POLYTECHNIC OF TURIN

Master's Degree in Mechanical Engineering

Master's Dissertation

Design of a tubular frame made of natural fiber reinforced composite with epoxy matrix for the cycling industry

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Abstract

This thesis focuses on the design and structural analysis of a bicycle frame made of composite material. Given the increasing necessity of reducing waste and recycling, the aim is to analyze its behavior when made with natural fiber reinforced composite compared to carbon fiber, looking for a trade off between sustainability and performance. It has been decided to apply these kind of materials on a bicycle typically used by amateurs, that can ride both on road both off road: a gravel bike.

The first section of the paper deals with design itself of the frame and explains the geometrical choices and constraints given by calculations, experience and standards developed through the years in the cycling world. In order to properly design a frame it has been necessary to choose the components to be mounted on the gravel and to study their interfaces with the frame itself. The CAD design of the frame has been performed on Solidworks by Dassault Systems and the final result is shown and described.

Sequently, the paper deals with the main principles of FEM analysis and it aims to explain the proper meshing process of such a structural component through Hypermesh.

Emphasis is then given on composite materials in general, describing their properties and potential and discussing one of their failure criterion: the Tsai - Wu failure criterion. This last one will give an idea of the structural reliability of the laminated component and it will be used by Hypermesh itself to run its calculations. Carbon fiber and hemp fiber are discussed into detail, as well as their mechanical characteristics and the data sheet of the exact materials used into the simulations.

Once the frame is designed and meshed, it is described how the material stratification is set on Hypermesh, as well as the model creation and settings. The analysis will be performed simulating the different loading conditions experienced by carbon frames during their everyday use, such as the pedaling fatigue, the static weight and the different torsion of the bicycle. The loads and their values are set from the standards that rule the bicycle frame testing made by manufacturers nowadays.

The last and most important step consists into performing an optimization of the laminate in order to minimize the material and maximize stiffness. A correct stratification will allow to obtain a light and functional component, while reducing waste and guaranteeing the required reliability. The results are shown both for the carbon fiber frame both for the natural fiber frame.

Part I
Introduction

The biking concept developed in the early 19th century and ever since then it never stopped evolving. Especially nowadays the necessity of a sustainable mobility pushes governments to invest into a wider infrastructure system for human powered vehicles and always more people chose to use a bike to move around the city. Furthermore, bikes are not only a transportation system, but they represent the hobby of many riders all over the world. There are several disciplines and each one has a proper bike with special components and designs. This is also a reason why the design of such products is becoming more and more complex and with different targets that make sport, mechanics, aerodynamics and electronics meet all together.

In this context, frames are of particular importance to give the rider the right balance, sensibility and shape to reach the best results possible. The experimentation around them doesn't end with geometry but involves innovative materials and production technologies as well. The bike and frame have to interact with the diverse practices, needs and desires of the different users: they allow people to use bicycles when they formerly couldn't or wouldn't do.

The main targets of a good modern frame are reduction of weight paired with high structural reliability. Design and comfort also play an important role, even though often at professional levels comfort is sacrificed to enhance performances.

Figure I.1: Examples of bike frames: road bike; xc bike; chrono bike

The design of a frame is usually made up of tubes and rocket bars connected together in triangle shape. Their geometry and material will strongly affect fatigue safety and rigid performance. By optimizing them, in fact, it's possible to enhance mechanical properties, also looking for a faster production of parts and lowering waste and costs.

Usual materials used for bicycle's frames are aluminum, steel and carbon fiber, but in the last years the new technologies allowed to explore different materials. One of the driving factors of research in this field is for sure sustainability and therefore the interest into natural fibers' applications into the automotive and cycling industry.

The dissertation will focus on describing step by step the process to create a bicycle frame. The first part will deal with the design itself of the component, taking into account the constraints and standards that rule this step nowadays. Design is fundamental both for structural, drive-ability and aesthetic reasons. This last one is an important aspect to not be forgotten when approaching to the bike world.

It is therefore interesting to understand the basics of modeling a component in order to make the proper structural analysis and lay down the materials. The software used will be Hypermesh and Hyperworks by AltairOne. This part will discuss the main principles that rule finite elements analysis and will explain how the parameters of the meshed frame have been chosen.

Once the geometry, shapes and sizes have been defined, it is important to have a look on the properties of the composite materials we'll make simulations with. Composites will be generally introduced and details will be given about carbon fiber and hemp fiber. Their behavior and mechanical characteristics will be very different, but both materials represent an interesting field of research to look for innovation and performance.

The last part introduces the optimization process on Hypermesh and sets the target and constraints to obtain a light-weight and stiff frame following the ISO4210 standards. All the passages are shown, as well as the results. This will be done both for carbon both for hemp fiber reinforced composite frames. All the final results are discussed and compared, running again the structural analysis and checking that the component has a sufficiently high factor of safety. Conclusions about the potential and limits of natural fiber applied on a bicycle frame are made.

The material datasheets have been provided by the collaboration with Micla Engineering & Design Srl.

Part II
Design

The design phase represents a key point that deals with the constraints given by standards and rider's comfort, but also the freedom of designing something appealing for the market and that follows the manufacturer's style. It often happens that bicycles can easily be recognized between one manufacturer and the other, even though the basic geometrical angles and measures don't strongly vary between different brands. Through the years, in fact, research and experimentation have returned standard measures that can be taken to have a stable and rideable vehicle. The frame itself, along with the bike, needs to be proportional to the rider's measures, but don't necessarily need to be tailored. Especially if the rider is not at the top level and if he has a normal body the standardized measures can be enough. Furthermore, standards guarantee also a good level of structural stiffness and ride-ability of the vehicle, while supporting the usual components depending on the type of bike. Mountain bike's wheels, for example, will need more space than racing bicycles. A similar argument can be made talking about sizes. Each manufacturer uses slightly different proportions in order to make the bike larger or smaller for the different riders, but the way that is done doesn't differ that much.

To design a bicycle frame it is also necessary to take into account not only the type of bike, but also its components and the customers' wealth range to pick or not the best quality parts.

In this project the idea has been to be able to mount some of the newest components in the market, or the ones that fit the best way on that model of bicycle.

The software used to draw the frame and its geometry as been *Solidworks* by Dassault Systems.

II.1 Gravel bike

The gravel world is actually one of the eldest areas of cycling. It stands for bicycles that have a geometry similar to the racing bikes, but with components that are suitable also for *gravel* - from here the name - roads. These bicycles can in fact ride on not paved roads and allow a good amount of freedom to the owner. What today has the specific *gravel* name back in the past was normal cycling: there were very few paved roads and Tour de France itself originally had a gravel profile. Years later bikers brought their bicycles also over mountain passes, for long rides, even though their discipline didn't have a specific name.

Another famous event is the Paris-Roubaix race, where the most part of the sectors are made of gravel, mud and shingles along 280 - kilometer distance. This race doesn't involve real gravel bikes, but mostly hybrid vehicles. After the arrival of mountain bikes the gravel world has had smaller interest from people, but it has been recently re-discovered by riders looking for comfort and freedom. Its components might not allow to ride a too rough terrain, but they let riders to run on unpaved compacted roads. For what concerns the geometries and the handlebar, though, the gravel bike resembles more a racing vehicle. Their heavier nature is not suitable though to run long marathons. It represents a great adventure vehicle to have freedom and versatility combined with comfort.

Figure II.1: Gravel bicycle on a gravel road

Getting into details, it is possible to start outlining some technical differences between a gravel and other types of bikes.

Contrary to mountain bikes, gravels don't have a damping system, but resembles more to racing bikes. Their wheels have a 28 inches diameter, with a carbon or steel frame. In this case, choosing steel guarantees more comfort, while carbon makes it lighter. For what concerns geometry the target is comfort compared to endurance bikes and the vehicle ends up being less responsive than ciclocross bicycles: the head tube is higher than the one of a road bike, allowing the rider to bike in a more standing position; the rear stay is quite long and this allows comfort and hosting bigger wheels. The bottom bracket has a lower position than for ciclocross because it is not necessary to jump from one obstacle to another and having it closer to the ground makes the drive easier. Moreover, talking about the angles of the tubes they are less sharp than racing bikes, making the bike less reactive and unstable on unpaved roads. The brakes are disc brakes and their presence combined with bigger wheels make the gravel's weight higher than the one of a classical road bike. Transmission is similar to the mountain biking one, but it usually has a double crown upfront as road bikes.

Being perfect even for long trips, for gravel bikes there are suitable accessories as mudguards, luggage racks and components like that.

Something that is taking place in the last years is also an increasing interest in gravel bikes' racing. The International Cycling Association is regulating the gravel world in order to be able to make a gravel world championship as well, so to be able to have bikes racing on unpaved roads similarly to the Paris-Roubaix competition. Innovation and technology will be therefore important for this universe as well.

II.2 Geometry

The bike geometry represents a fundamental step to build a bike with good handling and the right performances. Through the years manufacturers and standards made bicycles geometries don't drastically change from one model to another in the same category of bike.

It is important to understand the main measures to take into account when building or chosing a bike:

- *seat tube length*: it is the distance between the center of the bottom bracket to the top of the seat tube. Its height is important for the size of the bike's rider: it represents the upper and lower constraint a rider has to set the height of the saddle. This strongly affects the comfort and correct position of the rider on the bike, even though it doesn't affect the handling of the bike.
- *top tube length*: it is the horizontal line that links the top of the head tube to the center of the seat-post. Together with the reach it gives an idea of the space a rider has while biking. The reach, which will be discussed below, will anyway be the important factor to look at when designing a bike.
- *stack height*: the vertical distance from the center of the bottom bracket to the center-top of the head tube. Together with reach it gives an idea of the rider's position on the bike. A greater stack allows for a more standing position and therefore more comfortable. gravel bikes tend to have a stack higher than road bikes.

Figure II.1: Seat tube length, top tube lenght, stack height

- *reach*: it is the horizontal distance from the bottom bracket to the center of the top of the head tube and represents an important value to have an idea of the bike fitting on a rider. It defines how stretched forward the rider will be and it's related as well to the stack height. A lower reach means a more upright position and lets the rider being more relaxed and comfortable. While the seating position of the rider can be adjusted, stack and reach can't be modified later.
- *wheelbase*: it is the sum of the front-center and the rear-center lengths. It represents a good way to have an idea of the overall length of the vehicle. Generically speaking, the longer is the bike, the easier is to face uneven roads, descents and sudden braking, but

it will take more effort in turning. In fact, for road bikes it might be better a shorter wheelbase, leading to a more reactive vehicle.

Figure II.2: Front-center, rear-centre, down tube lenght, reach

- *bottom bracket height*: it is the vertical distance from the floor to the center of the bottom bracket. This parameter influences the center of mass of the rider. In order to have a better stability it is suitable to have a lower bottom bracket, which also helps turning. Something that affects this height is suspension sag and dynamic ride height: bikes with higher suspension travel need a higher bottom-bracket heights in order to not hit the ground with chain-rings. The possibility to scratch the ground with pedals, in fact, increases as the bottom-bracket length decreases.

- *head angle*: it is the horizontal angle of the steerer tube of the fork. it is important to note that it is not the angle of the line between the head-tube and the fork itself, but an offset can be seen between the two. The smaller is this angle, the heavier and less twitchy is the steering. The steeper is this angle, instead, the faster it'll be the steering response. When thinking of a bike going downhill, having a vertical head-tube would lead to a major predisposition to flip the rider in case of a bump or braking.

- *seat angle*: it is the horizontal angle of the seat-post and it grows the higher the saddle is set. Most part of bikes have a seat angle around 72 degrees, but many mountain bikes need instead to compensate for uphill gradients. This angle will also affect mass distribution on the bike and when going uphill and downhill can make the rider flip or the front wheel lift: the steeper is this angle the wider is the gradient before these problems happen.

Figure II.3: Bottom bracket height, head angle, seat angle, bar height

- *trail*: it is the horizontal distance between the front tire's contact point and the point at which the steering axis meets the ground. This value depends on the rake (the fork offset, which is the distance between the head axis and the center of the wheel), the head angle and the wheel size, and it gives an indication on the bike's stability in steering. As the trail augments, the steering becomes more stable, because a restoring force brings back the handle bar in a central position. Thinking to the trail as a virtual lever, the longer it is the less the steering angle will be affected when being kicked off the line (for example, by an obstacle). As the trail lowers, instead, the wheel print on the ground lowers as well and this allows a better handling while steering: a longer lever makes it in fact harder to initiate a turn with the handlebar. Being the rake and trail inversely proportional, it can be said that lowering the rake augments the trail and therefore stability, while a bigger rake ameliorates the handling of the vehicle. Having a positive trail is anyway something common, to avoid it to become negative when hitting a bump: this would have an unstable effect on the steering system.

Figure II.4: Trail

It is easy to understand the importance on geometry and its influence on the bike's use in different ways. A more aggressive geometry will be good for racing bikes, while comfort will affect positively endurance races.

In fact, the geometry mainly affects the handling and the rider's position on the bike, having a great effect on performances. Since most road bikes have the same size of wheels designers need to play on other measures of the bike, such as the frame.

For what concerns the gravel bike designed these have been the dimensions chosen, accordingly also to the today's standards:

Legend	Geometry	Measure	Unit of measure
Q	Wheel dimensions	700c	
A	Seat tube length	490	mm
G	Trail	51.29	mm
F	Rake	50	mm
L	Reach	387	mm
K	Stack	586	mm
C	Top tube lenght	560	mm
H	Wheelbase	1036	mm
E	Head angle	71.5	°
\	Central bracket	81	mm
D	Headtube lenght	165	mm
I	Rear stay lenght	435	mm

Table II.1: Geometrical dimensions of the gravel bicycle

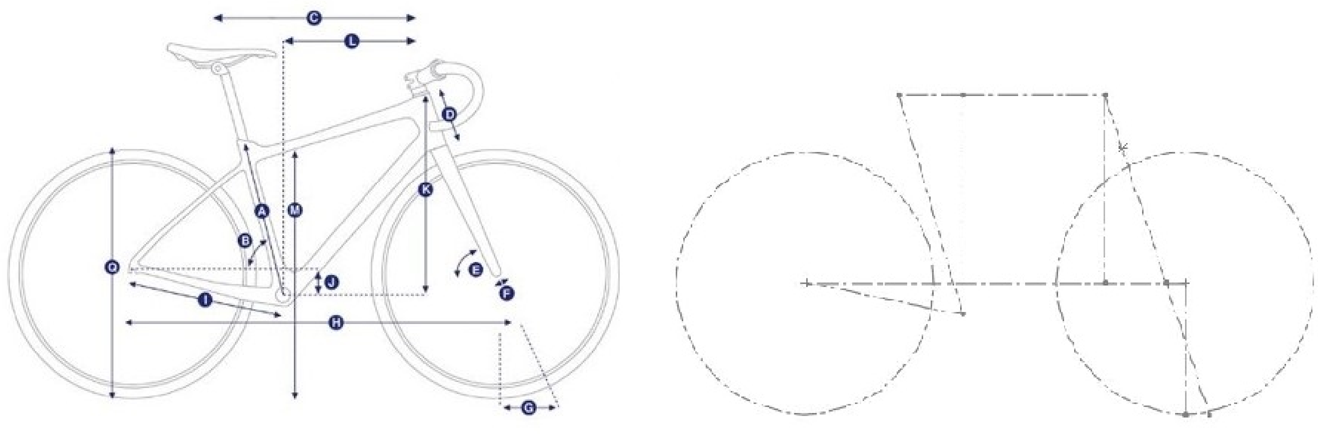


Figure II.5: First sketch of the gravel bike performed on Solidworks with the theoretical geometries

II.3 Components

Components mounted on a bicycle will also affect the way to design a bike. This will be depending both on mechanical and performance reasons, both on the market and the customer's needs. Costs vary very much from one component to another and not all the clients need the best ever item on the market. In any case, it is necessary to have a clear view on what will be the measures and mounting procedures for every component.

For the gravel bike it has been decided to use some of the best technologies on the market, to facilitate both the use both the maintenance of such a product.

