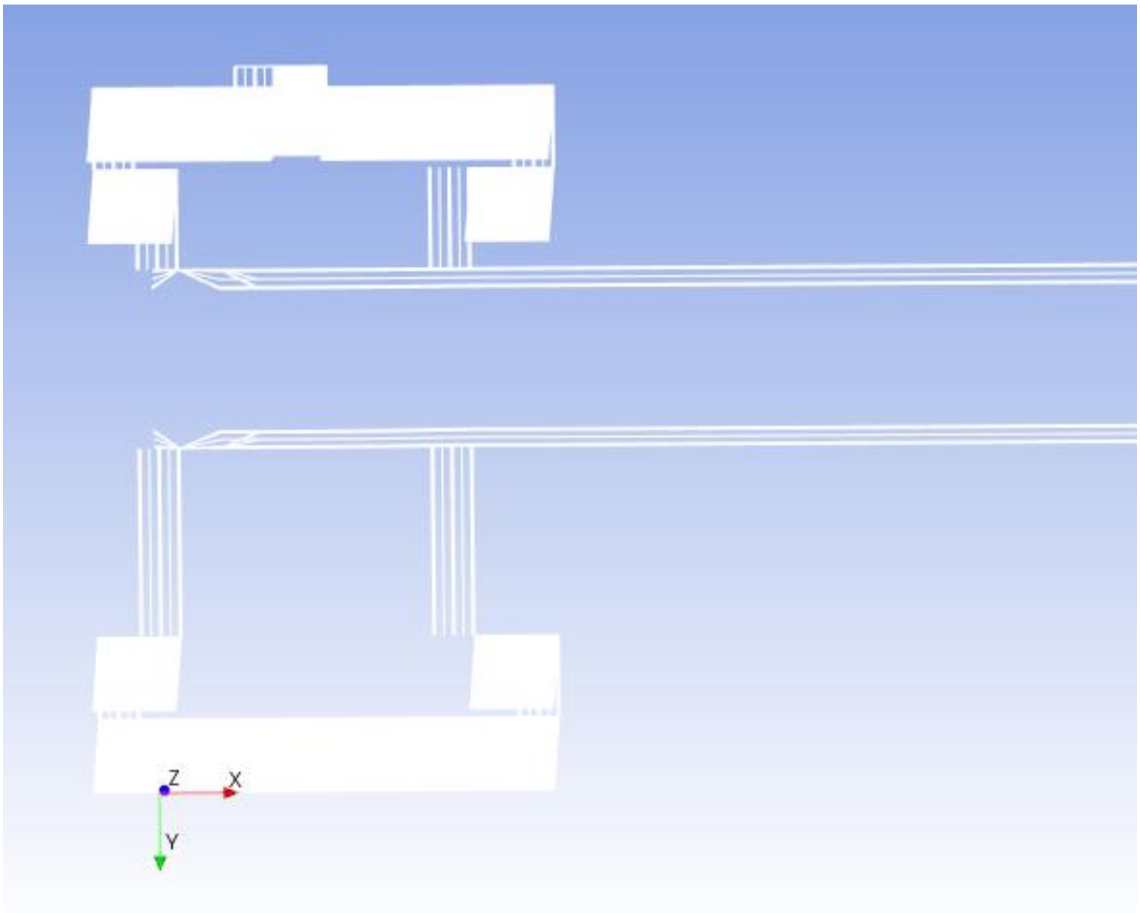


Figure 99. Cross section view of one of the rods from where you can see the stacks of composite that make up the rod.

9.2.2 Reasons for the fiber orientations:

As it was explained in *chapter 5.1 Composite material for the bogie*, carbon fiber reinforced polymers have one (or more) preferred orientation. These orientations are due to them being extremely strong in one direction, thanks to the direction the carbon molecules are pointing internally.

As mentioned in chapter 9.3 ACP (Pre) module, after generating the stackup, there are some noticeable changes to the mechanical behavior of both the woven epoxy carbon and the recycled unidirectional epoxy carbon. For starters, the woven after stacking it 45-degrees with respect to each other, it becomes fully isotropic *figure.95*. Super beneficial, as it simplifies the expectations massively from that component. As for the UD, after stacking it 90-degrees with respect to one another, it has 2 preferred orientations: one being longitudinal, and the other one being the transversal *figure.96*. Both were designed in that manner so that they fulfill a certain role.

Between both of the fiber composite, the one with the most strength is that of the UD; it is harder for that material to fail if the load is directed facing its preferred orientation. Knowing that the UD is the stronger of the two and knowing that the majority of bigger loads will be placed upon the top and bottom faces, the stronger material should ideally be placed on the top and bottom of the frame. The woven epoxy carbon, like it has anisotropic behavior, is located in an area where there will be a lot of tension because of deformation. In this sense, it is decided to put the woven (isotropic) stackup o the sides of the frames and the rods. For the honeycomb aluminum, we needed it to give rigidity and volume to the model while using a minimum amount of material. It came in handy, and it did the job for the rods and side of the frame, adding extra resistance for the lateral and unloading forces that will be applied ahead in the simulation scenario.

The fiber orientation is based on the stackups, considering that the UD has two preferred orientations (both at 90-degrees) *Figure 96*, then the most logical solutions are to orient them longitudinally over the top and bottom faces of the frame, *figure.97* so that you have XY plane experience the maximum resistance to deformation from the vertical loads that would be applied over them.

The fiber orientation selected for the woven (on the sides of the frames, the vertical cylinders, and the rods, a *Figure 94, Figure 95 and Figure 96* respectively) did not matter thanks to the stackups at 45-degrees giving it having an isentropic behaviour *Figure.91*.

In summary, the fiber orientation selection was chosen so that the model experiences the most effort against deformation as possible, making more secure aluminum honeycomb in the structure, coming closer to the safety and reliability standards.

9.3 Meshing the composite frame:

Now that the ACP (Pre) is mentioned, we would need to generate the mesh for the composite bogie frame. This mesh could not be the same as the one created for the structural steel frame, as you needed to go first through the ACP (Pre) module, making useless the structure steel mesh generated at the beginning of the 9th chapter.

Inside this ACP (pre) module, you define the mesh for the composite piece. The idea is the same as in static structure, but with subtle differences. One of these differences between the static structure module and ACP (pre) module is that the ACP (pre) uses shell geometry. Thus, the mesh will be a face mesh and it will be using instead of triangular shapes, it will use square shapes for the meshing – like shown in the upcoming figures.

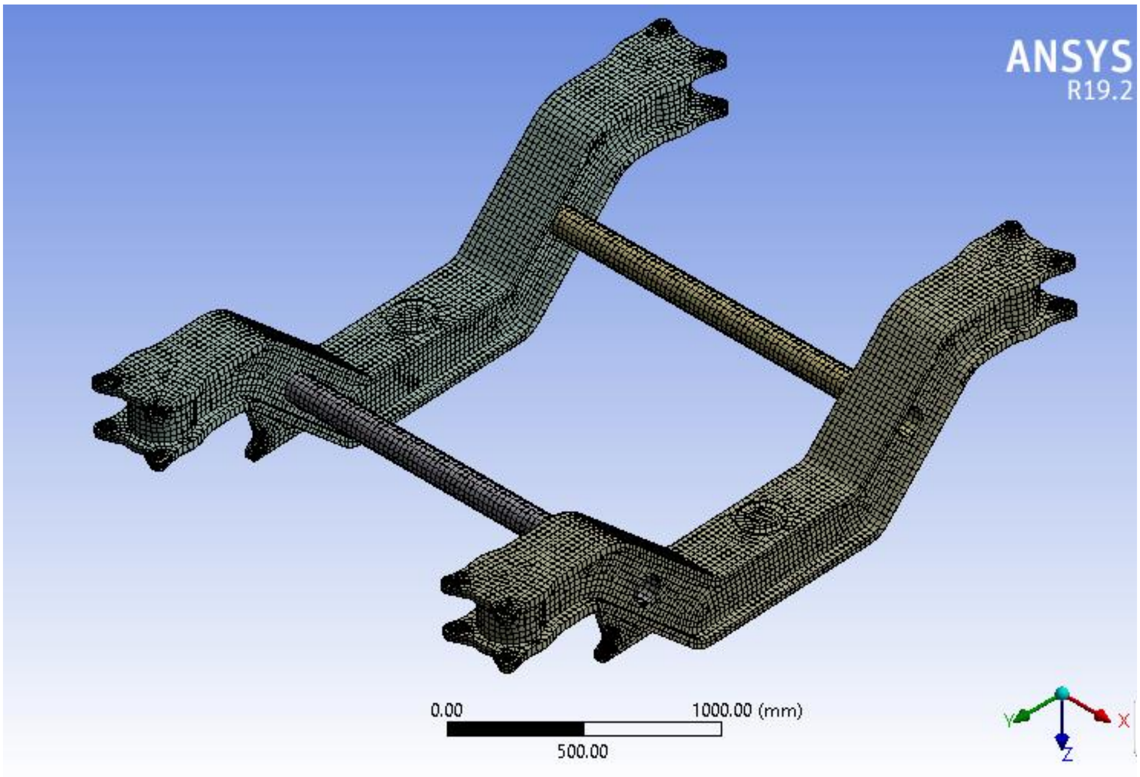


Figure 100. Screen capture of the mesh generated for the composite frame.