The following table will summarize all of the choices made:

Component	Commercial choice
Wheels	700c
Headset	Integrated Headset Orbit C40
Bottom bracket	Press-fit bottom braket from Shimano
Sprocket set	Shimano CS-HG800, 11-speed, 11x34
Chain	KMC X11SL-1
Crankset	Shimano GRX RX-810, 31/48 172.5mm
Hub	Deore XT FH-M8110 Center Lock E-Thru 12x142mm
Brakes	Shimano GRX RX-810 hydraulic, Shimano SM-RT800 rotors [F, R]160mm
Rear derailleur	Shimano GRX RX-815 Di2
Front derailleur	Shimano GRX RX-815 Di2
Rear dropout	D538 derailleur hanger for Focus, Diamondback bikes
Saddle	Giant Approach SL, d=30.9

Table II.2: Component's choice for the gravel bicycle

The next paragraphs will go more into details of the different components of bicycles.

II.3.1 Headset

The headset is the set of components that allow the fork to rotate in the head-tube of the bicycle frame, leading the bike to be able to steer. The headset is typically made of two cups containing bearings pressed into the lower and upper part of the head-tube. Nowadays headsets might be tapered in mountain-bikes: the lower bearing is bigger than the upper one, being the one carrying the most part of the axial load. This being bigger allows to carry more load, especially in descent. The upper bearing is the one to keep in place the fork, which needs to be well secured laterally, but remaining free to rotate.

The main difference in the types of headsets can be found on how the bearings are mounted and held in place:

1. Threaded headset: in this type of headset the fork is threaded, as well as a race screwed on top of it. After being inserted in the head-tube, the fork gets blocked with a lock-nut. As for other headsets, the bearings are pressed on the top and bottom of the head-tube inside their cups and allow the fork to properly rotate. This kind of system is not common on modern bicycles: it requires in fact a fork specifically designed for that frame and system, and sometimes these kinds of headsets tend to undo themselves.

2. Thread-less headset: here the fork is not threaded, but is kept in place by a stem mounted on top of the head tube that presses against it to keep it against the bearings. Usually a preload is applied on the stem when mounting the headset system and an expander is set inside spreading the load inside of the steering tube. This element in carbon frames will also enhance the stiffness of the tube. Depending on how bearings are fitted into the frame it is then possible to distinguish the followings:

- External thread-less headset: these are the original headsets and consists into having bearing cups on the outer top and bottom of the head-tube that hold inside the bearings. A conical interface between bearings and cups helps secure them inside when the preload is applied.
- Semi-integrated headset: here the bearings always fit in the cup, but the cup is inside the head-tube, which, in fact, has a larger diameter. This also enhances the frame's stiffness.
- Integrated headset: in the integrated headset there are not anymore the containing cups, but the bearings are simply positioned into the frame, that has been previously shaped so to hold them. The bearings don't fit in with interference, but will be secured in place when preloading the headset, pressing against the conical seat of the frame. For the gravel bike this kind of headset has been chosen.

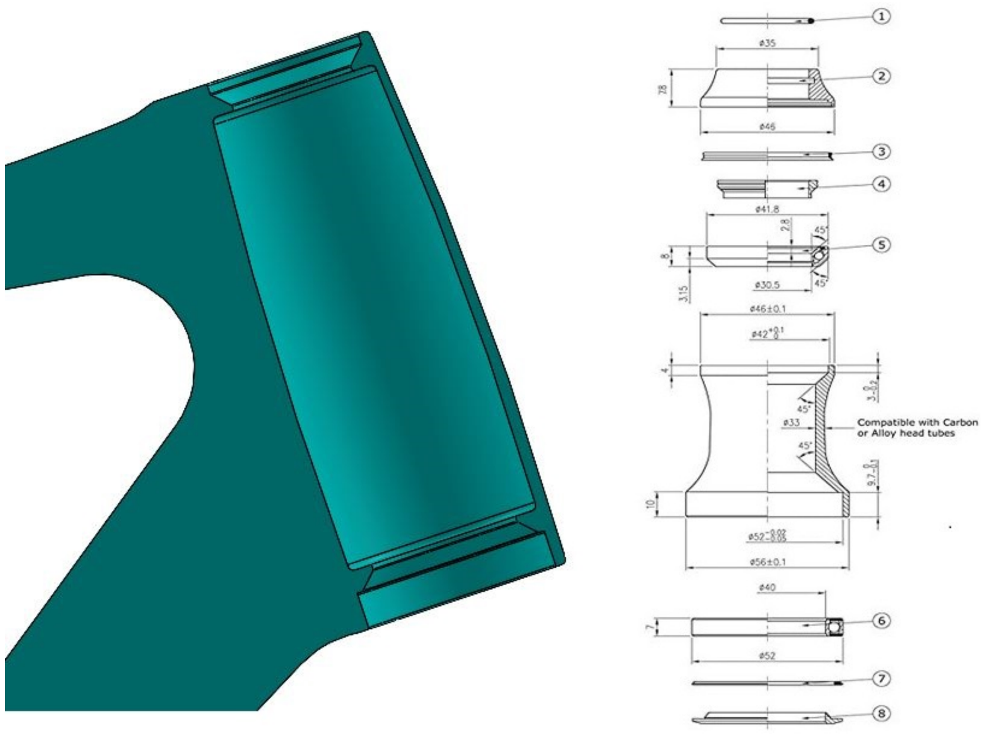


Figure II.1: Integrated headset Orbit C40 by Shimano

II.3.2 Bottom bracket

Bottom brackets connect the crank-set to the frame and allow the crank-set to rotate freely. Chain-rings and pedals are then attached to the crank.

The bottom bracket is principally made of a spindle at which the crank-set attaches and the bearings that allow it to rotate.

There are two main types of bottom brackets and they depend on the material of the frame.

In the past, frames were for the most part in steel or aluminum and it was therefore easy to fix the bottom bracket to the frame by screwing it inside a threaded shell inside the frame. The rising use of carbon frames, though, changed this kind of technology, since it was no longer possible to thread a shell into the frame. What has been done at the beginning was to fit proper threaded inserts into the frame, to keep everything in place. In the last years, though, to reduce weight the press-fit system has been developed: the bottom bracket gets to be inserted directly into the frame with interference, with a proper threaded press. There is an adapter to fit the bearings and to make sure the end up parallel. A cir-clip inside the shell ensures they keep staying in the right position.

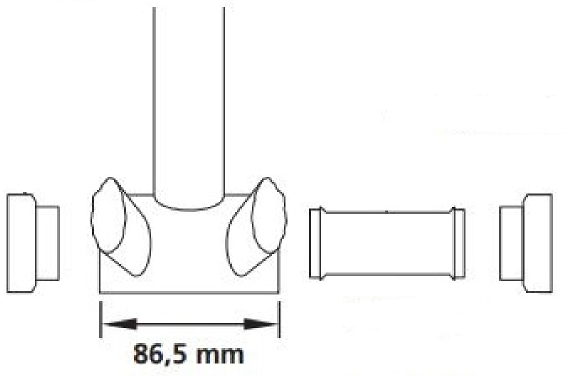


Figure II.2: Press-fit bottom bracket scheme

II.3.3 Rear dropout

The wheels of a bike attach to the bike through the fork-ends. If the rear wheels need to be removed without having to derail the chain, the fork end is called dropout and can be of different types. The derailleur hanger that is the part of the dropout where the derailleur is attached and in some bikes it can be removable. This is because in case of accident it can deform and brake instead of the frame or the derailleur itself. This is usually used in non steel-framed bikes. In fact, steel frames don't need a removable derailleur hanger, because a steel dropout usually is stronger and less likely to be damaged.

For the gravel bike a removable derailleur hanger has been necessary. It can host a through stud of 142 mm length and 12 mm of width.

Figure II.3: Dropout derailleur hanger

II.3.4 Break caliper holder

The disc of the bicycle is a disc brake of 160 mm. The brake caliper needs to be fixed on the frame: in this case a screw of 38 mm is sufficient.

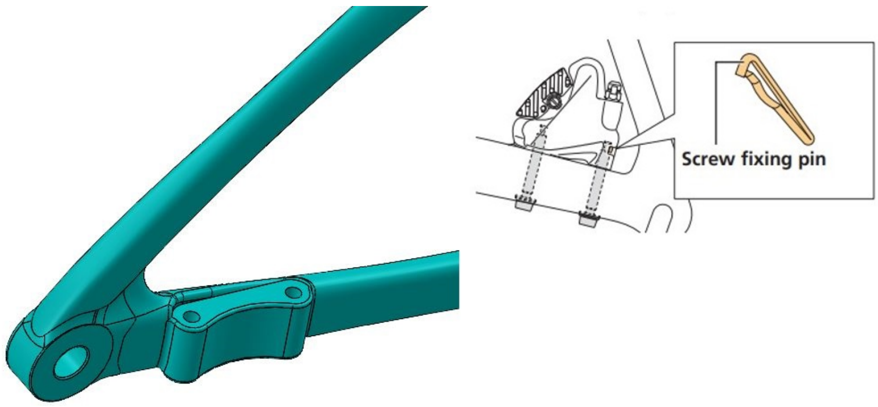


Figure II.4: Break caliper holder

II.4 Final result

The gravel bicycle frame design has been performed with Solidworks. After having defined the theoretical geometry as explained in the previous sections, the first elements that have been drawn are the seat tube and the top tube. All of the tube sections have been made using the *Loft* function of Solidworks. The head-tube has been chosen to have a tapered headset in the inside and was therefore drawn in order to host it. it followed the down tube, connecting the head-tube to the bottom bracket.

The final part that has been drawn has been the rear stay and its details, comprehending the following:

- rear dropout attachment
- brake caliper holder connection
- holes for cables passages

In the end all the necessary fillets have been set on the frame. There was a limit ratio of 2 mm given by the molding technology later used for the production.

Figure II.1: Drawing evolution of the gravel bicycle's frame

Some figures of the final result can be seen with a graphic simulating the hemp fiber which will be later used to make the frame:

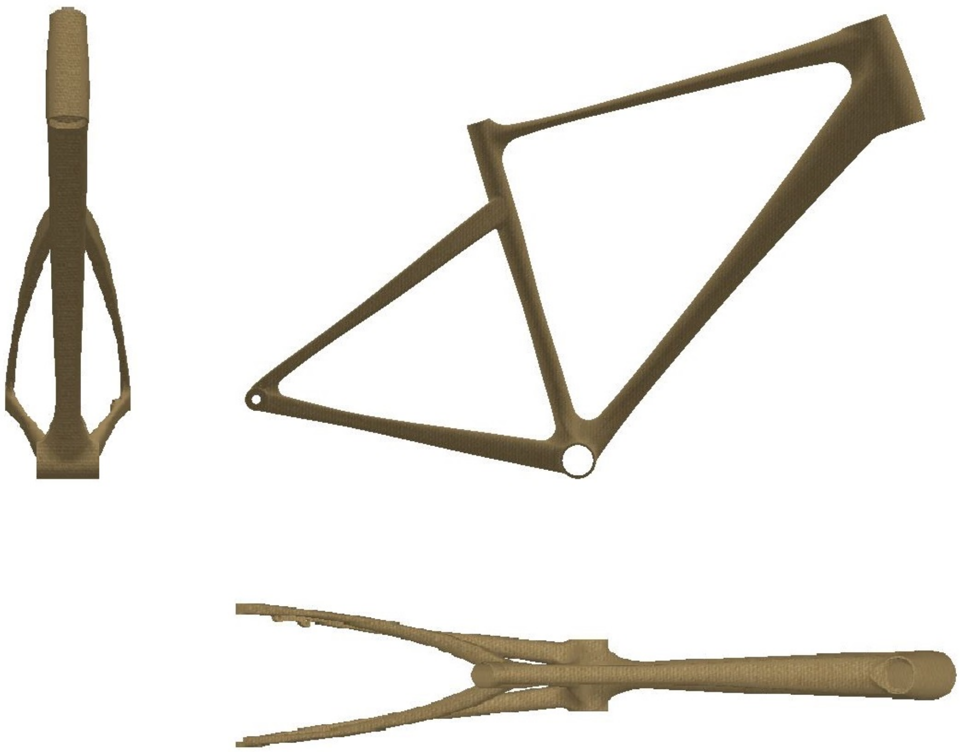


Figure II.2: Final result of natural fiber frame: frontal, lateral and upper view

Figure II.3: Natural fiber frame

Part III
Model

In order to solve an elastic 3D problem on a component it is necessary to create the proper model that can correctly be analysed by softwares. That usually consists in *meshing* the component through different software, such as, for example, Hypermesh from Altair One. To understand some of the theory behind it the following can be useful.

In the continuum mechanics it is required to solve a differential equation system that takes into account:

- component equilibrium equations
- compatibility equations
- material constitutive laws

The solutions to these laws can be given either with finite difference wither with finite element method.

Given a physical problem described by partial derivatives differential equations, a numerical solution is given in integral form on a finite domain.

The typical approach used for this kind of problem is the following:

- obtaining a functional equation starting from the physical problem
- properly discretize the domain through an approximation function
- obtain the final problem in a matrix form

The choice of the functional equation derives from an initial balance of the energy in the system: the virtual work principle puts together external and internal work. Once applied some forces, there will be stresses related to displacements. Taking into account the contribution of the superficial forces and works applied on an element the following can be evaluated [17] :

$$\int \{\delta\varepsilon\}^T \{\sigma\} \, dV = \int \{\delta u\}^T \{\Phi\} \, dV + \int \{\delta u\}^T \{t\} \, dA$$

Where:
$\varepsilon = strain$
$\sigma = stress$
$u = displacement$
$\Phi = volumeloads$, applied to the center of gravity
$t = normal$ and tangential superficial stresses

Now it is necessary to interpolate the functional through some functions called *shape functions*. Usually, they are polynomials with unknown coefficients. The choice of this function follows physical properties and the polynomial choice depends on the nodes. The evaluation of its coefficients depends on geometric conditions of the nodes/dofs chosen to describe the element [17] .

$$\{u\} = [n] \{s\}$$

Where:
$u = displacement$ of generic point P of the element

n = *shape* function
s = *displacement* of the nodes

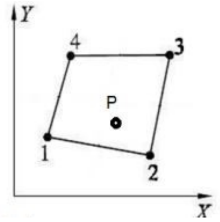


Figure III.1: Element scheme [17]

Stresses and strains will be correlated to displacements and, therefore, to the shape function as well.

A different choice on the type of element will change the interpolation of the shape function:

- the higher the number of nodes is the more precise the solution will be (it will have a higher computational cost, though)
- there will be a different polynomial grade of the approximation

An important aspect is also that, since we assign a displacement field, equilibrium will not be satisfied at each point, but there will be a residual stress due to the approximations we are dealing with:

$$\sum \frac{\delta \sigma_{ij}}{\delta x_i} + \Phi_j = \varrho_j$$

The theoretical solution of the problem will converge to the exact solution when the number of dofs will be infinite, bringing the residual ϱ_j to be 0.

The shape function must satisfy three main properties:

1. be a continuous function
2. represent the rigid motion (zero energy)
3. represent a constant strain rate

When meshing there will be an elementary stiffness matrix associated to the triangular element; summing all of the elements up it will be possible to calculate a system stiffness matrix.

In order to ameliorate the discretization, it is possible to augment the polynomial degree or to increase the number of elements.

If we are dealing with a plane shell, there might be different choices in the element's nodes [17]:

- 3 nodes element (PLANE 42)*: it will have 6 boundary conditions, a 1st degree polynomial function and it will have constant strains through the whole element. This last factor makes the element more rigid than in reality and it therefore needs some attention.
- 4 nodes element (PLANE 42): it will have 8 conditions, a 2nd degree polynomial and a 1st degree of strain. Still it might not be great to describe stresses gradients and concentrations: in fact, ε_{xx} varies only along the y direction, while ε_{yy} varies only along the x direction.

- 8 nodes element (PLANE 82): it will have 16 conditions and a 3rd degree polynomial. It has 2nd degree strains and it very good describing gradients and concentrations.

Depending on the element discretization chosen there will be effects on the stresses residual and it can be seen that the error on the overall elements mesh convergence will be higher at a lower number of nodes:

Number of elements	PRERR%		
	3 NODES	4 NODES	8 NODES
5	64	66	12
20	63	46	10
80	51	28	9
320	32	16	8
1280	18	10	8

Table III.1: Error on the mesh convergence depending on the number of elements [17]

Another approximation error that can be given by the finite elements model can be the element *distortion*: this happens when the realistic model doesn't adjust to the shape of the elements. This concept is related to the Jacobian matrix, which can be defined as:

$$[J] = \begin{bmatrix} \frac{\delta x}{\delta \xi} & \frac{\delta y}{\delta \xi} \\ \frac{\delta x}{\delta \eta} & \frac{\delta y}{\delta \eta} \end{bmatrix}$$

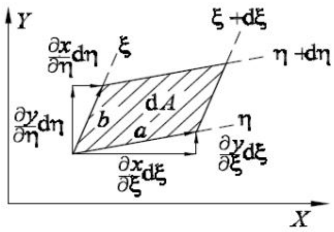


Figure III.2: Element scheme [17]

The determinant of the Jacobian needs to be different from zero. Empirically, it means that in critical areas the elements must be as much as possible square-shaped. In Hypermesh some of the mesh checks will be related to the Jacobian.

It is possible to see that the square shape guarantees a good convergence of the approximation, a low distorsion and has a lower stiffness than triangular elements, representing the reality more truthfully. The best would be using a 8 nodes element, but this would increase the calculation time.

To evaluate stresses it is important to note that they are not calculated on the nodes (which would seem desirable since their geometrical position is known), but on optimal interior points called Barlow points. It is in fact possible to interpolate stresses and strains over there, being far more accurate than on the nodes.

This theory is common to all CAE software even if each one of them might have different interfaces, pre-processing and post-processing methods. For this thesis Hyperworks and Hypermesh from Altair One have been used.

III.0.1 Meshing the frame

In order to prepare a good mesh it is important to follow different steps on Hypermesh, especially when importing a file from another software.

III.0.1.1 Geometry cleanup

The first passage consists into cleaning and preparing the surfaces that will be then meshed. The imported CAD could have, in fact, complex surfaces and fillets with discontinuities and gaps that could cause some problems to the mesh. The main idea when dealing with surfaces geometry is to simplify and clean up: ***cleanup*** can look for double edges, overlapping or missing surfaces; ***defeature*** can fill holes, take away finishing fillets; ***midsurface*** can take away subtle walls thicknesses and refer to the appropriate middle layer.

III.0.1.2 The mesh

Mesh represents the continuum discretization and its properties determine the quality of the analysis. The meshing structure can depend upon the type of geometrical entity that it has to represent:

- 2D mesh from a surface
- 3D mesh from a volume
- midmesh between two surfaces

The type of 2D elements are good for shells, plates and membranes and can be of different types:

1. Linear Tria CST (Constant Strain Triangle): here the displacement function is $u = a_0 + a_1x + a_2y$. There are 3 nodes and, therefore, 3 terms in the displacement function. Strains ε_{xx} and ε_{yy} are constant, making it a pretty stiff element.
2. Linear Quad 4: the displacement function is $u = a_0 + a_1x + a_2y + a_3xy$. One additional term compared to Tria makes it more accurate.
3. Parabolic Quad 8: the displacement function is $u = a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 + a_6x^2y + a_7xy^2$. This is the most accurate element.

3D elements can have a tetra, penta, hex or pyramid shape and are good describing solid elements.

The bicycle frame has been treated as a shell and it is therefore useful to make the following consideration on these kind of elements and the empirical rules to properly deal with them.

a) Pure quad elements; b) mixed elements; c) pure tria elements; d)R-tria

It is better to avoid irregular transitions and these could easily be caused by tria elements, that need in fact to be kept under the 5%. Usually a mixed or squared mesh is used.

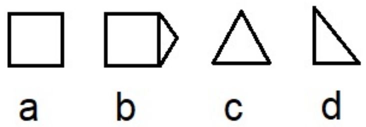


Figure III.3: 2D meshing options

In meshing it can be important to avoid having connecting trias, avoid trias on planar surfaces, avoid trias on edges or on holes. Smoothing also helps the nodes to align and have a regular and good-looking mesh.

For the bicycle frame a mesh size of 3 has been selected and following there is a figure of the meshing of the head-tube.

Figure III.4: Bicycle frame's mesh example

Usual mesh checks comprehend the maximum and minimum element's length, the aspect ratio (<5), the Jacobian (>0.6) and the overall quality index. In the case of the bicycle frame the failed elements percentage has been reduced to 0.9%, which is a very good value for a component with such complex shapes.

The following is the final result:

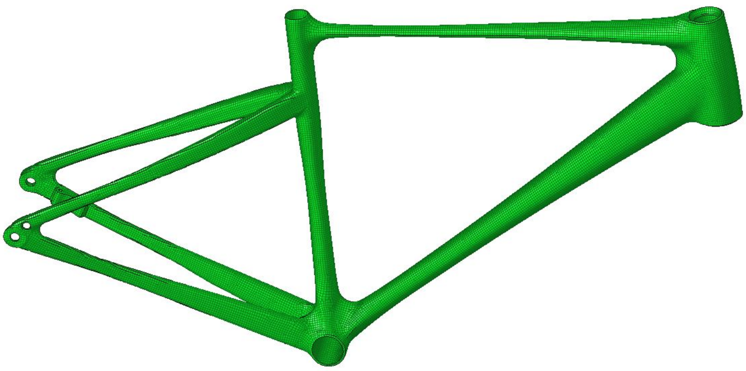


Figure III.5: Frame meshed with Hypermesh 2022

Part IV
Materials

The frame materials experienced many changes through the years: after a quick start with wood, steel soon became the main character of the frame industry until the nineties, showing a great fatigue resistance and resilience. It has been in the nineties that the aluminum boom brought many changes in the bicycle's industry, introducing also mountain bikes to the cycling world. Aluminum substituted steel because by increasing the frame pipe's section, and therefore making the bike more stable, it was possible to obtain an equally stiff frame, but lighter. In this way even production costs could be maintained low. Modern aluminum frames weight about 1 kg, are very stiff and reactive and can be seen as a cheap alternative to carbon fiber frames. The main issue of aluminum is comfort and minor fatigue resistance.

Titanium as well is a very interesting material to be used for a bicycle's frame: it has a very good stiffness and vibrations absorption ability, and, differently from steel, it can't oxidate. The complex welding of this material though makes its price very high and not affordable by average users.

Nowadays, anyway, thanks to the technological progress and research on composites, carbon fiber represents the more used material by frame manufacturers for what concerns medium-high frame range. Carbon fiber allows to reduce weight by making coexist stiffness and comfort, also by permitting freedom in the design and versatility in the industry.

The need for a sustainable mobility recently made way also to natural fibers into the studies around the frames.

IV.1 Composites

Composites are experiencing a widespread interest for their unique properties and potential. By properly merging completely different materials is in fact possible to obtain a new hybrid composite with high strength to weight ratio, ease of fabrication and freedom of design that makes it very attractive for the aerospace and automotive industry. Usually, a composite material is made by two constituents: a *fiber* that is characterized by strength and stiffness, surrounded by a *matrix* of a softer and more compliant material. There are many type of fibers, but their nature is to withstand stresses better along the longitudinal direction, making the material anisotropic. In fact, depending on the direction on which the load is applied their properties strongly differ. The matrix material, instead, can be polymeric, metallic or ceramic, although the most part of composites is made of thermosets (resins).

The characterization of their properties can be quite complicated, especially because sometimes the presence of the fiber modifies the crystallographic texture of the matrix itself or introduces internal stresses that need to be taken into account. Every combination of different matrices and fibers results on different final properties, depending also on the percentage of the two different constituents and the geometry of the fiber. Therefore a deep study of the micro-mechanics of these materials is necessary in order to represent the composite through an equivalent homogeneous material, estimating its main physical parameters and characteristics. The singularity of such materials is also the fact that the designer has to design not only the component and its dimensions, but also the material itself.

IV.1.1 The fiber

Fibers represent the matrix reinforcement and they bear the strain and stresses, representing the structural component of the composite. In fact, they act as a barrier to dislocation movements and crack's propagation. They can be long and continuous, used as a fabric, or short, used in injection molding processes. Usually, it is possible to obtain light fibers from elements with low atomic number, such as carbon, azote, oxygen, beryllium, borum and silicium. It is often desirable to have a high percentage of volume of fiber: realistic values are obtained occupying 60 -70% of the total volume (more would make the fiber get in contact, which would cause some problems related to stresses).

The material obtains a certain behavior depending on the spatial disposition and dimension of the fibers. In general, it is possible to state the following:

- every fiber strengthens along with its size and bears higher loads axially

- a major density and order of the fibers allows to distribute the loads and lower the weak and void points: realistic values are obtained occupying the 60-70% of the total volume (more would make the fiber get in contact, which would cause some problems related to stresses).

- it is possible to balance the composite properties by setting the proper directions and orientations to the fibers.

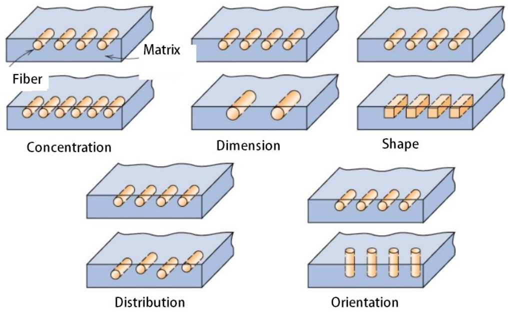


Figure IV.1: Fiber characteristics

Long fibers can then be assembled in different ways that affect the mechanical properties, the ability to adapt to a shape and porosity of the material:

- Unidirectional: all the fibers are lay down along a single direction, leading the material to be anisothropic. It is possible to demonstrate that the unidirectional fiber guarantees better mechanical performances that a isotropic material: the ideal would be having a 1D fiber for each one of the possible directions of the stresses. To reach this target fiber fabrics were created in order to have a material that can bear stresses along different directions (as in bidirectional fiber). Unidirectional fiber is often used to optimize the reinforcement of a component right where it is necessary.

- Bidirectional: the fibers cross themselves along two main directions (they can form plain, twill and satin fabrics). The flexibility of this type of fiber assembly allows draping and shaping to occur, facilitating use in non-planar structures. These characteristics will be affected by the directions between the warp and the weft. The cons of this solution is the difficulty to have a high fiber content and therefore makes this starting material not proper for demanding applications, even if easy to handle and process.

- Tridimensional: the fibers cross along three directions.

For what concerns bidirectional fibers there are three main kinds of woven fabrics:

1. *Plain*: here each warp fiber alternates up and down over every weft fiber. The fabric is stable and symmetrical and, generically, is more difficult to drape than other weaves. Mechanically it doesn't have the best characteristics, because of the high number of creases of the fiber.

2. *Satin*: there is a major number of weft fibers is crossed by the warp (typically 4, 5 and 8) before the fiber repeats the pattern. Satin weaves are very flat, have good wet out and a high degree of drape. The low crimp gives good mechanical properties. Satin weaves allow fibers to be woven in the closest proximity and can produce fabrics with a close 'tight' weave. However, the style's low stability and asymmetry needs to be considered.

3. *Twill*: the warp fibers alternately weave over and over two or more weft fibers in a regular manner. It ends up being easier to handle and drape than the plain one, maintaining a good stability of the fabric. It has good mechanical characteristics and a smoother surface.

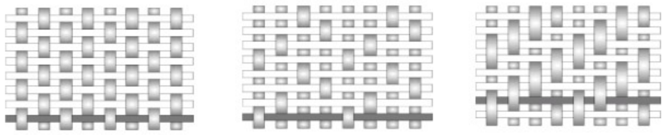


Figure IV.2: Plain, satin and twill woven fabrics

As shown, the fiber can be weaved in different ways, creating a single layer called *lamina* that constitutes the basic building block for composite structures. By superposing then more laminae in different directions it is possible to obtain a *laminate* with increased structural properties. This will allow to have more homogeneous properties than the ones of the single lamina.

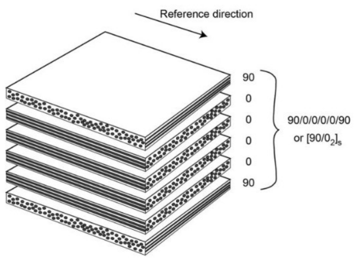


Figure IV.3: Example of laminate

The choice of the fiber affects therefore the mechanical behavior of the component under many aspects, as density, fatigue resistance, electrical conductivity, thermal expansion coefficient and, also, costs.

They can be produced in a wide range of different materials, usually with particularly high tensile strength and the main ones are the following:

- glass fiber: it has been one of the first high performance material that has a high ultimate tensile strength, superior to the most part of metals. It has great insulating capability and a very low coefficient of thermal expansion and is used in the naval, aerospace and automotive industry.

- carbon fiber: its atomic structure is similar to that of graphite, with planar hexagonal aggregates of carbon atoms. It represents the best combination between high resistance and module, but it has a low extension ability.

- aramid fiber: they are usually known with their commercial name, as Kevlar, twaron or nomex. They have a crystal structure and they have an excellent toughness. they don't experience a brittle failure as carbon fibers, but they brake in little fibrils oriented in the same direction of the fiber. These little fractures absorb a great amount of energy and are therefore used for bulletproof vests and protection devices.

The reinforcement cost rises as the dimension of the bundles to prepare the fabric diminishes:

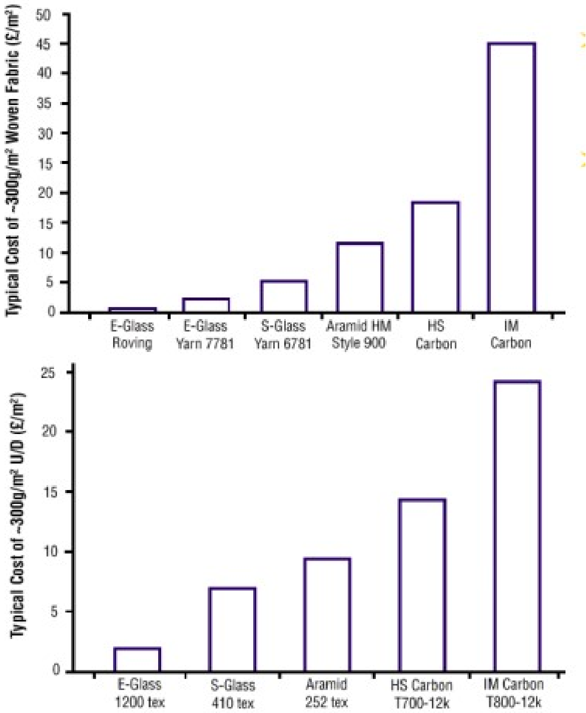


Figure IV.4: Cost comparison between reinforcement fibers

IV.1.2 The matrix

The ideal matrix is a material with low viscosity that can be transformed in a resistant solid, solidly anchored to the reinforcement fiber.

The characteristics required to a matrix are the following:

- good traction resistance
- high elastic modulus
- shear stress resistance
- fracture and impact resistance
- thermal degrade resistance
- low specific weight

The typical matrices found in composites are of these kinds:

1. Polymeric matrices: there are two main materials that can make the polymeric matrices. One is thermoplastic resins: they are made of linear polymers that lose stiffness when heated but then harden again at environment temperature. This means they can be

reshaped a lot of times. They have a major rupture elongation than the other ones and get used for short fibers: therefore their resistance is usually lower than the therm-hardening resin. The second type of polymeric matrix is therm-hardening resins: they irreversibly polymerize after the reaction with a proper chemical agent. Therefore, they can't be remodeled more than one time and can't be recycled. Mechanically, they properly combine with reinforcements and have a good resistance, making them more apt to structural applications than thermoplastic ones, even though they have a lower toughness.