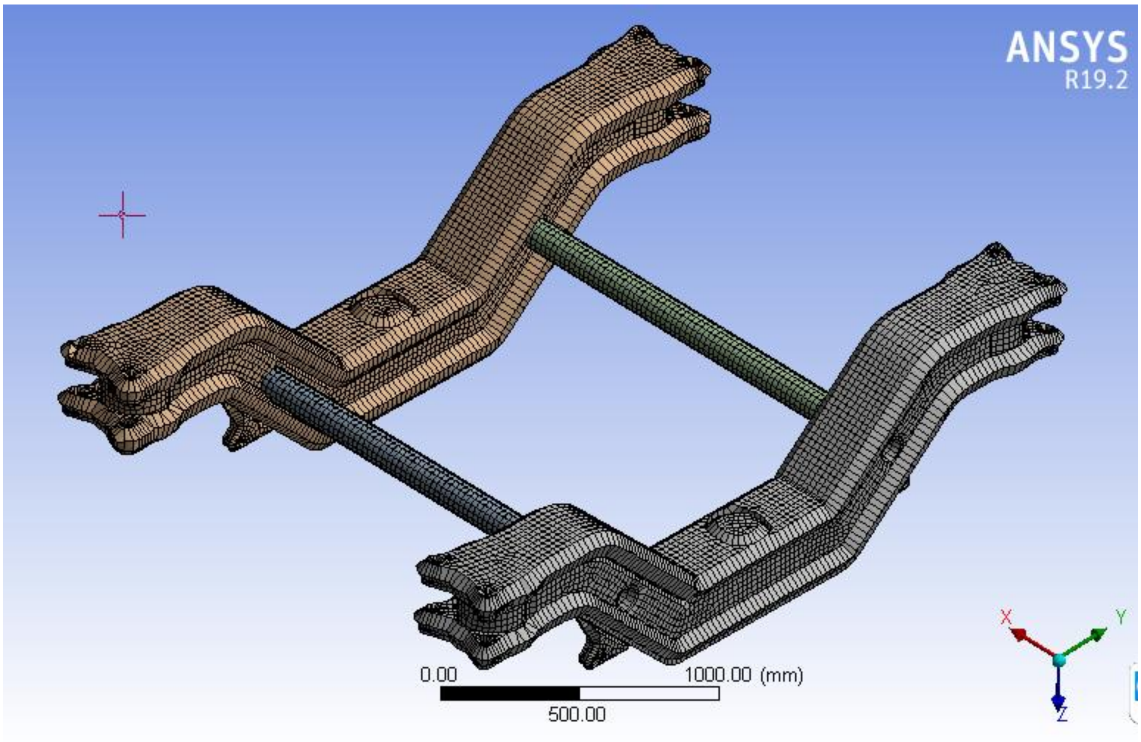


Figure 101. View of the mesh with the plies stacked up on top of one another forming the frame.

Another noteworthy difference between meshes is that for the composite frame, rather than just refining certain areas (like in the mesh for the structure steel S235), the sizing method was also added for the entire bogie frame. It was done taking into account that the composite frame is a stackup of different layers of composite, meaning the smaller the mesh elements and the more nodes there are, the higher quality the mesh is and the better and more reliable results are going to be retrieved.

The following figures will show the different faces selected for the refinement method and the faces selected for the sizing method utilized in the making of the mesh for the composite frame.

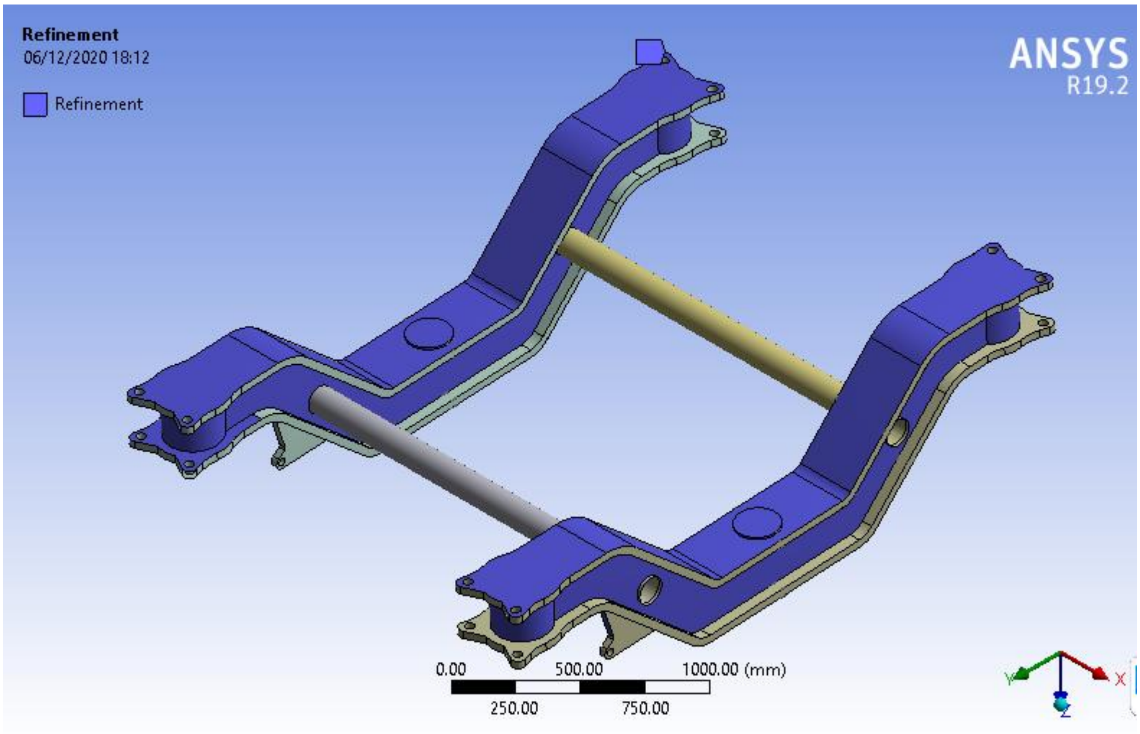


Figure 102. Faces that were selected for the refinement and the development of the mesh.

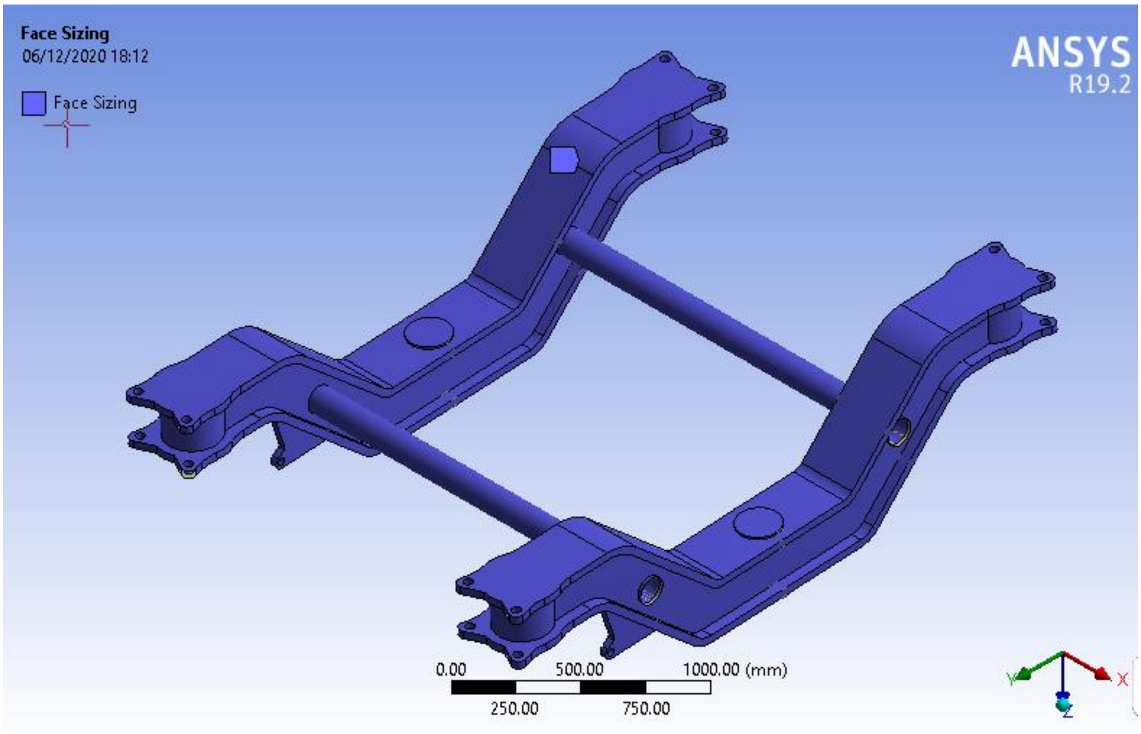


Figure 103. Faces that were selected for the sizing of the elements and likewise for the development of the mesh.

Despite the shell elements, there is still a needed to merge the localized nodes in the contact areas. It is done so that ANSYS does not give an error for pivoting nodes. It is a big step always to include when simulating models that have various contact areas. In this case, the total number of merged nodes is 68 nodes. After demonstrating the faces selected for the sizing, the refinement methods, and the node merging, it is essential to display the mesh statistics for the composite frame.