2. Metal matrices: the main metals used are aluminum, magnesium and titanium, but often they are alloyed with other elements to enhance their mechanical properties. These materials are ductile and often isotropic. Unlike polymeric matrices their stiffness with the reinforced material doesn't increase exponentially, but the improvements are about creep performance and wear characteristics. The main difficulty in using this kind of matrix is in their fabrication, but they find their place nowadays especially in the aerospace sector.

3. Ceramic matrices: the target of adding reinforcement to ceramics, often, is to improve their toughness. This happens by adding to the matrix particles of fiber or other compounds. The reinforcement needs to activate energy dissipation mechanisms to let it linearly deform even after the maximum load, without letting it have a brittle failure. The composites with this kind of matrix are good insulating materials and are good both for high performance applications both for electrical ones.

IV.1.3 Properties

The final properties of the composite depend on the different characteristics of the constituents. In order to evaluate the behavior of a composite component it's important to understand its properties along the different directions under different loads applied. The designer dealing with composite has the freedom to «adjust» its characteristics and variables in order to achieve a certain target, but he also needs to pay attention to unexpected results that may occur.

Starting with density, it can be evaluated as the weighted average of the volume of the fiber and matrices separated:

$$\rho_{composite} = V_{matrix}\rho_{matrix} + V_{fibre}\rho_{fibre}$$

This density though is only the theoretical one and might differ from the experimental one because of the voids present into the structure, caused by the air trapped in the matrix during the composite formation process. The void's percentage affects the mechanical characteristics of the composite: in general, the mechanical properties lower as the voids augment. In fact, in a good composite, the void's volume needs to be minor than 1%.

For sure, one of the main point of attention of composite materials is their anisothropic behavior and how to deal with it:

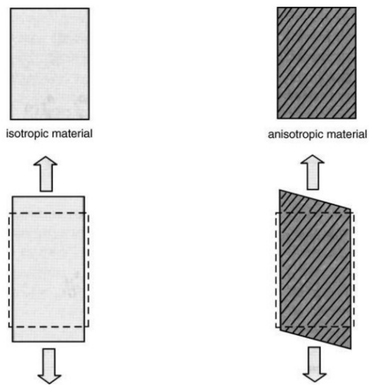


Figure IV.5: Isotropic vs anisothropic material deformation

For a *isotropic* material, there can be found three main elastic constants: E, G and ν, where:

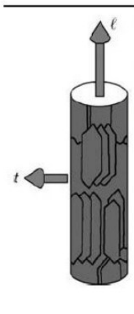
- E: represents the longitudinal elastic modulus (Young Modulus), defined by the Hooke law
- G: represents the shear modulus, given by $G = \frac{\tau}{\gamma}$
- ν: represents the Poisson coefficient and accounts for, given the longitudinal elongation of a material, its transversal shrink or elongation.

Looking at a composite, its matrix is usually an isotropic material, and so are its fibers. But when combined the composite becomes a *orthotropic material* (it has a different behavior depending on the different directions).

For *anisothropic* materials the deformation matrix becomes [21]:

$$\left\{ \begin{array}{c} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{array} \right\} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \left\{ \begin{array}{c} \sigma_x \\ \sigma_y \\ \sigma_z \end{array} \right\}$$

Here it can be seen that the matrix is still symmetrical, but there are five elastic constants: two elastic modulus ($E_x$and E_y), two Poisson coefficients and one shear modulus G_{xy}. It is therefore more difficult to characterize the material and there is need to know more information.



	Glass E	Kevlar	Carbon H.R.	Carbon H.M.
fiber longitudinal modulus in ℓ direction Ef_ℓ (MPa)	74,000	130,000	230,000	390,000
fiber transverse modulus in t direction Ef_t (MPa)	74,000	5400	15,000	6000
fiber shear modulus $Gf_{\ell t}$ (Mpa)	30,000	12,000	50,000	20,000
fiber Poisson ratio $vf_{\ell t}$	0.25	0.4	0.3	0.35
	Isotropic	Anisotropic		

Figure IV.6: Elastic modules comparison [21]

For what concerns stiffness, some considerations can be done: the stiffness of the composite along the fiber direction is similar to the one of the fiber, while along the transversal direction to the one of the matrix.

The directions along and perpendicular to the fiber are defined as *principal axes* of the material.

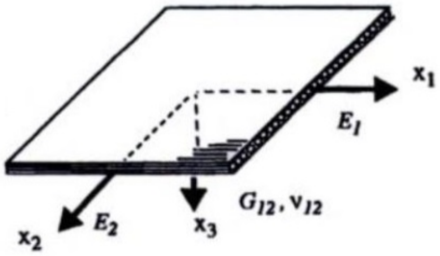


Figure IV.7: Orthotropic material properties

Some of these coefficients can be evaluated by considering the composite constituents, while others need to be measured. For example, it is possible to show that the maximum longitudinal and transversal stiffness are achieved in the case of maximum fiber volume fraction. In this case the specific stiffness along the fibrosis direction is about the 84% of the one of the fibers, while the stiffness along the transversal direction is more than 3.3 times that of the matrix material.

For what concerns the major Poisson ratio ν_{12}, it is defined as the ratio between the deformations along the two main directions (under loads acting only along the direction 1):

$$\nu_{12} = -\frac{\varepsilon_1}{\varepsilon_2}$$

The minor Poisson ratio, instead, can be written as

$$\nu_{21} = -\frac{\varepsilon_2}{\varepsilon_1}$$

These values are related to the other elastic properties through the reciprocity relations:

$$\nu_{21} = \frac{E_2}{E_1}\nu_{12}$$

A usual value for carbon fiber composites is a $\nu_{12} = 0.26$.

When evaluating stresses on a laminate it's then necessary to compare them to the material strengths in order to obtain a factor of safety. A laminate has different characteristics depending on the direction and, experimentally, it is possible to define the values of strength as follows:

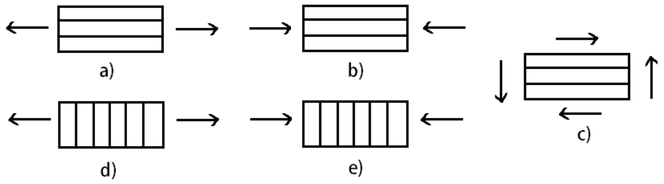


Figure IV.8: Stress cases

Case a): Axial tension (X_T= tensile strength)

$$\sigma_1 = X_T$$

Case b): Axial compression

$$\sigma_1 = X_C$$

Case c): Torsion test (S = in plane shear stress)

$$\tau_{12} = S$$

Case d): Transversal tension

$$\sigma_2 = Y_T$$

Case e): Transversal compression

$$\sigma_2 = Y_C$$

In order to evaluate the behavior of a composite component it's important to understand its properties along the different directions under different loads applied. The designer dealing with composite has the freedom to «adjust» its characteristics and variables in order to achieve a certain target, but he also needs to pay attention to unexpected results that may occur.

IV.1.4 Composite failure criteria

Seen the complexity of dealing with anisothropic materials such as composites, it can be difficult to build a proper failure criterion to predict the occurrence of fiber braking, resin cracking or fiber buckling.

For isotropic materials the Tresca and Von Mises criteria are sufficient to predict the behavior of a certain component, assuming failure if any of the stress components reach the strengths associated with that component, but those can't properly deal with composites. For some applications, in fact, it can also occur that the failure of a single layer may not result in the ultimate failure of the laminate.

Through the years one of the theories the is mostly used nowadays to predict the composite failure is the *Tsai-Wu criterion*. This theory aims to predict the first ply failure and to compare laminate design. It can also be useful to deal with yielding of isotropic materials. It must be said, though, that physical testing remains one of the best ways to check the behavior of a composite-made component.

The Tsai - Wu criterion says there is failure when [8]:

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j = 1$$

with $i, j = 1, 2, ...6$

where F_i and F_{ij} are strength tensors, respectively, of the second and forth order.

For a plain stress case the equation can be written as follows:

$$F_1\sigma_1+F_2\sigma_2+F_6\sigma_6+F_{11}\sigma_1^2+F_{12}\sigma_1\sigma_2+F_{16}\sigma_1\sigma_6+F_{21}\sigma_2\sigma_1+F_{22}\sigma_2^2+F_{26}\sigma_2\sigma_6+F_{61}\sigma_6\sigma_1+F_{62}\sigma_6\sigma_2+F_{66}\sigma_6^2 = 1$$

where $\sigma_6 = \tau_{12}$ and $F_{ij} = F_{ji}$

Some of the terms can be calculated by analyzing tension, compression and shear cases:

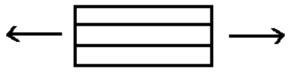


Figure IV.9: Tensile stress

At failure $\sigma_1 = X_T$, $\sigma_2 = \tau_{12} = 0$

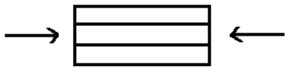


Figure IV.10: Compression stress

At failure $\sigma_1 = X_C$, $\sigma_2 = \tau_{12} = 0$
Inserting these in Tsai - Wu:
$F_1 X_T + F_{11} X_T^2 = 1$
$F_1 X_C + F_{11} X_C^2 = 1$
By solving simultaneously it is possible to find:

$$F_{11} = -\frac{1}{X_T X_C}$$

$$F_1 = \frac{1}{X_T} + \frac{1}{X_C}$$

Similarly, in the transverse direction:

$$F_{22} = -\frac{1}{Y_T Y_C}$$

$$F_2 = \frac{1}{Y_T} + \frac{1}{Y_C}$$

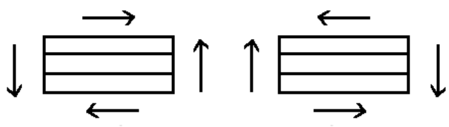


Figure IV.11: Shear stress

For the two cases above, at failure $\sigma_1 = \sigma_2 = 0$ and τ_{12} is respectively $\tau_{12} = S$ and $\tau_{12} = -S$
Inserting into Tsai - Wu:
$F_6 S + F_{66} S^2 = 1$
$F_6(-S) + F_{66}(-S^2) = 1$
By solving simultaneously it is possible to find:

$$F_{66} = \frac{1}{S^2}$$

$$F_6 = 0$$

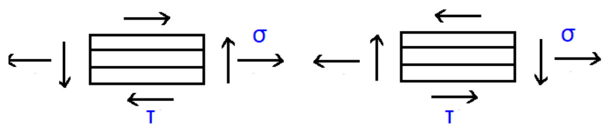


Figure IV.12: Shear and normal stress

At failure $\sigma_1 = \sigma^*$, $\sigma_2 = 0$ and τ_{12} is respectively $\tau_{12} = \tau^*$ and $\tau_{12} = -\tau^*$
By inserting them in the Tsai - Wu criterion it is possible to evaluate:

$$F_{16} = 0$$

$$F_{26} = 0$$

The term $F_{12}$is instead difficult to solve experimentally, but it hasn't much effect on the final result.

Therefore, the final formulation of a in plane stress states that failure happens when:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 - F_{11}\sigma_1\sigma_2 = 1$$

where:

$$F_{11} = -\frac{1}{X_T X_C}$$

$$F_1 = \frac{1}{X_T} + \frac{1}{X_C}$$

$$F_{22} = -\frac{1}{Y_T Y_C}$$

$$F_2 = \frac{1}{Y_T} + \frac{1}{Y_C}$$

$$F_{66} = \frac{1}{S^2}$$

Later, an extension of the theorem introduced progressive failure analysis, that was not considered yet. Tsai and a scientist called Liu defined the strength ratio R as the linear scaling factor for the loading vector (ex: $\frac{X_T}{\sigma}$or $\frac{-|X_C|}{\sigma}$) [8]. Failure occurs if $R = 1$. The *composite failure index* is defined as the inverse of R and it therefore needs to be minor than 1. It represents the linear scaling factors for each separate stress component ij. What often is argued is that the Tsai-Wu criterion doesn't discriminate between different failure modes, but in literature there are modified definitions of the failure indexes that can predict which one of the stresses is responsible for the failure.

IV.1.4.1 Interlaminar shear strength

Another important aspect to evaluate the failure of a composite is to study its propensity to delamination. This phenomenom is the failure at the interface between different layers and is one of the most common and critical failures of laminates.

The parameter that characterizes the resistance against delamination is interlaminar shear strength (ILSS). It is measured experimentally, even though there is a lot of research upon the methods to estimate it and predict the behavior of such complex materials. It can be seen that all numerical ILSS results are higher than the experimental results. After the first delamination, the stress transfers from the outer to the inner region and leads to higher shear stresses at the ultimate load level. It is always better to use the lower bound of the ILSS to be more cautionary.

IV.2 Carbon fiber

Carbon fibers are made by a polymer of carbon atoms in graphitic shape: carbon hexagons linked one to the other. Nowadays is one of the most used composite for applications that require a high strength-to-weight ratio, despite its pretty high cost. The fiber filaments are extruded and woven into different shaped fabrics; every fabric will be impregnated into epoxy resins and laid down layer by layer to create the laminate that will constitute the final component.

The atomic links between carbon atoms on a same plane are covalent and make the elastic modulus higher on it. On the contrary, the links in between the planes are weaker and therefore with lower elastic modulus. These fibers are obtained by compounds derived from carbon and petroleum, extruded both in long both in short filaments. Their diameter is very small, in between 5 and 15µm.

Once bundles of filaments are created they can be soaked into the matrix either before either during the creation of a component: if they're already imbued in the matrix they are called *prepreg*; in this process the fibers are homogeneously impregnated and form a fabric that is easy to shape and model around the mold. In order to avoid the hardening of the resin, pre-pregs are stored at low temperature. This method allows to use the right amount of resin, lowering the weight of the final component, while keeping the mechanical properties high.

For what concerns the matrix, it is common use to utilize the polymeric ones, especially the therm-hardening ones. There are two main types of resins used for carbon fiber: epoxy and polyester. Epoxy needs to be prepared in a very precise way, looking at milligrams when mixing it with the catalyst. Its mechanical properties are very good and they can be used both on coarse both on smooth surfaces.

Polyester needs less precision into the mixture and is very good to be used with glass fibers thanks to its high permeation properties. After its hardening it resists well to elements and sea water. Its price is much lower than epoxy.

IV.2.1 Overview on carbon lamination

There are different ways to properly impregnate the fibers into the matrix, but the important aspect in all of them is to grant a good cohesion between the fibers and minimize the amount of resin needed. What's also common to all the different methods is to superpose manually layer by layer of carbon fabric and let it reticulate to create a final composite without the less amount of voids possible.

The original way of laminate carbon was *manual lamination*. Its is used nowadays for very big components and for sure it is not suitable for mass production. In manual lamination the layers of carbon fiber are superposed over a mold one by one, applying for each ply the resin with a manual roller. The resin hardens at environmental temperature and pressure and it sometimes needs a catalyst to speed the process up. The main issue that can arise is the final presence of air bubbles that weren't properly expelled with the roller.

Figure IV.1: Manual lamination made by Team Policumbent

If higher mechanical properties are needed the *autoclave lamination* enhances the composite's performance. Autoclave looks like a big tank where the mold gets inserted after the lamination and can control through valves and heaters both pressure both temperature. In this process prepreg fabrics are used, they are laid on the molds and wrapped with a nylon bag where later a vacuum is created. The autoclave system applies a certain pressure and temperature and presses together the different laminates pushing out the resin excess. The resin reticulates in a proper way and the final result is both mechanically solid both aesthetically satisfying.

Figure IV.2: Autoclave lamination made by Team Policumbent

When instead there are molds made of two separate external parts *resin transfer molding* is used [16]. In this case the fabrics is laid on one side of the mold (that has been previously heated up), starting to reticulate. After the mold gets closed the resin is injected and polymerizes. This method presents a good automation level. Sometimes, if a polyester resin is used, it is necessary to substitute one half of the mold with a nylon bag to avoid emissions into the environment: this is called *resin infusion* [16]. The use of the bag allows flexibility in the shape and lowering of costs. Here the resin enters the bag through some tubing and permeates the fabrics homogeneously.

Figure IV.3: Resin infusion of Team Policumbent's wheel-covers

For what concerns the lamination itself, it is important to define prior to the layer application a *ply-book* that describes one by one the passages to superpose the plies in the way established by the designer. The direction of the layer's fiber and the sequence of the different plies will strongly influence the final mechanical properties of the component. In order to do it, usually, a principal fiber direction is identified and a code is written to give directions over the laminate's orientation sequence.

A good adhesion of the laminates depends on the prepreg characteristics and the drapeability of the fabric. A temperature rise helps to augment it and is therefore used by laminators to heat up the laminates after they are applied. The final vacuum helps adhesion as well, eliminating air bubbles and squeezing together all the different layers.

A good lamination process represents one of the essential points to avoid delamination and fibers' rupture.

IV.2.2 Nanotubes additivated

Thanks to the flexibility to build different composites, it is possible to add multi-walled carbon nanotubes to the epoxy matrix of a carbon fiber composite. These particles can enhance the damping performance and impact resistance of the composite. Most of carbon fiber reinforced composites suffer a poor capability to sustain out-of-plane loads and it would be therefore desirable to enrich the fiber-matrix interface, enhancing its properties. The reason why carbon nanotubes are used as a matrix filler is its extraordinary mechanical, electrical and thermal properties. There are different ways to insert carbon nanotubes into the composite, but the most efficient is to blend it into the matrix: this will bring into an increase in the interlaminar shear strenght. Also, by incorporating nanotubes into the matrix the frictional sliding at the interface of filler-matrix augments and dissipates more energy, improving significantly the composite's damping performance.

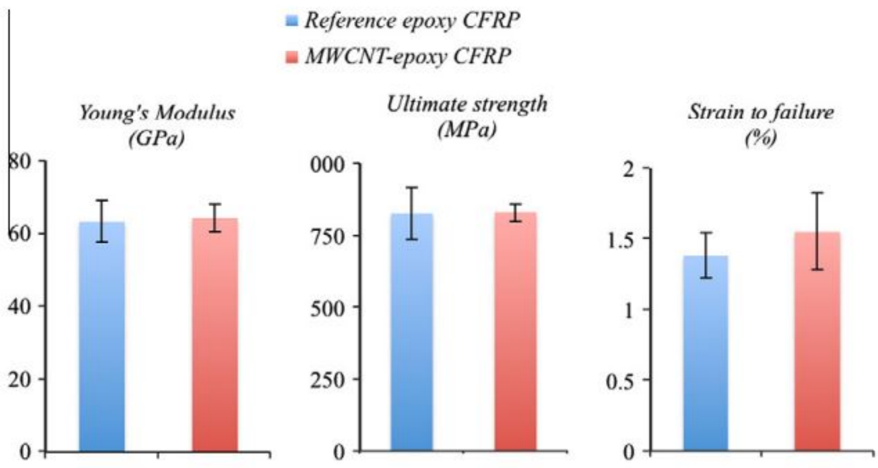


Figure IV.4: Tensile properties for composite systems: without and with carbon nanotubes [20]

The carbon nanotubes act as barriers that stop dislocations and cracks to propagate into the matrix and therefore the material can carry loads even after the crack was initiated. The fiber keeps being the main character that dominates the tensile modulus and strength properties of the composite, while the matrix reliefs stresses and enhances the strain-to-failure.

The tensile modulus and strength of the CFRPs are dominated by their fiber phase properties and hence the improvements in the stiffness and strength of the matrix slightly affect the overall tensile properties.

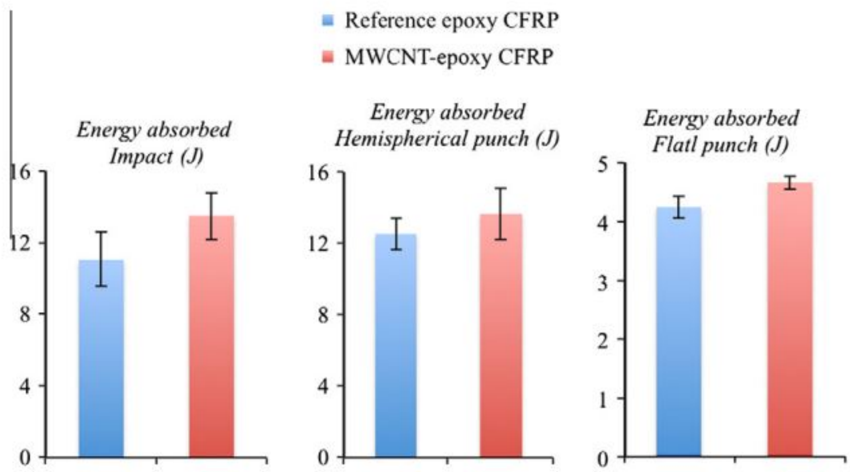


Figure IV.5: Dissipation properties of composite systems: without and with carbon nanotubes [20]

IV.2.3 Nano-lite

NANO-LITE N125L is a nano-engineered toughened epoxy prepreg developed to improve mechanical performances with a significant decrease of the composite components weight. It is designed for structural applications where an increase in compression strength combined with an additional component lightness is necessary. It processes as easily as conventional prepreg and could be cured from 120°C to 135°C. Typical applications of this system include primary and secondary structural components and sandwich panels for various applications due to its high adhesion to honeycomb and foam cores.

IV.2.3.1 Matrix properties

Measurement	Method	Value
Glass Transition Temperature [°C]	DSC-ASTM D3418	120
Enthalpy Δh [J/g]	DSC-ASTM D3418	226,3
Resin density [g/cm^3]	\	1,18
Tack	\	3

Table IV.1: Matrix properties [13]

Looking at rheology it is possible to study the flow and deformation of matter, describing its response to force, deformation and time.

An interesting aspect is *viscosity*, that describes how fluid components flow from one another. The correlation between the viscosity and temperature of the thermoset resin cure of prepreg systems is important: in order to properly infiltrate the resin in the material during the autoclave process it is necessary to have a good control of the viscosity. It can be observed that at the beginning an increase in temperature leads to a decrease in viscosity due to the destruction of the existing Van der Waals forces, then the curing reaction occurs and the viscosity augments: there is the formation of cross-linked chains.

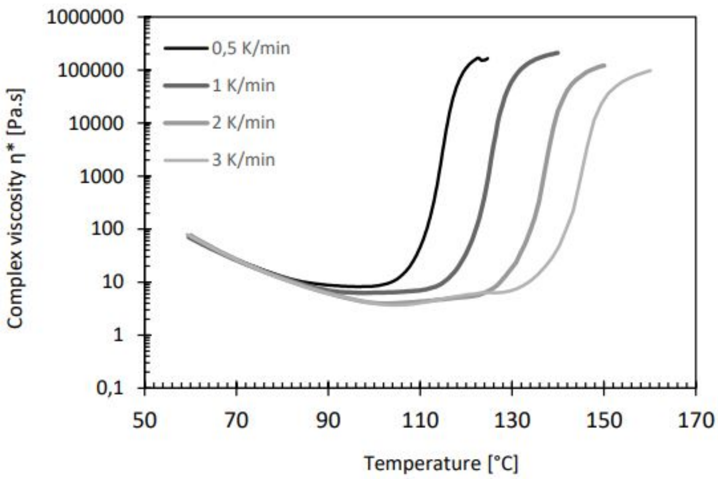


Figure IV.6: Oscillating frequency: 10 rad/s; Shear strain 1% [20]

Another important parameter to take into account is the *gel time* of the epoxy resin: once the resin is mixed with the hardener it will gradually thicken and won't flatten again. This phase is called 'gel phase' and right after the resin will solidify. It is therefore important to check the temperature of the gel time in order to not let the resin cure too quickly.

Temperature [°C]	Gel time [min]
90	160
100	71
110	34
120	17
130	9
140	5,5

Table IV.2: Gel time dependence on different temperatures [20]

The following curing cycle explains the different phases of the resin's curing:

1. Apply full vacuum (1bar)
2. Apply 6 bar gauge autoclave pressure
3. Reduce the vacuum when the autoclave pressure reaches approximately 1 bar gauge
4. Heat at 2-3°C/min to 110°C
5. Hold at 110°C for 20 min
6. Heat at 2-3°C/min to 135°C
7. Hold at 135°C for 60 min
8. Cool at 2-3°C/min to 60°C
9. Cool at 3-5°C/min

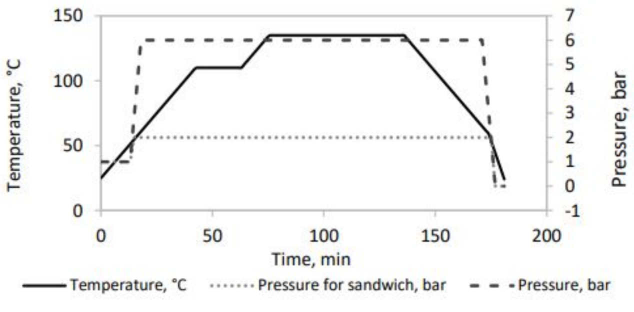


Figure IV.7: Standard curing cycle [20]

Storage modulus is the indication of the ability to store energy elastically and increases with frequency.

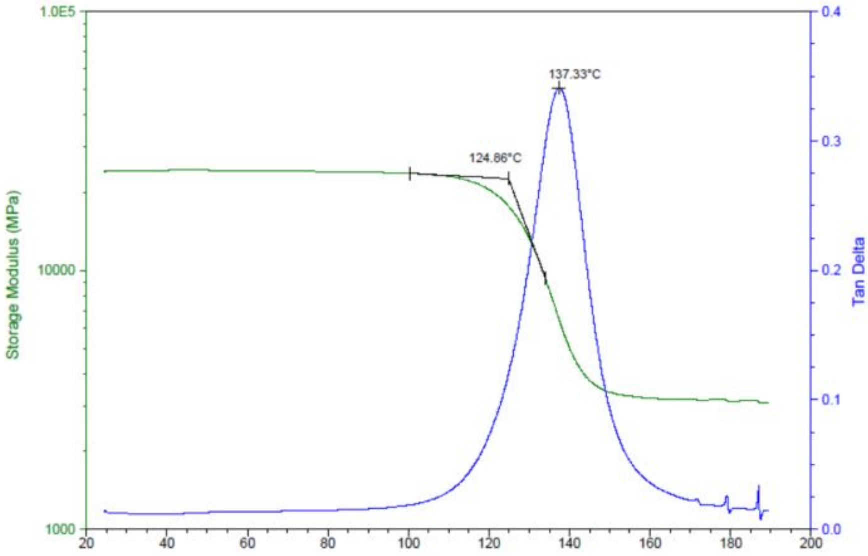


Figure IV.8: Storage modulus [20]

IV.2.3.2 Mechanical properties of the Twill laminate

Tests carried out on a 2x2 Twill 200 g/$m^2$and 400 g/m^2high strength carbon fiber prepreg cured as suggested above.

Physical properties	Unit	CF200T2HS	CF380T2HS
Fiber weave mass	g/m^2	200	400
Nominal cured ply thickness	mm	0,20	0,40
Nominal laminate density	g/cm^3	1,48	1,52
Nominal fibre volume	%	54,8	58,3

Table IV.3: Physical properties of twill laminate, part 1 [20]

Property	Method	Unit	Value CF200T2HS	Value CF380T2HS
Tensile modulus 0° (E_1)	ASTM 3039	GPa	67	70
Tensile modulus 90° (E_2)	ASTM 3039	GPa	67	70
In plane shear modulus (G_{12})	ASTM D3518	GPa	3,8	3,8
Tensile strength 0°	ASTM 3039	MPa	866	855
Tensile strenght 90°	ASTM 3039	MPa	866	830
Compression strenght 0°	ASTM D695	MPa	772	620
Compression strenght 90°	ASTM D695	MPa	772	557
Interlaminar shear strenght	ASTM D2344	MPa	60	70,2

Table IV.4: Physical properties of twill laminate, part 2 [20]

IV.2.3.3 Mechanical properties of the unidirectional laminate

These are the results of tests carried out on unidirectional intermediate modulus carbon fiber cured as suggested in the previous section.

Physical properties	Unit	CF200T2HS
Fiber weave mass	g/m^2	200
Nominal cured ply thickness	mm	0,16
Nominal laminate density	g/cm^3	1,56
Nominal fibre volume	%	61,3

Table IV.5: Physical properties of unidirectional laminate, part 1 [20]

Property	Method	Unit	Value CF200UDIM
Tensile modulus 0° (E_1)	ASTM 3039	GPa	154
Tensile modulus 90° (E_2)	ASTM 3039	GPa	9,2
In plane shear modulus (G_{12})	ASTM D3518	GPa	3,8
Tensile strength 0°	ASTM 3039	MPa	2070
Tensile strenght 90°	ASTM 3039	MPa	40
Compression strenght 0°	ASTM D695	MPa	853
Compression strenght 90°	ASTM D695	MPa	853
Interlaminar shear strenght	ASTM D2344	MPa	89

Table IV.6: Physical properties of unidirectional laminate, part 2 [20]

IV.2.3.4 Storage conditions

NANO - LITE N125L prepreg should be stored as received in a cool dry place or in refrigerator. After removal from refrigerator storage, prepreg should be allowed to reach room temperature before opening the polythene bag, thus preventing condensation.

Storage life [months]	12 months at -18°C
Out life [days]	30 days at RT

Table IV.7: Storage conditions [20]

IV.3 Natural fiber

Composites offer nowadays a broad amount of possibilities to create new materials for different uses. The increasing demand for reducing energy consumption and petroleum consumption is driving research and manufacturing towards renewable and recyclable materials, such as natural fibers. Natural fibre reinforced components are therefore collecting interest among businesses and customers and can represent a good starting point for the path towards sustainability.

The primary advantages of natural fibers is their biodegradability, light weight, relatively low price (especially when compared with carbon) and possibility of good mechanical properties. The barriers that they are facing today, though, are related to their heterogeneous characteristics (such as variation in the cell structure, composition and geometry), defects, hidrophilicity and thermal instability. This last one, for example, makes it necessary to select proper matrices that can be cured below the 200°C [12]. Most natural fiber reinforced composites cured with the three common polymer matrices show a maximum tensile strength that varies in between 20 to 140 MPa and 1 to 10 GPa [12], but there are anyway some methods to enhance their properties lowering the disadvantages.

Before analyzing them, it is possible to have a look at the basic natural fibers that cover the market nowadays, classified depending on the plant species and tissue:

- bast: banana, flax, hemp, jute, ramie, linoleum
- leaf: banana, pineapple, istle, coroa
- seed and fruit: coconut, cotton, rice
- stalk: bamboo, wood, corn

Properties	Carbon fiber composite	Glass fiber composite	Linoleum fiber composite
E_1[GPa]	113.6	44.60	28.75
E_2[GPa]	9.650	17.00	4.310
E_3[GPa]	9.650	16.70	4.290
ν_{12}[−]	0.334	0.262	0.370
ν_{13}[−]	0.328	0.264	0.360
ν_{23}[−]	0.490	0.350	0.480
G_{12}[GPa]	6.000	3.490	2.210
G_{13}[GPa]	6.000	3.770	2.230
G_{23}[GPa]	3.100	3.460	1.490
ρ[kg/m^3]	1,265	1,900	1,100

Figure IV.1: Properties comparison between synthetic and natural fibers [9]

In the Table it can be seen that carbon fiber has the supremacy for its elastic and strength-to-weight ratio properties, but glass fiber and linoleum fiber are instead comparable. Linoleum is lighter and this compensates for the lower Young Modulus compared to glass fiber. This shows how interesting can natural fibers be in some of the applications that nowadays still use synthetic fibers composites.