Table 16. Statistics of the mesh generated for the composite frame.

Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	24.213 Mm
Sizing	
Use Adaptive Sizing	No
Growth Rate	1.2
Mesh Defeaturing	Yes
Defeature Size	0.12106 Mm
Capture Curvature	Yes
Curvature Min Size	0.24213 Mm
Curvature Normal Angle	30.0°
Capture Proximity	No
Bounding Box Diagonal	3752.2 Mm
Average Surface Area	37521 Mm²
Minimum Edge Length	11.998 Mm
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical
Target Quality	0.95
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	2
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number Of Cpus For Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Use Sheet Thickness For Pinch	No
Pinch Tolerance	0.21792 Mm
Generate Pinch On Refresh	No
Sheet Loop Removal	No
Statistics	
Nodes	210,554
Elements	219,758

Finally, Figure.103 shows the end quality of the mesh generated for the composite bogie frame. The quality of the mesh ranges from the lowest 26.5 % to 99.99%. The 26.5% quality is considered enough to proceed with the study.

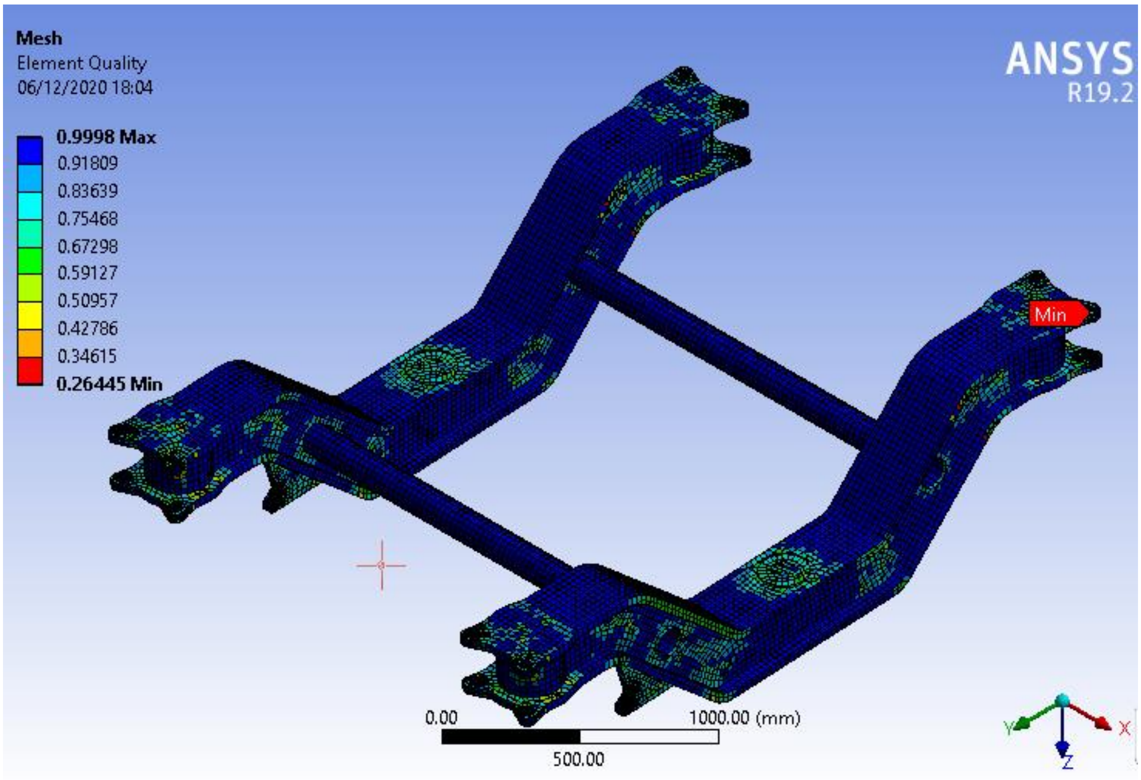


Figure 104. Element quality for the composite frame.

10. Results of the Ansys simulations:

The results will be separated in *two parts* (structural steel S235 and CFRP w/Aluminum honeycomb) to compare solutions and arrive at conclusions based on the results.

10.1 Boundary definition of the structural steel S235 bogie frame:

Solving the mechanical problem with Ansys simulation, it is needed to initially associate the bogie frame with the slightly modified version of structural steel that ANSYS had available. The following table will summarize the material property that the structure steel S235 has according to EN1993-1-1:2005.

Table 17. Material property for structural steel S235 according to EN1993-1-1:2005

Material Property	Abbreviation	Units	Values
Youngs Modulus	E	GPa	210
Poisson's Ratio	N	-	0.3
Density	P	kg/m^3	7850
Yield Strength	σ_s	MPa	235

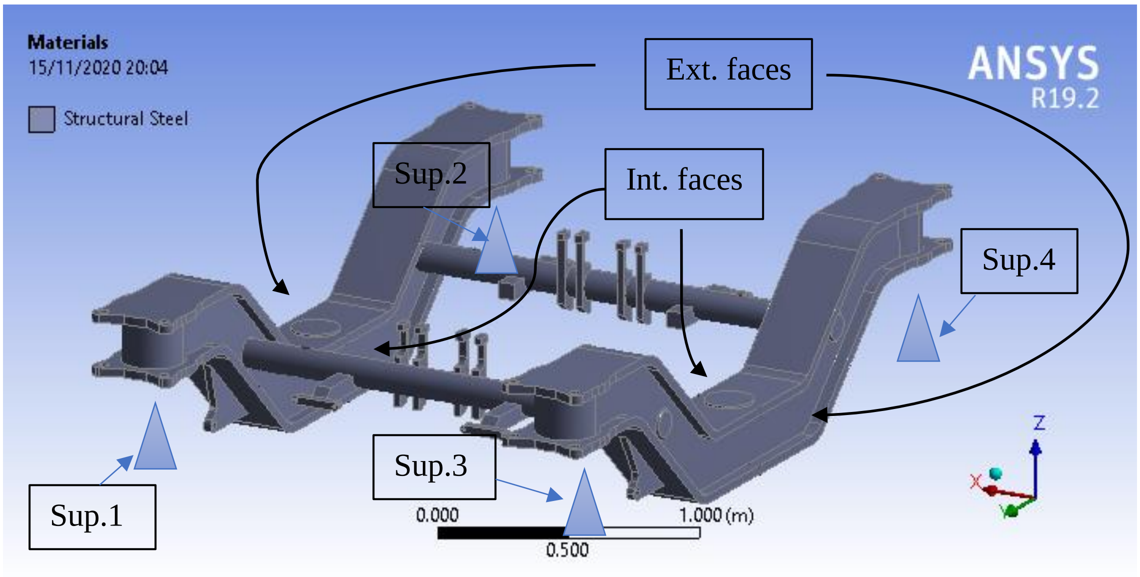


Figure 105. Material selection for the first round of solutions.

There is a need to clarify where the supports and the faces are located because ahead, there will be a table that relates them with the loads and restrictions on the model.

Table 18. List of the forces for all the cases in the study of the structure steel S235 bogie frame.

	Vertical loads	Lateral loads				Longitudinal loads			
	F_Z [N]	F_{Yss} [N]		F_{YLstop} [N]		F_{XLonz} [N]		F_{XLong} [N]	
Cases ↓	Pad	External face1	External face2	Internal face1	Internal face2	Support 1 &2	Support 3 & 4	Support 1 &2	Support 3 & 4
1	-134,888	0	0	0	0	0	0	0	0
2_1	-134,888	14,000	14,000	72,344	72,344				
2_2		-14,000	-14,000	-72,344	-72,344				
3_1	-44,145	0	0	0	0				
4_1	-134,888					31,783	-31,783		
4_2						-31,783	31,783		
5_1	-134,888					0	0	16,628	16,628
5_2								-16,628	-16,628
6_1	-91,734							0	0
7_1		29,065	29,065						
7_2		-29,065	-29,065						
8_1		0	0			11,626	-11,626		
8_2						-11,626	11,626		

Table 19. List of the restrictions for all the cases in the study of the structure steel S235 bogie frame.

	Support 1			Support 2			Support 3			Support 4		
Cases ↓	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]
1	10	10	0	10	10	0	10	10	0	10	10	0
2												
3	10	10	0	10	10	10	10	10	0	10	10	10
4	10	10	0	10	10	0	10	10	0	10	10	0
5												
6												
7												
8												
Cases ↓	Rx [°]	Ry [°]	Rz [°]	Rx [°]	Ry [°]	Rz [°]	Rx [°]	Ry [°]	Rz [°]	Rx [°]	Ry [°]	Rz [°]
1	0.1	0	0	0.1	0	0	0.1	0	0	0.1	0	0
2												
3	0.1	0	0	0.1	0.1	0.1	0.1	0	0	0.1	0.1	0.1
4	0.1	0	0	0.1	0	0	0.1	0	0	0.1	0	0
5												
6												
7												
8												

Since some of the cases are repeated (due to the force acting on the opposite direction), we will simulate the first variation for each of the repeated cases. There is no need to simulate all of the cases, because some of them will return mirroring results.

In the ***Appendix I.***, there are the images from the results we got from the different cases in the following order: Total Deformation > Von Mises stress > Safety factor - for the explicit loads and the fatigue loads: Safety factor > Life expectancy.

10.1.1 Results of the different loas scenerios for the structural steel S235 bogie frame:

Ahead are in table form the results that we retrieve after analysing the structure steel S235 bogie frame. In the Appendix I, you will find the visual representation of all the results of all the load cases, as well as the total deformation, Von-Misses stress, and safety factor.

Table 20. Results of the first half of the case studies for the structure steel S235 – Exceptional loads.

	Total Deformation		Von-Misses Stress		Safety Factor	
Cases ↓	Max [m]	Min [m]	Max [Pa]	Min [Pa]	Max []	Min []
1	0,0148	0,0136	5,70E+07	1,58E+07	15	4,38
2	0,0147	0,0135	6,76E+07	1,82E+07	15	3,68
3	0,0179	0,0126	1,75E+03	1,90E-04	15	0,14
4	0,0148	0,0136	6,86E+07	1,94E+02	15	3,64
5	0,0146	0,0135	2,84E+08	1,94E+02	15	0,88

Table 21. Results of the second half of the case studies for the structure steel S235 – Service loads.

Cases ↓	Safety Factor		Life Expectancy	
	Max []	Min []	Min Cycles	Max Cycles
6	15,00	2,21	1,00E+06	1,00E+06
7	15,00	2,58	1,00E+06	1,00E+06
8	15,00	2,15	1,00E+06	1,00E+06

10.2 Boundary condition definiton of the composite bogie frame:

Ahead in table form are all the mechanical properties of the composites that make up the composite frame (i.e., Woven epoxy carbon prepreg, recycled unidirectional epoxy cabron prepreg and the Aluminum honeycomb).

Table 22. Table of mechanical properties for woven epoxy carbon Prepeg, available in ANSYS R19.2

Density [Kg/m^3]								
1420								
Orthotropic Elasticity								
Young's Modulus X direction [Pa]	Young's Modulus Y direction [Pa]	Young's Modulus Z direction [Pa]	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY [Pa]	Shear Modulus YZ [Pa]	Shear Modulus XZ [Pa]
6.134e+10	6.134e+10	6.9e+09	4.e-02	0.3	0.3	1.95e+10	2.7e+09	2.7e+09
Orthotropic Stress Limits								
Tensile X Direction [Pa]	Tensile Y Direction [Pa]	Tensile Z Direction [Pa]	Compressive X Direction [Pa]	Compressive Y Direction [Pa]	Compressive Z Direction [Pa]	Shear XY [Pa]	Shear YZ [Pa]	Shear XZ [Pa]
8.05e+08	8,05e+08	5.e+07	-5.09e+08	-5.09e+08	-1.7e+08	1.25e+08	6.5e+07	6.5e+007

Table 23 Table of mechanical properties for Recycled Unidirectional Epoxy Carbon Prepeg, available in ANSYS R19.2.

Density [Kg/m^3]								
1490								
Orthotropic Elasticity								
Young's Modulus X direction [Pa]	Young's Modulus Y direction [Pa]	Young's Modulus Z direction [Pa]	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY [Pa]	Shear Modulus YZ [Pa]	Shear Modulus XZ [Pa]
1.17e+11	8.3e+09	8.3e+09	0.27	0.4	0.27	4.7e+09	3.1e+09	4.7e+09
Orthotropic Stress Limits								
Tensile X direction [Pa]	Tensile Y direction [Pa]	Tensile Z direction [Pa]	Compressive X direction [Pa]	Compressive Y direction [Pa]	Compressive Z direction [Pa]	Shear XY [Pa]	Shear YZ [Pa]	Shear XZ [Pa]
1.91e+09	2.49e+07	2.49e+07	-1.082e+09	-1e+08	-1e+08	6.e+07	3.2e+07	6.e+07

Table 24 Table of mechanical properties for Aluminum honeycomb, available in ANSYS R19.2

Density [Kg/m^3]								
80								
Orthotropic Elasticity								
Young's Modulus X Direction [Pa]	Young's Modulus Y Direction [Pa]	Young's Modulus Z Direction [Pa]	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ	Shear Modulus XY [Pa]	Shear Modulus YZ [Pa]	Shear Modulus XZ [Pa]
1.e+06	1.e+06	2.55e+08	0.49	1.e-03	1.e-03	1	3.7e+07	7.e+07
Orthotropic Stress Limits								
Tensile X Direction [Pa]	Tensile Y Direction [Pa]	Tensile Z Direction [Pa]	Compressive X Direction [Pa]	Compressive Y Direction [Pa]	Compressive Z Direction [Pa]	Shear XY [Pa]	Shear YZ [Pa]	Shear XZ [Pa]
0	0	5.31e+06	0	0	-5.31e+06	0	1.21e+06	2.24e+06

Following these tables of mechanical properties is the *Figure.105* that demonstrates where ***are*** the faces and supports for the composite material. This figure is needed so that the following ***Table.26*** of of the boundary conditions are understood.

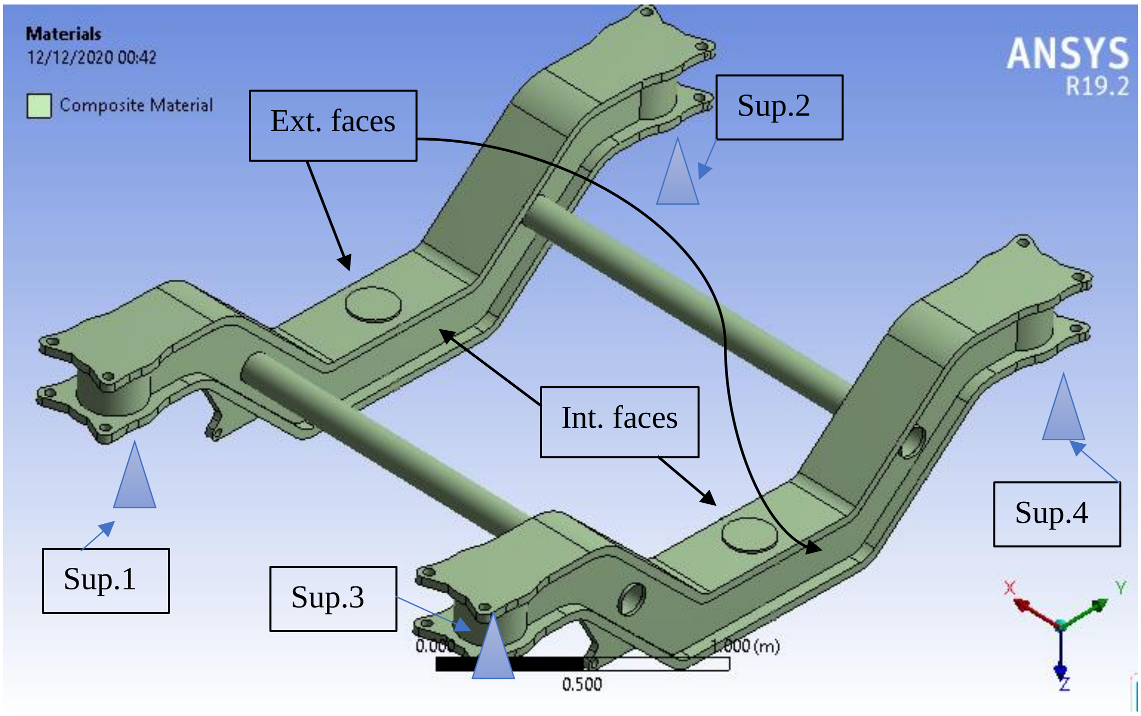


Figure 106. Material selection for the second round of solutions.

Table 25. List of the forces for all the cases in the study of the composite bogie frame

	Vertical Loads	Lateral Loads				Longitudinal Loads			
Combinations →	F_z [N]	F_{yss} [N]		F_{ylstop} [N]		F_z [N]		F_{yss} [N]	
Cases ↓	Pad	External Face1	External Face2	Internal Face1	Internal Face2	Support 1 &2	Support 3 & 4	Support 1 &2	Support 3 & 4
1	147753	0	0	0	0	0	0	0	0
2_1	147753	14000	14000	63882	63882				
2_2	147753	-14000	-14000	-63882	-63882				
3_1	53692	0	0	0	0				
4_1	147753					9646	-9646		
4_2	147753					-9646	9646		
5_1	147753					0	0	14199	14199
5_2	147753							-14199	-14199

Table 26. List of the restrictions for all the cases in the study of the composite bogie frame.

	Support 1			Support 2			Support 3			Support 4		
Cases ↓	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]
1	10	10	0	10	10	0	10	10	0	10	10	0
2												
3	10	10	0	10	10	10	10	10	0	10	10	10
4	10	10	0	10	10	0	10	10	0	10	10	0
5												
Cases ↓	Rx [°]	Ry [°]	Rz [°]	Rx [°]	Ry [°]	Rz [°]	Rx [°]	Ry [°]	Rz [°]	Rx [°]	Ry [°]	Rz [°]
1	0.1	0	0	0.1	0	0	0.1	0	0	0.1	0	0
2												
3	0.1	0	0	0.1	0.1	0.1	0.1	0	0	0.1	0.1	0.1
4	0.1	0	0	0.1	0	0	0.1	0	0	0.1	0	0
5												

Since some of the cases in ***Table.26*** are repeated due to the force acting on the opposite direction (for example 2_1 and 2_2), there is no need to similate all the repeated cases. Giving 5 total load sceanarios from which conclusion will be derived.