There are different ways to handle natural fibers that can enhance their mechanical properties. For example, by treating and modifying the fiber it is possible to ameliorate the fiber-matrix adhesion. This can be done by pre-treating the fiber, removing oil, wax, lignin and hemicellulose from it: this will guarantee a major degree of cristallinity, improving the strength and stiffness, and it will augment the surface roughness and surface energy, which will cause a better interlocking between fiber and matrix, having a better compatibility [12]. It is also possible to use surface coating to add an agent that enhances inter-facial bonding and reduces hydrogen bond formation. In general, a good adhesion is related to the crystalline morphology: the trans-crystalline super-structure shows significantly higher inter-facial shear strength than amorphous structure. In the atomic scale, the added agent helps distributing the stress affecting mechanical interlocking [12].

Also, fiber hybridization can be helpful to increase the mechanical properties of the composite. It can happen to mix natural fibers with synthetic ones, leading the composite to increase its mechanical properties even by ten times. A mixture is possible even between different natural fibers, but this will cause only a little improvement in the composite behavior [12].

Nanocellulotic fillers are sometimes used to enhance the properties and reinforcing the materials: they provide a large surface for linking and bonding the matrix. The important is to balance it well, otherwise the risk is to have problems with fibres' aggregation and defect generation[12]. Manufacturing processes have as well an impact on mechanical performances of the fiber, especially molding temperature, pressure and compression time. When talking about natural fibers it is crucial to take care of wetting and fiber dispersion: a major temperature and pressure guarantee a better penetration of the polymer in natural fibers [12].

The sustainability aspect of natural fiber reinforced composites is a central key point of these field of research. It can be shown that energy saving because of the light weight of such composites makes them having a lower environmental impact than glass or carbon fiber. Furthermore, there are different ways to end the life of natural fibers without wasting them, such as land-filling (which sequesters carbon, lowering the greenhouse gasses), incineration (and consequent energy recover) and recycling.

IV.3.1 Hemp

Hemp fiber is one of the strongest and stiffest available in nature.

It is made up of 75% cellulose, 14% hemicellulose, 5% lignin, 1% pectin and 6% of others [17] and it ends up having a remarkable tensile strength (100 - 1040 MPa [10]).

Hemp's mechanical properties strongly depend on the harvesting and cultivation method. Modification of fibers, in fact, can result in a lower strength and Young modulus, even though it can lower water absorption. This is one of the reasons why when harvesting, often, strips are made instead of having single fibers as the basic unit. Retting breaks down pectin and other natural resins that could be structurally useful: separating strips instead of fibers allows to gentler decorticate them without breaking down unretted fibers in the fiber bundles [10].

Also, the period of the year of the harvesting is impacting: autumn frozen stems make it easier to detach the strips (tough) from the shives (brittle), letting then them dry for several days. This is very cheaper than drying the whole stem.

Afterwards, strips are laid into a plywood with adhesive epoxy, reaching a tensile strength typically of 100-200 MPa [10].

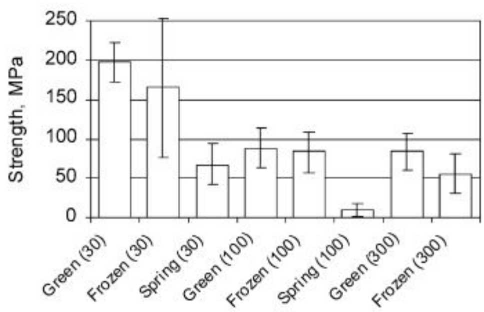


Figure IV.2: Hemp strength depending on the type of stem [10]

Another way to collect hemp fibers is mats: contrary to the strip case, here the single strip doesn't bear the load but it is the whole network to bear it. Fibers in the mat are manufactured from dew retted flax or hemp fibers industrially woven in a randomly oriented 3D fiber network [10]. These kind of material is found more useful even for automotive applications and can have mechanical performances similar to the ones of glass fiber. This kind of fiber will be used for the frame study case.

The results of epoxy/fibre mat composite strengths

Fibre raw material and treatment	Fibre or strip, % of mass	Max. bending stress (MPa)	Young's modulus (GPa)
Flax mat, needle punched from dew retted plants	61	128 ± 7	4.4 ± 0.4
Hemp mat, needle punched from spring harvested plants	51	146 ± 8	6.4 ± 0.5
Hemp strips, green, frozen, machine detached	77	86 ± 16	7 ± 2
Hemp strips, green, frozen, hand detached	73	64 ± 4	6.9 ± 0.5
Hemp strips, green, dry, hand detached	68	60 ± 8	3.2 ± 0.5

The compression during the manufacturing was 8 MPa (strips) or 6 MPa (mats).

Figure IV.3: Hemp mat mechanical properties [10]

The typical matrix associated to hep fibers is polypropylene (PP), but emerging studies are focusing on hemp fiber as reinforcement to an epoxy matrix. Introducing 30 vol% of hemp fiber, in fact, can increase more than 60% the tensile strength of the epoxy and 80% of the elastic modulus [9]. It can be seen in the following table that hemp reinforced epoxy surpassed the corresponding flexural strength and modulus of polyester:

	Flexural strength	Elastic modulus
PP	49 MPa	1.2 GPa
Epoxy	77 MPa	3.8 GPa

Table IV.8: Epoxy vs PP matrix reinforced with hemp fibers [9]

The volume percent of hemp fibers has an impact on the energy absorption amount. It can be seen that an initial 10 vol% of hemp can decrease the mechanical properties of epoxy, having the fibers acting as flaws in the material structure. The fracture will be brittle since the matrix is the one bearing the most part of the load. Increasing therefore hemp fibers content to 20-30 vol% can improve these conditions, leading to better properties due to a major interaction of the fabric with the matrix.

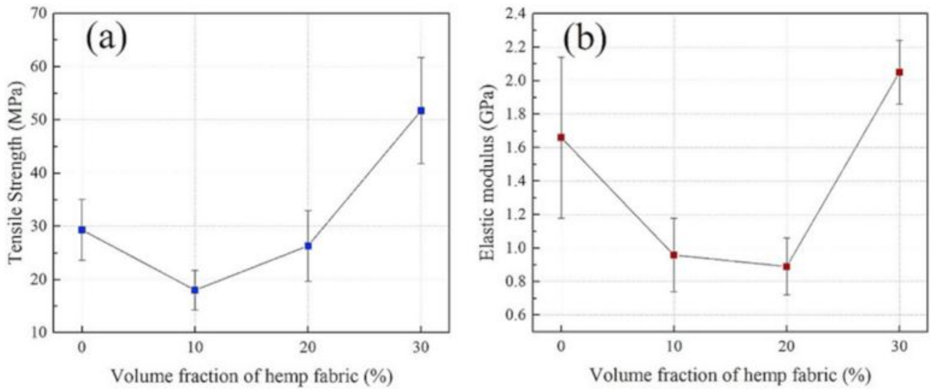


Figure IV.4: Mechanical properties of epoxy compared with an increasing amount of hemp fibers reinforcement [9]

Hemp fiber content also affects the thermal behavior of the composite. In general it leads to a lower maximum temperature because of the lower thermal stability of natural fibers in general: lignin starts its degradation at about 220°C [9]. The initial peak shown in the image can be related to the moisture absorption. The volume reduction when adding hemp fibers is much higher than for neat epoxy because of the hidrophilicity of fibers.

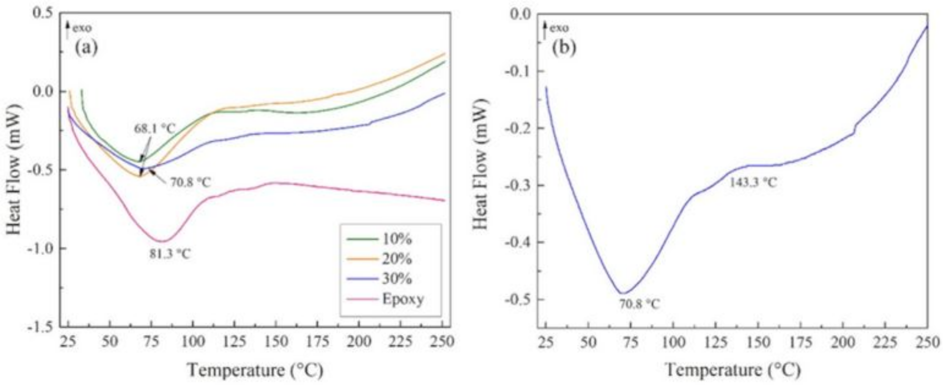


Figure IV.5: Thermal properties of epoxy compared with an increasing amount of hemp fibers reinforcement [9]

Hemp fiber represents an interesting field to make research upon and will be more and more discussed in the next years. Making a bicycle frame with it can have some uncertainties, especially because its mechanical properties are still far from the ones of carbon fiber, but it can be interesting to see the obtainable results with a correct material optimization and stratification.

IV.3.2 NAB-PREG N110B

N110Bio is a fast cure epoxy prepreg specifically developed for a variety of applications that will be used for the simulations made on the bicycle carbon frame.

Figure IV.6: Hemp N110 Bio [13]

Its key features are its curability in autoclave and a good tack.

IV.3.2.1 Matrix properties

Measurement	Method	Value
Glass Transition Temperature [°C]	DSC-ASTM D3418	108+114
Enthalpy Δh [J/g]	DSC-ASTM D3418	360+380
Tack	\	4
Tensile strength	\	51 MPa
Young's modulus	\	3,3 GPa

Table IV.9: Matrix properties [13]

IV.3.2.2 Curing conditions

Following there is its autoclave curing cycle:

1. ramp 2 °C/min up to 95 °C
2. hold at 95 °C for 40 min
3. ramp 2 °C/min to 135 °C
4. hold at 135 °C for 60 min
5. cooling 2°C/min to 50 - 60 °C

IV.3.2.3 Storage conditions

N110B prepreg should be stored as received in a cool dry place or in refrigerator. After removal from refrigerator storage, prepreg should be allowed to reach room temperature before opening the polythene bag, thus preventing condensation.

Storage life [months]	6 months at -18°C
Out life [days]	21 days at RT

Table IV.10: Storage conditions [13]

IV.3.2.4 Mechanical properties of the twill laminate

Tests carried out on a 2x2 Twill 110 g/m^2hemp mat made of strips as described in the theoretical section: green, frozen and hand detached:

Physical properties	Unit	N110Bio
Fiber weave mass	g/m^2	110
Nominal cured ply thickness	mm	0,43
Nominal laminate density	g/cm^3	1,48
Nominal fibre volume	%	44
Moisture	%	10,8
Fiber mat construction	\	Weft and Warp

Table IV.11: Physical properties of twill laminate, hemp fiber, part 1 [13]

Property	Unit	Value N110Bio
Tensile modulus 0° (E_1)	GPa	132
Tensile modulus 90° (E_2)	GPa	132
In plane shear modulus (G_{12})	GPa	3,4
Tensile strength 0°	MPa	115
Tensile strenght 90°	MPa	115
Compression strenght 0°	MPa	90
Compression strenght 90°	MPa	90
Interlaminar shear strenght	MPa	61

Table IV.12: Physical properties of twill laminate, hemp fiber, part 2 [7]

IV.3.2.5 Mechanical properties of the unidirectional laminate

These are the results of tests carried out on unidirectional hemp fiber. This one has its physical properties very close to the ones of glass fiber.

Physical properties	Unit	N110BioUD
Fiber weave mass	g/m^2	110
Nominal cured ply thickness	mm	0,37
Nominal laminate density	g/cm^3	1,38
Nominal fibre volume	%	54

Table IV.13: Physical properties of unidirectional laminate, hemp fiber, part 1

Property	Unit	Value N110BioUD
Tensile modulus 0° (E_1)	GPa	132
Tensile modulus 90° (E_2)	GPa	64
In plane shear modulus (G_{12})	GPa	3,4
Tensile strength 0°	MPa	115
Tensile strenght 90°	MPa	40
Compression strenght 0°	MPa	80
Compression strenght 90°	MPa	77
Interlaminar shear strenght	MPa	62

Table IV.14: Physical properties of unidirectional laminate, hemp fiber, part 2 [7]

The lack of a reliable and accurate database for the mechanical properties of hemp fiber laminate and the scattering of such properties, the suggestion is to have a more conservative approach as regards the number of plies to use and the failure indexes.

Part V
Optimization and results

V.1 Hypermesh plies and laminate

In general, in order to build a *composite component* on Hypermesh it is important to follow the following procedure.

First of all it is necessary to check the component's normal's direction. This information will be important for the program to understand in which direction to lay down the plies.

>2D>Composites>element normals>color display>display

Here there is need to check that all the element's normals are in the same direction. If not, select it and click the button ***reverse***.

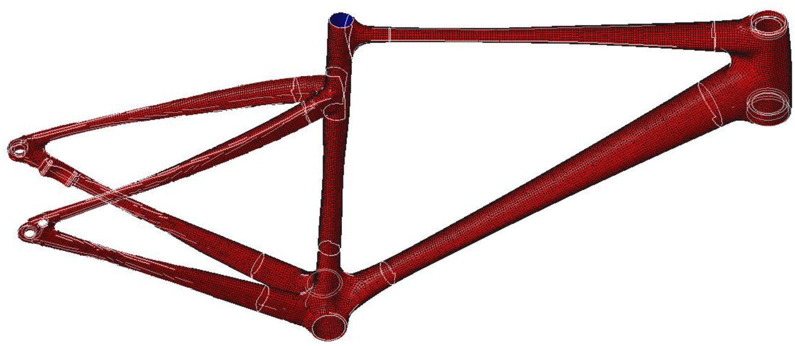


Figure V.1: Element normals of the frame displayed by color

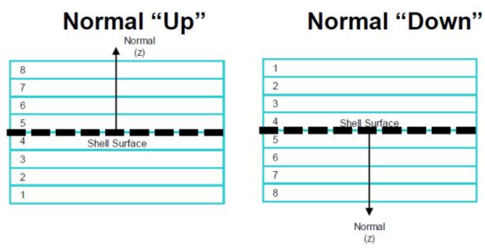


Figure V.2: Definition of stacking direction [14]

Afterwards there the elements direction must be defined. This will be considered the main direction of the fiber.

>2D>Composites>material orientation

At this point it is possible to select the components and the reference system choosing a specific direction. This will be important when giving different orientations to the material: if a unidirectional fiber, for example, is set on the frame with an angle of 45°, it means that it will be rotated of 45° in relation to the white vector shown in Figure V.3:

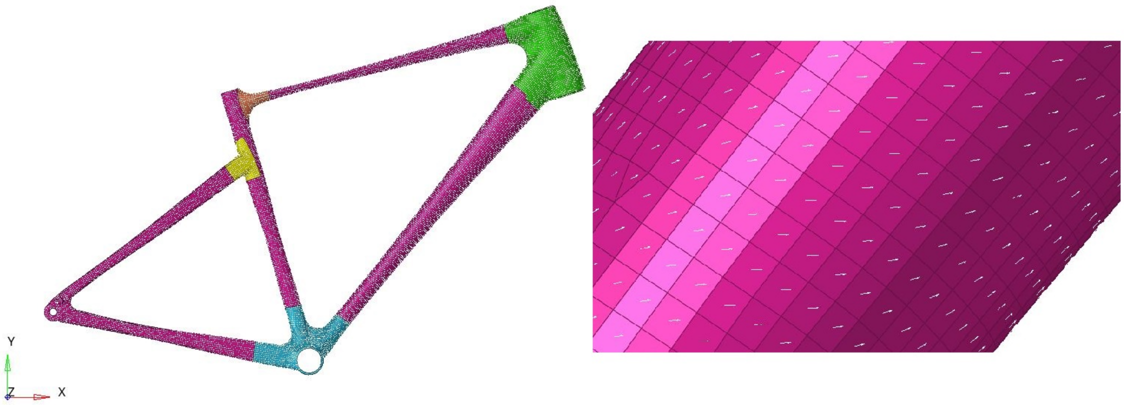


Figure V.3: Element's orientation

It is now necessary to create a ***Property*** of the component using the Card Image *PCOMPP*. This will tell the program it is dealing with a composite. Then, within the property, it is possible to decide the Failure Theory code. In the thesis, it'll be taken into account the Tsai-Wu criterion selecting the option *TSAI*.