10.3 Results of the different cases for the composite frame:

As in chapter 10.1.1 a summary table with the different load scenarios for the composite bogie frame will be added. To visually see the different results from all the load scenarios, you must address yourself to the appendix where they will be all displayed.

Table 27. Results of the case studies for the composite bogie frame – Exceptional loads.

	Total Deformation		Von-Misses Stress		Safety Factor		Invers. Safety Factor	
Cases ↓	Max [m]	Min [m]	Max [Pa]	Min [Pa]	Max []	Min []	Max []	Min []
1	0,0144	0,0139	2,16E+08	2,73E+03	1000	1,105	0,904	0
2	0,0146	0,0121	2,27E+08	1,80E+03	1000	1,09	0,911	0
3	0,0180	0,0136	1,36E+08	9,83E+03	1000	1,77	0,563	0
4	0,0145	0,0139	2,16E+08	2,66E+03	1000	1,103	0,906	0
5	0,0144	0,0139	2,16E+08	2,66E+03	1000	1,103	0,906	0

11. Commentary on the results:

The results gave a very surprising outcome for both of the materials, and the layout of the results will help conclude a final commentary. It is important to point out that the structural steel S235bogie frame is two cases where the model does not pass the safety factor test. This and more will be discussed in the following subchapter.

I would like to reaffirm that the visual representation of the restrictions and the results of all the cases and materials are available in Appendix a.

11.1 Commentary on the structural steel S235 bogie frame results:

The result gathered in ***Table.21*** and ***Table.22*** are very surprising. Before anything, I wanted to mention that these tables were separated so that there is a more fluent reading of both of the different load cases (exception & normal service loads).

Like mentioned at the introduction of this chapter, there are two cases in which the bogie frame fails due to it not surpassing the safety factor ($SF \geq 1$). The main reason for this is ***not*** that the structural steel S235 is a lousy material for this particular scenario, but rather that the geometry of the location from where it failed was not appropriately designed. If you were to look at *Fig.23* and *Fig.40* in the *Appendix document*, you could clearly see that the location of the failure is that of geometrical stress concentrators. The edges that give us these results could have been avoided by rounding the edges, increasing the Safety factor, and allowing the test to continue. This points out why it is crucial to simulate an analysis with a CAD program. If this had been a structural steel S235 prototype in the lab, the bogie frame would have snapped, potentially costing the company hundreds of thousands.

We will analyze the first half and second half of the load cases separated due to them being of a different nature.

The first half of the load cases (i.e., the exceptional loads) produced a very similar deformation throughout the 5 cases. We suspect that this similarity for the total deformation is a response to the vertical load of a magnitud of Fz = 134888 [N], which was used for all load scenarios except the 3rd load scenario. The presence of this force (F_z = 134888 [N]) is enough to generate a similar deformation through all of the 4 load scenarios that the structure steel S235 bogie frame was put under. The reason as to why the 3rd case had greater deformation is because it was under tougher restrictions. Due to the bogie frame in the 3rd scenario having less freedom than the rest of the cases and subjected to a force, the frame deformed more than the rest of the other 4 cases.
Moving onto the Von-Misses stress, the case that produced the least amount of stress is the 3rd case, which was the case that only had a vertical force of a lower magnitude than the initial one. This mentioned vertical load was that of F_z = 44145 [N], whereas the other vertical load was that of F_z = 134888 [N], making it evident that the vertical force has a huge roll on the Von-misses stress results.

We touch upon normal service loads for the second half of the tension study for the structure steel S235 bogie frame. These normal service loads have a significantly lower magnitude compared to those in the exceptional loads, but in contrast, it is applied for 1 million cycles to produce fatigue on the model. The results that we got after doing the service load simulations were very pleasing. When doing a fatigue study, you look for the safety factor and life expectancy. These two solutions combined tell you if the model survives the load you are applying and for how many cycles. ANSYS (version R19.2) allows the structure steel S235 to be iterated for 1 million cycles (in case that it has infinite life). This being said, analyzing the *table.22* you can see that the structure steel S235 bogie frame survives all the load scenarios for fatigue testing, and as such the life expectancy for the bogie frame was that of 1million cycles.

11.2 Commentary on the composite bogie frame results:

There were many concerns as to how the composite bogie frame could have failed during the tests. That being said, in none of the load scenarios the composite bogie frame failed - It is true that the fatigue analysis was not explored, but from what we know of the composite materials (that they perform very well under fatigue analysis), it should not have any problems succeeding in that too.

For this analysis, we will dive into the exceptional loads' cases applied for the composite bogie frame. As you may see (*Table.27*), the composite frame's vertical forces F_z had a larger magnitude than that of the structure steel S235, because the forces were associated with how much the bogie weighed. If we reduced the weight of the frame, we also reduced the subtracting force factor in the *equation.8* and *equation.29* giving a larger F_z for the composite bogie frame.

As for the structure steel S235 bogie frame, the composite bogie's total deformation followed a pattern. Orient your attention to *Table.28* and observe the total deformation. If you glance over to the 3rd load case, you can see that the total deformation diverges from the pattern that the other load scenarios were following. Like in the structure steel S235, the vertical force for the 3rd load scenario is of a lower magnitude. This detail can be correlated and helps explain why the 3rd case has a different total deformation than the rest of the cases. Because the other load scenarios share the same vertical force, they all have similar deformation, except the 3rd scenario has a vertical force of lesser magnitude. Analzying *Table.28*, we focus our attention on the Von-Misses stress. The case that suffered more interior stress was the second case. This was once again an issue of stress concentration in an area that was not rounded; if that section were to be rounded, the stresses would decrease, resulting in a less critical mechanical result with respect to load demand that was put under.

*N*ew incorporation to the indicators is the inverse safety factor., this inverse safety factor tells you how close the model is to fail. The closer it gets to 1, the worse for the model. In all the composite frame results, the bogie gets too close to 1 bt does not surpass 1 - meaning that it is recommended to add some more so that the inverse safety factor gets further from 1. Finally, we focus our attention on the last indicator that helps us analyze the mechanical behavior of the composite frame, the safety factor. The safety factor for all the load scenarios is above 1, which indicates that the ply selection was correct and accurate. If we were to do an average of the safety factor, it averages SF=1.10, which means that the composite bogie frame surpasses all of the tension scenarios that it was put under.

11.3 Comparative between the structural steel S235 and the carbon fiber w/ epoxy resin:

There is much to say about comparing the structural steel bogie frame and the composite bogie frame. Both have successfully passed the load cases (except for 2 cases for the structure steel S235 bogie frame) and both bogie frame variations performed with absolute satisfaction through all the simulations. When comparing the deformation between both bogie frames, it is clear how the deformation for both frames is about the same.

Another important point when comparing both bogie frames is that the stresses generated inside the composite bogie frame were greater than that of the structural steel frame. This behaviour could probably be explained by the nature of the composite and how it is constructed. A composite is a stack of layers of different materials that together generate a mechanical behaviour that is beneficial. Stacking these materials (i.e., creating the plies of composites) makes the material vulnerable to shear tension. Thus, by combining the tension generated by the deformation from the vertical force and the shear tension that the plies experience, you get that the total tension of the composite bogie frame is larger than that of the structural steel bogie frame. This shear tension will always be present independently of the composites you use, but a way to prevent that the composite frame will fail when under the test condition is by using a very strong resin (as to why we chose Epoxy, the strongest resin for composites).

The safety factor aspect was shocking. On the one hand, the structure steel bogie frame failed on two separate occasions, during the unloading load scenario and the longitudinal load scenario, respectively - but like mentioned previously, this was due to a geometrical tension concentrator that would be easily suppressed by rounding the edges that caused the problem in the first place (address your attention to the appendix for the visual representation). On the other hand, we have the safety factors of the composite frame. Notice that the safety factor barely surpasses the limit. To avoid this, you ideally would want to add more plies to the structure and simplify the geometry even more. This advice not being followed during the development of this study is because the initial intention was to respect as much as possible the geometry of the bogie frame so that there could be fair comparisons between both versions of the bogie frame.
Other than that, I think it is safe to say that the composite frame came out on top if we take into account that the composite bogie frame did not fail the safety test even without rounding any edges either, a surprising and promising outcome.

12. Conclusions:

To summarize the aim of this thesis, it is to compare the outcome of the results for both versions of the bogie frame, that being structural steel S235 bogie frame and composite bogie frame in distinct scenarios following the EN 13749:2011 standard as a guideline. It is evident that the composite frame was not thoroughly analyzed due to the inability to go forward with the fatigue test, but conclusions will be made.

As the world progresses, there are changes in technology, these changes produce different needs, for the better or worse, and in 2050 the zero-emission norm comes into reality [2]. It is clear that we need a change in the train transport sector if we wish to fulfill that norm. A method that could be used to achieve this zero-emission goal is creating a composite bogie frame. Even though composite materials are still being studied, their application is broad as their potential and this study is proof of that.

During the lifetime of a bogie frame, the frame experiences different load scenarios, of which the toughest scenarios make up the bulk of this thesis. The study follows a thorough methodology to guarantee that it follows EN 13749:2011, allowing the study to have high reliability.

A composite material frame is a wonderful alternative that should be considered for the future of railway transport, not only for the passenger trains but also for the freight/cargo trains. From a governmental perspective, it is beneficial to pay less in maintenance because the bogie weighs considerably less. The amount of money you would need to pay for maintenance would be substantially reduced, making the composite frame an even more tempting alternative to modifying the bogie frame. As we have demonstrated in the previous chapters, the composite frame is more than capable of comparing itself with the standard material, but rather outperforms it in some cases. Increasing the pressure to change our old ways of fabricating a bogie frame.

As a conclusion to this study and based on the quantitative and qualitative analysis done in the previous chapters, I would leap forward in this direction for the future of railway vehicles. Making the train lighter, and likewise more efficient is something that we should all be aiming for, not only for the environment but also for what it could potentially suppose for the future of any transport. This exciting field is in constant fluctuation, allowing development, design, and creation of new and different ideas nonstop.

13. Climate Impact:

It is evident that the world is changing and changing fast, and as such, it is necessary to change how we treat our environment and adapt to the new norms surrounding climate change. In 2030, we should have achieved a 55% reduction of the CO_2 emitted by any vehicle. In 2050, we need to create a zero-emission train [1, 2]. All these norms are placed due to our irresponsibility concerning our ecosystem, and we need to take action now.

When considering the creation of the composite bogie, one detail stands out from the rest: the use of recycled unidirectional epoxy carbon for the formation of the composite bogie frame. As the world progresses, so does our understanding of complex and new materials like composites, and in recent years the utilization of thermal recycling has been put under the spotlight so that we could develop a method to recycle carbon fiber composites. This belief that carbon fibers could make a massive difference in how we see the world and how we treat it fuelled thousands of engineers and entrepreneurs for a sustainable and environmentally friendly world.

The bogie frame is composed of 3 composite materials, recycled unidirectional epoxy carbon, and waved epoxy carbon and aluminum honeycomb. All the materials present in the composite bogie frame are materials that can be recycled and reused in the future for some other product. Aside from being recyclable, carbon fiber composites contribute significantly to the curbing of global warming. A study has shown that combining virgin and recycled composite carbon fiber to create a composite bogie frame can potentially save up to 64.7 tons of CO_2 emitted to the atmosphere over 35 years per bogie [32]. For example, the *RENFE* R-598 diesel locomotive train that travels around the Catalonian region this intercity commuter train is made up of 9 passenger railcars [33]. If we considered that the train is a non-articulated train counting with 2 bogie frames per carbody, we are looking at 18 bogies for the train. You can quickly see how the numbers rapidly increase when multiplying the numbers of bogies in a train and the tons of CO_2 that are not emitted to the atmosphere.

The following table will be used to gather basic information to estimate the CO_2 in tons that will not be emitted into the atmosphere.

Table 28. A summary list gathers the basic information to calculate the total amount of CO_2 that is not emitted to the atmosphere in a 35 year period.

Designation	Abbreviation	Value	Unit
Total amount of CO_2 that is not emitted to the atmosphere in a 35 year period.	T	2861.4	Tons CO_2/35years
Number of passenger railcars	n_c	9	-
Number of bogies per railcar	n_b	2	-
Amount of CO_2 of emission reduction per bogie in a 35 year period	e_{co_2}	64.7	Tons CO_2/35years

Ahead is the equation that will be used to estimate the amount of CO_2 will not be emitted to the atmosphere in a 35 year period. It combines the amount of CO_2 emission reduction per bogie in a 35 year period, the number of bogies there are per railcar and the number of railcars per train

$$T \ = n_c \cdot n_b \cdot e_{co_2} \ = \ 9 \cdot 2 \cdot 64.7 = 1164.6 \, Tons \ of \ \frac{CO_2}{35 \ years}$$

Equation 36. Equation to estimate the amount of CO2 that will not be emitted to the atmosphere thanks to the use of a composite bogie frame.

After applying *Equation 36*, we can conclude that a total estimate amount of 1164.6 Tons of $\frac{CO_2}{35 \ years}$ would not be emitted to the atmosphere if we were to implement a full bogie composite frame that combines virgin and recycled composite carbon fibers.

Considering everything mentioned previously, it is clear the climate advantages that using a composite bogie frame has over the traditional steel structure bogie frame is magnificent and if we wish to make a difference in the railway transport world, this is most certainly the wait to go.

14. Budget review:

The budget review for a project that involves the production of the bogie frames is an essential part of a study of this sort. This chapter will help compare the estimated amount of money that will be needed to create a structure steel S235 bogie frame and the estimated amount of money that will be needed to create a composite fiber bogie frame, as well as to know how much of a profit is there when making a structural steel and composite frame.

There will be a separation of costs, the engieering costs, and the manufacturing costs for the correct understanding of this budget review. I would like to clarify that some of these figures are estimates based on educated guesses, and as such, the real amount would be more.

14.1 Engineering costs:

The engineering costs are the cost for designing the bogie frame when considering some basic description of what goes into a designing process. For both the composite and structure steel bogie frame, this amount of money would be spent equally and there will not be any need to split this into two subgroups.

As we know from sources, it takes around 5 years roughly to complete the manufacturing of an entire train and as such, it is safe to assume that in those 5 years, the total amount of time they spent to create the bogie is about 2 years [34, 35] for the design aspect of the bogie frame. It is supposed that we needs a total of 5 engineers (the engineering workforce is composed of 3 CAD technicians, 2 Finite element analyst (FAE), and 1 technical project manager) with different salary per hour (35 €/h, 45€/h, and 60€/h respectively). These engineers would not participate to the same degree and so, it is estimated that the CAD technician is present for about 75% of the time, the FAE analyst for half of the design period (i.e., 50%), and the technical project manager for all the duration of the design aspect (i.e., 100%). Lastly, it is estimated that each engineer would work a total of 1750h/annually to complete this project and will all data that was estimated just, it is possible to calculate the number of hours per project that there each engineer dedicated for the development of this project

$$T_{project} = h_{annualy} \cdot T_{project} \cdot P_{project}$$

Equation 37. Total time that each engineer spends per project.

Where,
$T_{project}$ is the amount of time each engineer spends per project.
h_{anualy} is the amount of annual hours a engineer has.
$T_{project}$ is the duration in years of the project.

$P_{project}$ is the participation of each engineer per project.

Lasty, to estimate the amount of money needed for the design of the bogie, we multiply the the amount of time each engineer spends on the project and their pay per hour.
As such, the following table will summarize the amount of money for the engineers.

Table 29. Summary of the engineering economic assumptions.

Nº of Years for development of the bogie	2				
Engineering workforce	Amount of engineers	€/h	Project participation	Hours/ project	Cost
CAD technician	3	35,00 €	0,75	2625	275.625,00 €
FEA analyst	2	45,00 €	0,5	1750	157.500,00 €
Technical project manager	1	60,00 €	1	3500	210.000,00 €
Total amount of money for all the engineers					643.125,00 €

We then can see that the total amount of money needed to pay the engineers for the 2 year design period is about 643.125,00€. Next is the estimation of the workstations of the engineers. Each engineer would need one workstation with all the desk equipment and all the commodities that they would need and the portable laptop that they use daily with all the licenses of the programs that would be needed to design the bogie frame. The added programs are CAD software used to structural steel S235 and composite bogie frames (i.e., Solidworks and Ansys) [36].

The following table will summarize the total amount of money needed for the workstations and the commodities for all the engineers and the licenses they would need to design the bogie frames.

Table 30. Summary of cost of the licenses and the workstation commodities

Commodities	Amount	Cost
Workstations	5	3.000,00 €
Laptops	5	3.000,00 €
Ansys Mechanical Enterprise	1	31.029,82 €
Ansys Mechanical Enterprise Solver	1	31.035,26 €
ANSYS Spaceclaim Direct Modeler	1	5.010,08 €
ANSYS Geometry Interface For Parasolid	1	2.047,86 €
ANSYS Mechanical Enterprise Preppost	1	13.651,28 €
ANSYS Ncode Designlife Standard	1	27.249,37 €
SOLIDWORKS Premium Annulay	2	26.400,00 €
Total amount of money for the licenses and the commodities		142.423,67€

The total amount of money needed to pay for the workspace of the engineers are in the realm of 142.423,67 €. Finally, to know the total amount of money needed for the bogies' engineering design is the sum of the 643.125,00 € and 142.423,67 € to give you a total of 785.548,67 €.

14.2 Manufacturing costs:

In the manufacturing of the different bogie frames, there was the need to use two very distinct materials, and as such, the obvious choice is two split the manufacturing in two different subgroups to explain the process in more detail.

14.3 Manufacturing the Structural Steel S235 bogie frame:

For the manufacturing of the structure steel S235 bogie frame, there is the need to make assumptions once more. The number of years to manufacture a bogie frame will be about 6 months (or 0,5 years). The estimated number of people needed to manufacture a bogie frame will be around 10 workers on-site to assemble and test the manufactured bogie frame. These 10 workers are 8 welding technicians, 2 quality control engineers, and 1 production manager. Each has different salary pay per hour, and each has different participation in the project, like in the previous engineering example. The estimated salary and amount of participation are 25€/h with 100% participation for the welder technician, 37€/h and a 50% particpation for the quality control engineer, and a 50€/h and 80% participation for the production manager. Equation. *37*, let us calculate how many hours per project were dedicated per project.