The Z_0 OPTIONS will allow to decide in which way the layers of the laminate will be laid on the meshed surface. By selecting TOP the layers will be laid down from the top of the geometry surface to bottom. This direction will be indicated by the normals of the component defined in the previous step. If a value for Z_0 is set it will give an offset from the starting point from which to start the first layer.

For the gravel bicycle frame the geometry designed was intended as the outer surface of the final product: the plies will be set in the inner apart in order to keep that unchanged.

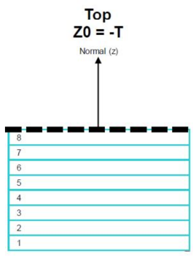


Figure V.4: Offset Top option in OptiStruct [14]

SB will be the interlaminar shear stress.

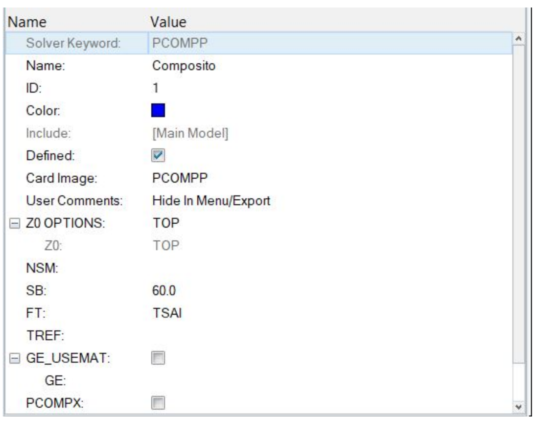


Figure V.5: Property card on Hypermesh

It is now possible to assign to each composite component the composite property.

Once this is done, it is necessary to define the *laminate* of the component.

The first step is to create a new material representing the fabrics of composite described in the previous section.

>Create>Material

In the Material card one must select the *MAT8* option, which corresponds to orthotropic materials such as composites. Here it's important to insert all the known properties and parameters of the fabric. Usually, twills have a very similar Young's Modulus along the two main directions and some other parameters are pretty common for many fibers. In order to give back as a result also the Composite Failure Index it is necessary to insert the values of X_T, X_C, Y_T and Y_C.

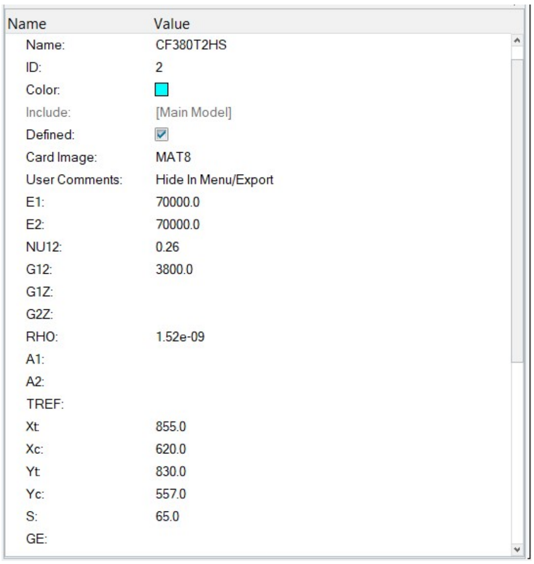


Figure V.6: Material card on Hypermesh

It is smart to divide the component into different ***Sets*** of elements that might will have some difference in the stratification sequence. This can be done by creating a Set and selecting the elements associated to it, either later when defining the ply (this last option only if the different sets are already different components), either before already defining a certain element's collector. A precisely prepared Set is very useful if the component has diversified stratification, otherwise an automatic Set will be created within the Ply.

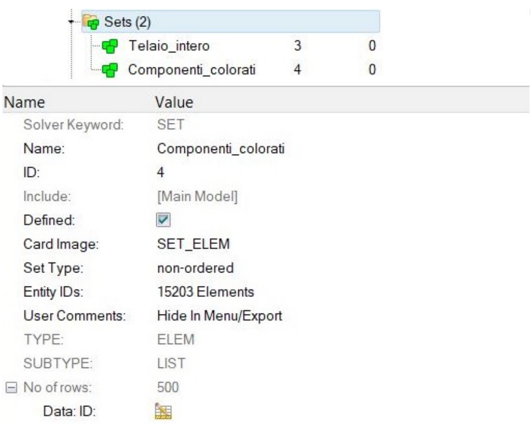
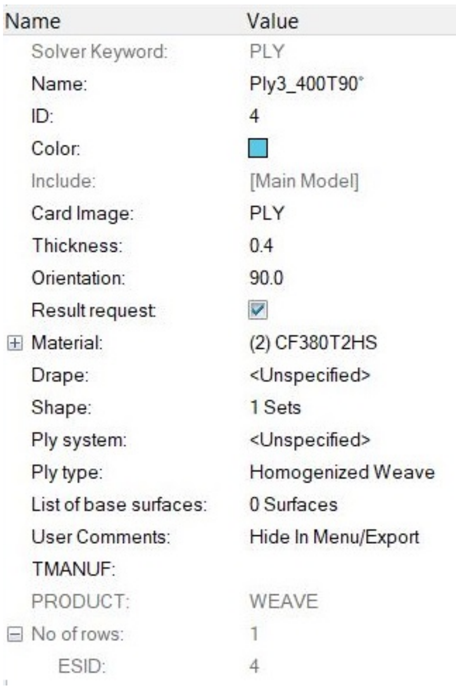


Figure V.7: Sets card on Hypermesh

One of the final steps is to define each ply and its properties by ***>Create>Ply***:

Each ply will have a name and a certain thickness. It's important to define its orientation with respect to the element's orientation set in the earliest passages. Every ply will have a *material* and a *Ply type*. In the *Shape* field the program will ask for the Set: if already specified it will appear and be ready to be selected, otherwise it will be possible to choose to which elements associate that ply in that moment. Actually, creating plies in HyperMesh resembles cutting out a contour with a specific orientation from a fabric [14].



Name	Value
Solver Keyword:	PLY
Name:	Ply3_400T90°
ID:	4
Color:	
Include:	[Main Model]
Card Image:	PLY
Thickness:	0.4
Orientation:	90.0
Result request	☑
⊞ Material:	(2) CF380T2HS
Drape:	<Unspecified>
Shape:	1 Sets
Ply system:	<Unspecified>
Ply type:	Homogenized Weave
List of base surfaces:	0 Surfaces
User Comments:	Hide In Menu/Export
TMANUF:	
PRODUCT:	WEAVE
⊟ No of rows:	1
ESID:	4

Figure V.8: Ply card on Hypermesh

Once there is a ply associated to every layer, it's time to create the ***Laminate***.

Here it will be possible to select and order all the ply layers that have been prepared. It can be seen that the plies will be allocated only for the selected Sets and there will be the therefore the possibility to have a diversification in the stratification.

To see in detail the different plies laid on the component it is possible to click on ***>Composite Layers*** on the visualization panel:

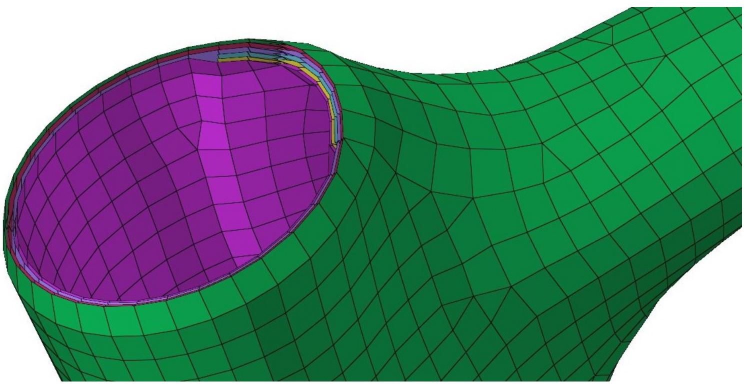


Figure V.9: Laminate example on Hypermesh

V.2 Optimization on Hypermesh

Research on materials and composites is giving to the industry a lot of benefits and possibilities to strive for performance and sustainability, but when talking about composites it is very important to take into account as well costs and manufacturing needs. Their structural properties are great only under certain conditions, that often correspond to higher complexity and costs. To understand how and where to properly locate all the layers of material there is need of an optimization process performed by the program and the designer himself. In the bicycle's world this is done as well and the result is often a complex sequence of plies with different shapes and sizes to set one after the other to build the component. This stacking sequence requires knowledge and time to be laid down, as well as complex shapes of pre-formers. As usual in engineering, choices will be made also by making some trade-offs between performance and costs.

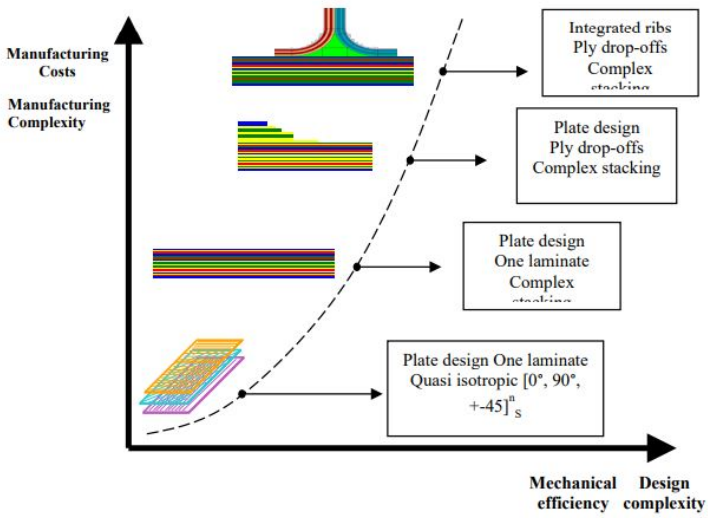


Figure V.1: Cost VS design complexity in composites [1]

In this dissertation costs won't be take into account and the goal will be to maximize performance and comfort by reducing weight and following the optimization procedure is explained.

In order to decide how many layers and in which direction to set them Hypermesh allows to set and run a material optimization.

This procedure can be divided in different steps, which can be summarized as:

1. Free-size optimization: it shall provide the information of load paths within the component and deliver a proposal about the fibers orientation of material in certain areas of the component. In this step Optistruct will subtract material from the layers and will analyze the role of each ply in each section. A first idea about the overall behavior of the system will be given.

2. Size-optimization setup: the second phase of the optimization-cycle tracks two goals. On one hand manufacturing constraints shall be considered, on the other hand in this phase the optimizer shall aim at discrete, manufacturable ply thicknesses [14].

3. Shuffle-optimization setup: here the real manufacturing constraints should be taken into account before calculating the optimum stacking sequence.

What needs to be done in order to make a first optimization is to create a model with the main and heavier loads and constraints, so that the optimizer can provide the right information about the most stressed zones.

The first step consists into modifying the plies setup, creating *super-plies* with over-thick layers. The program can, in fact, only subtract material and it is therefore necessary to set a thickness that might not be correlated to reality and manufacturing, but that can give to the program the right amount of material to take away.

Before running the optimization, there are some settings and passages to create the right model to be analyzed. The creation of *super-plies* can be dealt in different ways. Sometimes over-thick layers of different materials are set on the whole component homogeneously, with alternating orientations, to allow the optimizer to make all of the proper considerations. Sometimes, as in the bicycle frame case, it has been decided to already set some initial differences in the laminate depending on the diverse parts of the components. In order to do so, the frame has been divided into five main areas of interest, set as follows:

1. The horizontal tube
2. The down-tube
3. The seating tube and head-tube
4. The superior rear stay
5. The inferior rear stay

Figure V.2: Frame subdivided into different components

Every area will have a slightly different stacking sequence and this has been decided by looking at standards and general knowledge when laminating bicycles. Basically, the rear stay has a few less layers and, over there, unidirectional orientation is preferred.

The materials used will be two twill fibers of NANO-LITE N125L and CF200UDIM provided by Micla Engineering [13], and they will be arranged as follows:

	Thickness	Material	Orientation	Components
Super-ply Sequence	0.2	CF200T2HS	0°	1,2,3,4,5
	0.5	CF200UDIM	0°	4,5
	0.5	CF380T2HS	45°	1,2,3,4,5
	0.5	CF380T2HS	90°	1,2,3
	0.5	CF380T2HS	-45°	1,2,3,4,5
	0.5	CF380T2HS	0°	1,2,3
	0.5	CF200UDIM	0°	4,5
	0.2	CF200T2HS	0°	1,2,3,4,5

Table V.1: Carbon fiber frame's super-plies laminate

The first layer is only aesthetic and the expectation is that it won't bring a lot of structural contribution, as well as the inner layer, always made of the same material. The other areas of the frame will have both unidirectional material both twill plies oriented in different ways. The optimizer will tell which ply is the most important and in which orientation it should be laid down.

Once these plies are defined, a model including loads and constraints will be built in order to make a proper simulation.

The fatigue cases have been chosen to take into account some of the worst case scenarios on the frame's loading.

With the super-plies configuration described above the frame will have the following weight, calculated by ***>Tool> mass calc >***:

Total frame's weight	1.37	kg

Table V.2: Frame weight with super-plies

V.2.1 Load cases

First of all, there is need to create a model that displays the major loads applied on the frame, so that the simulation will take them into account to understand where there is need of more material.

The load cases chosen have been taken from standards ISO4210-6, provided by Gregario srl [9]. We'll be using the three main fatigue tests loading cases creating different *Load Steps* on Hypermesh.

One of the most significant load cases is the biker padalling on the bicycle, applying all of his power and weight on pedals, torsioning the entire frame under his movements. The standards represent the following scheme as one of the best ways to represent it. It is important to notice that the following load case refers to a real test performed by manufacturers to empirically study the frame's behavior. Around bicycles and composites, in fact, there is still a great contribution to research given by the testing phase.

V.2.1.1 Pedaling fatigue

The underlying asset in V.3 will represent the ***first Load Step***:

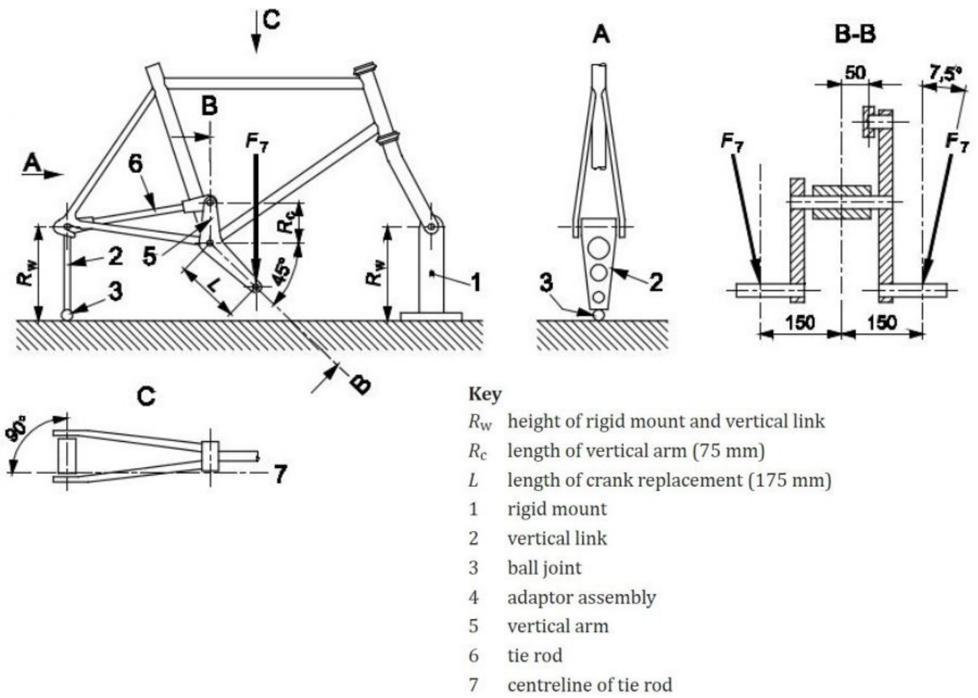


Figure V.3: Forces on pedal spindle [9]

For what concerns the value of the forces on pedals the standards are:

Bicycle type	City and trekking	Young adult	Mountain	Racing
Force, F_7 [N]	1000	1000	1200	1100

Table V.3: Pedaling forces standards [9]

This kind of scheme has been implemented on Hypermesh, simulating the front fork with a *Beam*, as well as for the pedals, for the seat tube and for the vertical link number 2 shown in Figure V.3 (using beams of different sections). The tie rod (element number 6 in Figure V.3) has been simulated as a *Rod* element.