Lastly, to know the total estimated amount of money it is needed for the production force, you multiply the number of hours per project time by the amount they get paid per hour. Table 31 summarizes the before explained economic estimations for the production workforce

Table 31. Summary and calculus of the money needed for the production workforce.

Nº Years to produce a frame	0,5				
Production workforce	Amount of personnel	€/h	Project participation	Hours/project	Cost
Welding Technician	8	25,00 €	1	875	175.000,00€
Quality Control Engineer	2	37,00 €	0,5	437,5	32.375,00€
Production Manager	1	50,00 €	0,8	700	35.000,00€
Total amount of money for the production workforce per project					242.375,00€

The total amount of money needed for the production workforce is about 242.375,00 €. In the manufacturing process, there are non-recurrent costs, these costs are the ones that would only need to be spent once and that is all.

These non-recurrent costs involve the welding machines, jigs & tools, and the welding certificate that the welding technician should have to weld certain areas of the bogie frame (i.e., norm EN 15085). Table 32 displays the costs of all the explained previously.

Table 32. Summary and calculation of the non-recurrent costs of the manufacturing process.

Manufacturing none recurrent costs	Quantity	Cost
Welding Machines	4	30.000,00 €
Jigs & Tools	1	300.000,00 €
Welding Certification (EN 15085)	8	48.000,00 €
Total amount of money of the non-recurrent costs		378.000,00 €

Next is the calculus of the amount of material used for the bogie frame. The structure steel S235 in the market is seeling for 600kg/ton provident from china. It is expected that a percentage of the material bought will not be used but should be counted for when buying the material. The amount of waste is assumed to be 20% of all the structure steel bought. Thus, the following table will display the total amount of money needed to buy the structure steel S235 material.

Table 33. Display of the money needed to buy the material structure steel s235.

Materials	€/kg	Structure weight (kg)	waste (%)	Structure cost
Structural Steel S235	0,60 €	5650	0,2	4.068,00 €

Finally, the total manufacturing cost a bogie frame would be the sum of the amount of money needed of the non-recurrent costs and the workforce, without considering the amount of material needed (because that would be added later). Thus, 378.000 € plus 242.375,00 € will give you a total amount of 620.375 € for the manufacturing phase using structure steel S235 as the main material for the bogie frame.

14.4 Manufacturing the composite bogie frame:

For the composite frame, the same idea as the strcture steel s235 will be followed, first is needed to calculate the amunt of hours per worker and then use the salary per hour to get the total amount of money per project. This time as it is the 3rd time explaining, I will give myself the liberty to express the table directly and express the differences ahead.

Table 34. The amount of money needed for the workforce that manufactures the composite bogie frame

Nº Years to produce one frame	0,5				
Production Workforce	Amount Of Personnel	€/H	Project Participation	Hours/ Project	Cost
Composite Technician	5	37,00 €	1	875	161.875,00 €
Quality Control Engineer	2	37,00 €	0,5	437,5	32.375,00 €
Production Manager	1	50,00 €	0,8	700	35.000,00 €
TOTAL					229.250,00€

The main difference that *Table 34* has with *Table 33* is that there is new production workforce personnel. There has been a swap for the personnel needed to manufacture the composite bogie frame as it is a more specific sector. The composite technician will be extremely helpful for creating and selecting the plies and the manufacturing of the bogie.

The assumption that there will not be any need to have as many as welding technicians will be made, summing up a total of 5 composite technicians.

Now, as for the calculation of the non-recurrent cost for the manufacturing of the composite frame. There are different necessities as that of the structural steel bogie frame. The table will be slightly modified.

Table 35. Summary of non-recurrent expenses for the company creating the composite bogie frame

Manufacturing Non Recurrent Costs	Quantity	Cost
Ply Machines	4	60.000,00 €
Jigs & Tools	1	300.000,00 €
Total		360.000,00 €

Followed is the amount of money spent on the materials for creating the composite bogie frame. As we all know, composites are very expensive materials, but a good property that the recycled epoxy carbon has is that it is 40% cheaper than the virgin alternative [37]. As such, the total amount of money of a UD epoxy carbon would be that of 48€/m2.The other composite used in the making of the composite bogie frame was the woven epoxy carbon. This material on the market is sold for 90€/m^2 [38]. The last material used is the aluminum honeycomb could be found for 30€/m2 [39]. For the correct sum of all the meters used for the plies, ANSYS has an option to calculate based on a price/meter parameter to calculate the amount of money to invest in forming the composite model. Using this tool and considering the current prices of recycles UD epoxy carbon, woven epoxy carbon and the aluminum honeycomb, the total sum of material is 25.474,80 €, including a 20% waste.

Table 36 displays the money so that there is a clear understanding of the cost of the materials used in the composite bogie frame:

Table 36. Summary of the expenses with regards to the materials for the composite bogie frame.

Materials	€/M2	Structure Cost	Waste (%)	Structure Cost With Waste
Recycled UD Epoxy Carbon	48,00 €	21.229,00 €	0,2	25.474,80 €
Woven Epoxy Carbon	90,00 €		0,2	
Aluminum Honeycomb	30,00 €		0,2	

The total amount of money needed for the manufacturing process for the composite bogie frame will be the sum of the manufacturing workforce and the non-recurrent costs. Such that, 360.000 € plus 229.250,00 € will give you a total estimate amount of 589.250,00 € for the manufacturing phase using composite materials as the main material for the bogie frame.

14.5 Example of a contract deal:

There will be a real-life example of a contract paid for the trains' manufacturing for the correct understanding of the budget assumption. In 2019, RENFE bought 211 commuter trains and paid 2.726 Million € [40]. It was a macro-purche that does not come often but has enough information to use as an example. It is first necessary to know the amount of money the train was bought for

$$M_{per\ train} = \frac{2.726M€}{211} = 12.919.431{,}28\ €$$

Equation 38. Money payed in the RENFE contract per train

After knowing the amount of money paid for each train, it is convenient to estimate the amount of money paid for all the bogies. Then, it is assumed that 30% of the budget was dedicated to cover the cost of the bogies, as such

$$M_{for\ all\ the\ bogies} = \frac{12.919.431\ € \cdot 30}{100} = 3.875.829{,}38€$$

Equation 39. Money paid in the RENFE contract for all the bogies

The next step is to calculate the amount of money per bogie. It is also assumed that the train that was bought has an articulated configuration (i.e., has a shared bogie with the adjacent passenger railcar) and has a total of railcars, which sums up 6 bogies per train.

$$M_{per\ bogie} = \frac{3.875.829{,}38\ €}{6} = 645.971{,}65\ €$$

Equation 40. Money paid in the RENFE contract per bogie.

From this total destinated, it is assumed that 60% of the money per bogie is for the frame, such that

$$M_{bogie\ frame} = \frac{645.971{,}65\ € \ \cdot 60}{100} = 387.582{,}94\ €$$

Equation 41. Money paid in the RENFE contract per bogie frame.

Now that we know the total amount of money per bogie frame paid, we need to know how many bogies were there for the 211 trains. For that, we will multiply the 211 per 6.

$$N_{bogie} = 211 \cdot 6 = 1.266\ bogies$$

Equation 42. Number of bogies that were bought in the RENFE contract.

Finally, the amount of money that RENFE paid for manufacturing the bogie frames for all the 211 commuter trains in 2019.

$$M_{for\ all\ the\ bogie\ frames} = 1.266\ bogies\ \cdot\ 387.582{,}94\ €\ = 490.680.000{,}00\ €$$

Equation 43. Money paid in the RENFE contract for all the bogie frames.

The total estimated amount of money that RENFE paid to create 1.266 bogie frames was 490.680.000,00€. This amount of money is used to estimate the benefits a company has for both the composite and structural steel bogie frame.

14.6 Benefits per project:

As two different bogie frames are proposed, it is needed to separate these bogies to understand the benefits a company has for both bogie frames.

14.7 Benefits for the structural steel S235 bogie frame project:

The first step is to calculate the full cost of the design and manufacturing process that the company has to calculate the benefits.

For the structure steel s235, the total cost will be calculated by adding the total engineering cost calculated in *Chapter 14.1*, the total manufacturing cost and the cost for the materials used in the manufacturing process, both calculated in *Chapter.14.2.1*.

$$P_{\substack{cost\ of\ the\ manufacturing\\ and\ designing\ of\ a\\ structure\ steel\ frame}} = 785.548{,}67\ \text{€} + 620.375{,}00\ \text{€} + 4.068{,}00\ \text{€} = 1.409.991{,}67\ \text{€}$$

Equation 44. Cost of the manufacturing and designing of a structural steel bogie frame.

Now that we have the total amount of money needed to make a bogie frame, we should calculate the amount of money it is needed to make all 1.266 bogie frames bought by RENFE.

$$P_{\substack{cost\ of\ the\ manufacturing\\ and\ designing\ of\ all\\ structure\ steel\ frames}} = (785.548{,}67\ \text{€} + 620.375{,}00\ \text{€}) + (1.266 \cdot 4.068{,}00\ \text{€}) + (1.266 \cdot 242.375{,}00\ \text{€}) = 313.160.386{,}67\ \text{€}$$

Equation 45. Cost of manufacturing and designing all of the 1266 structure steel bogie frames

Notice that the manufacturing and designing phases are only counted as one entire operation because the design and manufcturing are done only 1 time, but the workforce and the material cost will be used 1.266 times.

The benefits that the company has with the contract that was signed with RENFE in 2019 is the following

$$P_{\substack{benefit\ after\ the\ manufacturing\\ and\ designing\ of\ all\ the\\ structure\ steel\ bogie\ frames}} = 490.680.000{,}00\ \text{€} - 313.160.386{,}67\ \text{€} = 177.519.613{,}33\ \text{€}$$

Equation 46. Total amount of benefit for the company if taking into account the 1266 structure steel bogie frames.

The total estimated amount of net benefit when only counting the bogie frames that the company that accepted the RENFE contract would have if they manufactured a structure steel S235 bogie frame is 177.519.613,33 €.

14.8 Benefits for the composite bogie frame project:

In case that the company wanted to manufacture the a composite bogie frame, it is necessary to update the budget to calculate the benefits. The same logical order will be followed as the previous subchapter.

First, it is needed to calculate the total cost of designing and manufacturing a composite bogie frame.

$$P_{\substack{cost\ of\ the\ manufacturing\\ and\ designing\ of\ a\\ composite\ frame}} = 785.548{,}67\ € + 589.250{,}00\ € + 25.474{,}8\ € = 1.400.273{,}47\ €$$

Equation 47. Cost of the manufacturing and designing of a composite bogie frame

Next, considering that there was a total of 1.266 composite bogie frames bought in the contract, it is needed to know the amount of money it takes to manufacture and design all the 1.266 composite bogie frames.

$$P_{\substack{cost\ of\ the\ manufacturing\\ and\ designing\ of\ all\\ composite\ frames}} = (785.548{,}67\ € \cdot + 589.250{,}00\ €) + (1.266 \cdot 25.474{,}80\ €) + (1.266 \cdot 229.250{,}00\ €) = 323.856.395{,}47\ €$$

Equation 48. Cost of the manufacturing and designing of all composite bogie frames

Now that we know the amount that the company had to spend on making all the 1.266 composite bogies frames, we can calculate how much benefit is there when accepting the contract of 1.276 M€ with RENFE.

$$P_{\substack{benefit\ after\ the\ manufacturing\\ and\ designing\ of\ all\ the\\ composite\ bogie\ frames}} = 490.680.000{,}00\ € - 323.856.395{,}47\ € = 166.823.604{,}53\ €$$

Equation 49. Net benefit after the manufacturing and designing of all the composite bogie frames.

The total estimated amount of net benefit when only counting the bogie frames that the company that accepted the RENFE contract would have if they manufactured a composite bogie frame is 166.823.604,53 €.

14.9 Commentary on the budget results:

After going through the budget for both the structure steel bogie frame and the composite bogie frame, it is worth noting that the structural steel bogie frame's expected outcome is cheaper to manufacture was achieved. It is surprising that with the estimates that were done in the budget development, it is only 9.718,2 € more expensive to manufacture a composite bogie frame than it is to manufacture a structure steel bogie frame.

It is a very promising result when taking into account the contract signed with RENFE for the 1.266 bogie frames, manufacturing the bogie frames with structural steel material will result in a 177.519.613,33 € benefit and as for the manufacturing of the composite bogie frame, the benefit is that of 166.823.604,53 €. There is a considerable amount of difference between both benefits of 10.696.008,80 €. On one hand, as time progresses and we learn more about the composite material, this difference will be narrowing down until it is basically as expensive to create a bogie frame out of composite materials as it is to make it out of structural steel. On the other hand, the need to make the trains eco-friendly and sustainable is growing and making these type of modifications to the trains will allow the government to have the trains running for longer, thanks to it matching the regulations. In summary, the production of composite frames will reduce in price with time as the material becomes more accesible and manageble, and by doing so the trains will be more eco-friendly with the use of recycled carbon reinforced polymers a circular economy will be achieved which highlights the sustainability of this model.

15. Project planning:

This chapter talks about the project planning for the composite fiber reinforced polymer frame bogie thesis study. Ahead will be a table that relates the 19 tasks that were overcome so that the study could be clear and understandable for the reader and the time needed to complete the task.

Table 37. Project planning tasks list.

No.	Tasks	Start Date	Duration (Days)	End Date
1	Problem Analysis	25-sep	7	02-oct
2	Train Distinction Research	03-oct	5	08-oct
3	European Railway Industry Research	09-oct	3	12-oct
4	Research Of What Composes A Bogie	13-oct	8	21-oct
5	Composite Material Research	22-oct	7	29-oct
6	Comprehension Of The EN 13749:2011 And Other Norms	30-oct	5	04-nov
7	Calculus Of The Forces Present For Both Versions Of The Frame	05-nov	1	06-nov
8	Solidworks Modelling	07-nov	4	11-nov
9	Solidworks Drawings	12-nov	1	13-nov
10	ANSYS Simulations Boundary Condition Settings #1	14-nov	5	19-nov
11	ANSYS Simulations Result Analysis #1	20-nov	1	21-nov
12	ANSYS Simulations Boundary Condition Settings #2	22-nov	7	29-nov
13	ANSYS Simulations Result Analysis #2	30-nov	1	01-dic
14	Commentary Of The Different Results For #1 And #2	02-dic	1	03-dic
15	Conclusion	04-dic	1	05-dic
16	Climate Impact Research	06-dic	4	10-dic
17	Budget Analysis Research	11-dic	4	15-dic
18	Appendix Formation	44181	3	19-dic
19	Development Of The Literature Including The Different Iterations	25-sep	92	26-dic

The Gantt chart displays the number of days dedicated per task. The total number of days for the development of the literature, the research, the designing and the simulation was 92 days = 3 months and 2 days.

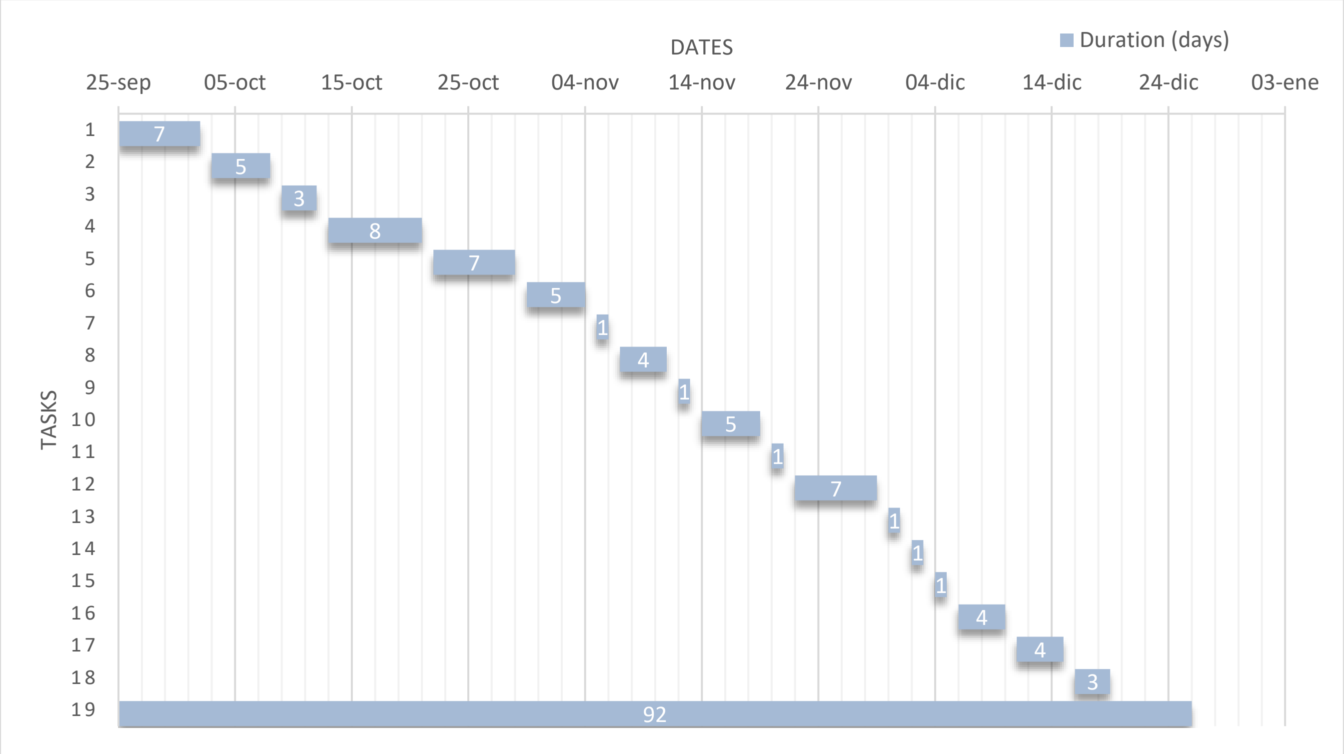


Illustration 3. Project planning timeline – Gantt chart

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LIST OF APPENDICES:

The list of appendices will be in the accompanying document so that the main information is localized in this memory.

This list of appendices includes:

a. Appendix I – Visual representation of each boundary conditions, followed by the result of each study case.

b. Appendix II - Steps needed in ANSYS to simulate both bogie frames.

c. Appendix III – Technical drawings.

d. Appendix IIII - Technical data sheet of the materials in the study.