The bottom bracket and the headset have been represented through 1D elements called *rigids* that are formed by one central *master node* surrounded by *slave nodes* that will follow its movements and bear its loads depending on the degrees of freedom set between them and the master. For example, to properly simulate the headset, a new local reference frame has been created, with the z axis oriented in the head-tube direction; a master node has been associated to that system and the slave nodes have been created with the 6 dof free to rotate around that axis, in respect to the master node.

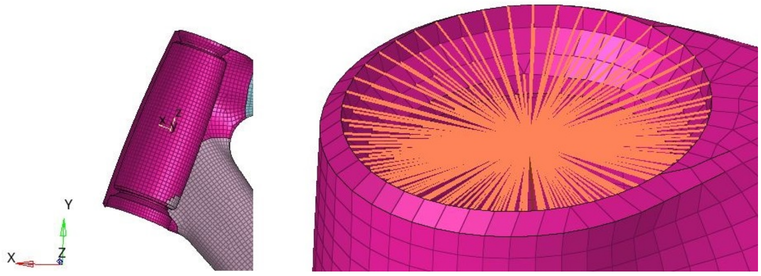


Figure V.4: Headset RBE2

The constraints applied are the following. The global reference system shall be considered as shown in Figure V.4:

Location of the constraint	Type of constraint	Dofs constrained
Rear wheel - to - ground	ball joint	123
Front fork - to - wheel	hinge	12345

Table V.4: Constraints - pedaling fatigue

The other hinges have been simulated through the RBE2 elements, as previously explained. The loads applied are mainly two:

Location of the load	Type of load	Load magnitude [N]
Top of the seat tube	Rider's weight	800
Center of the pedal	Standars force for pedaling	1200

Table V.5: Loads - pedaling fatigue

The pedaling force has been chosen from standards that refer to mountain bicycles since the gravel bike is also apt to ride on gravel roads and trails. This choice is also to be more cautious in the calculations.

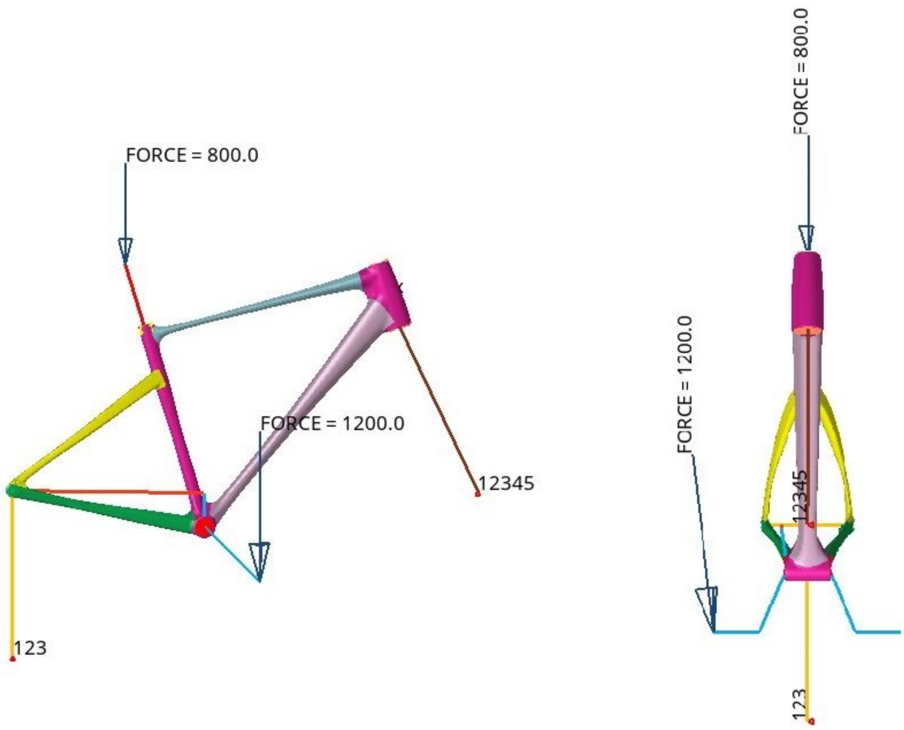


Figure V.5: Hypermesh model of pedaling forces

V.2.1.2 Horizontal fatigue

The ***second Load Step*** will refer instead in a condition where the bike is braking downhill with the rear wheel and where the front wheel will feel all the load. Hypermesh allows to create different load steps that all contribute to the final optimization. A structural analysis will be run for each load step.

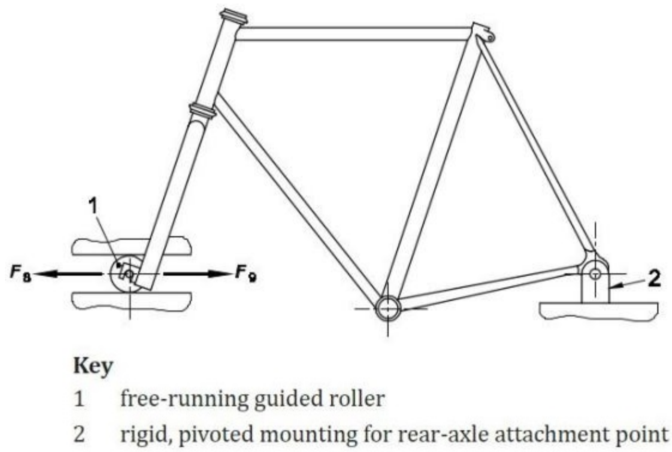


Figure V.6: Forces on front fork dropout [9]

The rear pin will be modeled as a hinge, while the front fork dropout will serve as a roller, where the force will be applied. The value of the force on the front fork will be chosen, again, from the mountain bike world. This because gravel bicycles are apt to got downhill as well, even if slower and with no jumps. The idea is to be as cautious as possible, especially since we are talking about fatigue:

Bicycle type	City and trekking	Young adult	Mountain	Racing
Force, F_8 [N]	450	450	1200	600

Table V.6: Forward force standards [9]

This time the loads and constraints have been outlined as follows, but the commands are all similar to the previously described. It has been necessary, however, to create a separate *Load Collector* for the new sub-case.

Location of the constraint	Type of constraint	Dofs constrained
Rear stay pin	hinge	12345
Front fork - to - wheel	roller	23456

Table V.7: Constraints - horizontal fatigue

The loads applied account for the biker's weight transitioning to the front wheel of the bicycle when braking or going downhill:

Location of the load	Type of load	Load magnitude [N]
Front fork dropout	Rider's weight	1200

Table V.8: Loads - horizontal fatigue

Figure V.7: Hypermesh model of forward forces

V.2.1.3 Vertical fatigue

In a similar manner it has been introduced also a ***third Load Step***, representing the rider's load on bikes over bumps. Here the load is applied on the saddle and the frame stretches and bends under this stress.

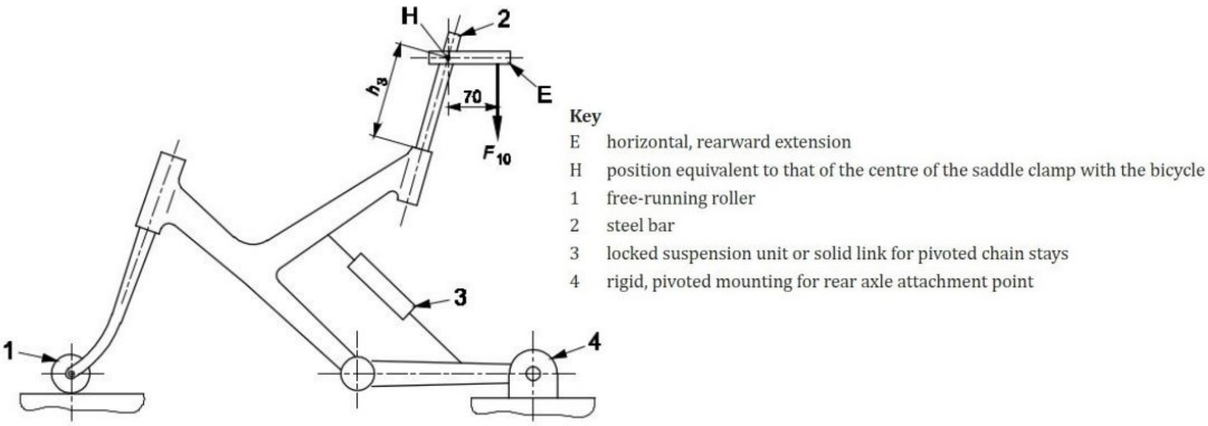


Figure V.8: Forces on seat stem [9]

For simplicity the suspension has not been introduced into the model, but the frame has been studied with the rear stay and seat tube as well. The force will again take into account a mountain bike value:

Bicycle type	City and trekking	Young adult	Mountain	Racing
Force, F_{10} [N]	1000	500	1200	1200

Table V.9: Force on seat stem standards [9]

The rear pin has been represented with a hinge and the front fork with a roller, similarly to the horizontal fatigue sub-case. Here the force load is vertical and applied on the edge of the seat.

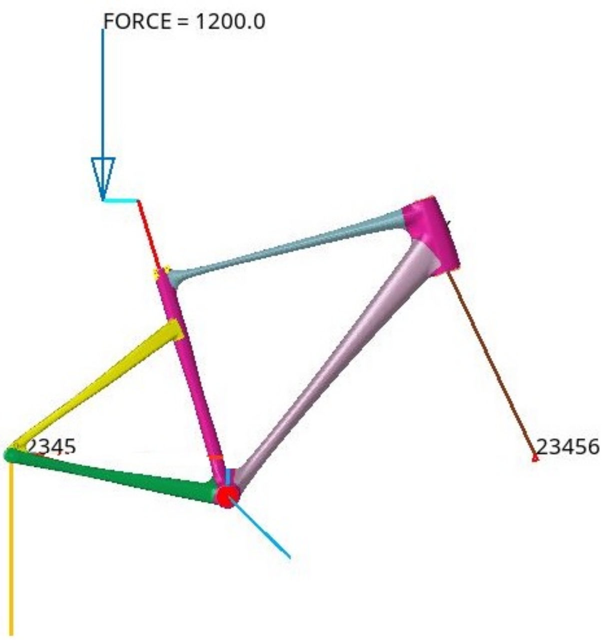


Figure V.9: Hypermesh model of seat stem force

These three load cases will be important to simulate the bicycle behavior under the most damaging conditions and they will serve the optimization to properly take material off.

Something that is important to do before starting the optimization itself it is to run an Analysis on OptiStruct, in order to check that everything runs well and that the results of the loading type make sense.

To ask to the program for the wanted results, the expected outputs must be selected on the CARDS:

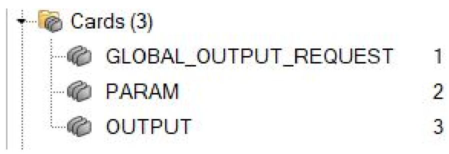


Figure V.10: Output cards

In our model the following are the *global output* requested:

- CFAILURE: composite ply-level failure index will be given as a result. It is defined to contour plot the elements/region which fails during the analysis according to the failure theory defined in the property [1].
- CSTRAIN: composite ply-level strain. It defines the composite ply strain output at the middle of each ply.
- CSTRESS: composite ply-level stress. It defines composite ply stress output at the middle of each ply.
- SRTAIN: composite laminate-level strain
- STRESS: composite laminate-level stress

In the *Parameters* section the following boxes are checked:

- CHECKEL
- SRCOMPS

In the *Output* box the word FSTOSZ is chosen in between the *Keywords*: it allows an automatic generation of a size optimization model at the last iteration of the free-size optimization [1].

The Analysis is therefore run. Some of the results of this first attempt are shown for the pedaling fatigue sub-case. The frame is oversize with super-plies and it should be far away from any kind of failure.

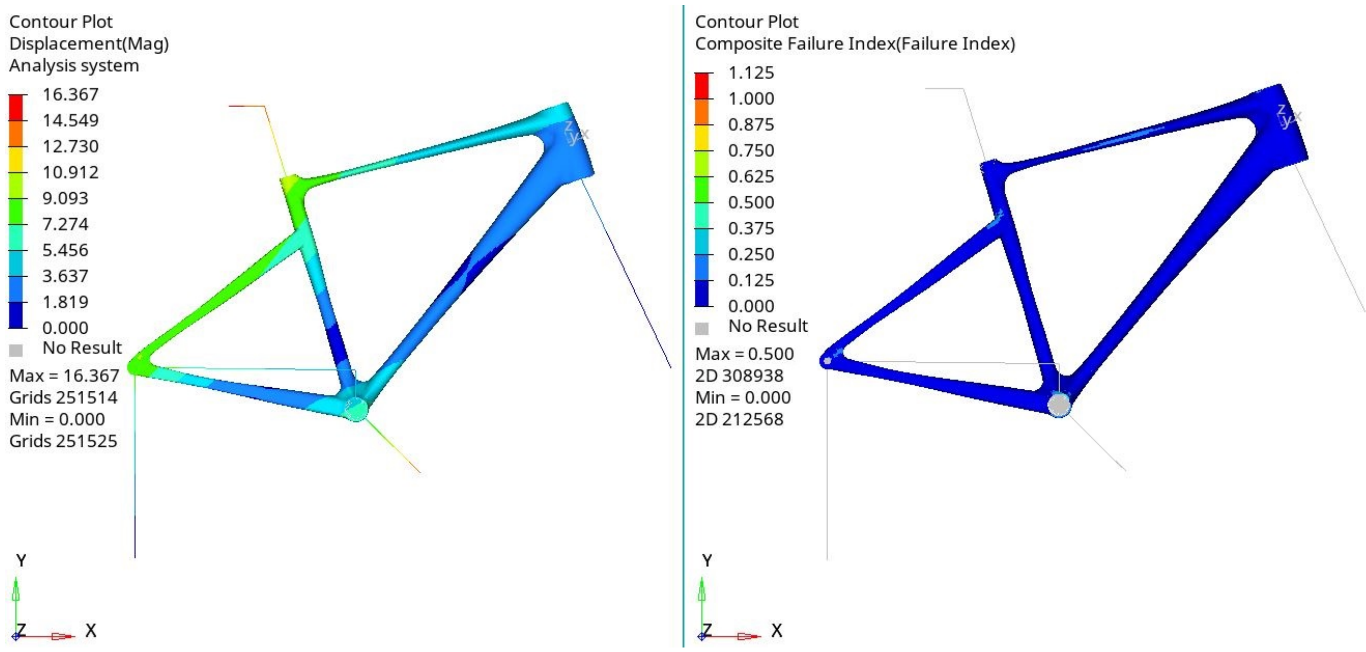


Figure V.11: Displacement and composite failure index

It is possible to see how pedaling ends up in a significant displacement in the z-direction especially of the seat tube and rear stay. This is not necessarily an issue, because when biking a slight deformation of the frame is normal in the biking world. In order to enhance performance and transfer all the power of the rider to the bike and the ground the frame needs to be stiff, but if stiffness is extreme attention must be paid on the possible fragile behavior of the component. Furthermore, for what concerns comfort, a little deformation is appreciated: especially for gravel applications comfort must be taken into account.

The Composite Failure Index shown in Figure V.11, instead, is very low and the frame bears well all of the torsion. In order to consider fatigue, it will be important to be very cautelative considering this index and stresses. There will be need of a high safety factor even after the material has been optimized.

This kind of reasoning needs to be done both for the horizontal fatigue both for the vertical fatigue as well. In all of the three cases the frames needs to withstand with some margin the loads and stresses.

For what concerns stresses, Hyperworks shows as well the stresses area by area through the frame, as in Figure V.12:

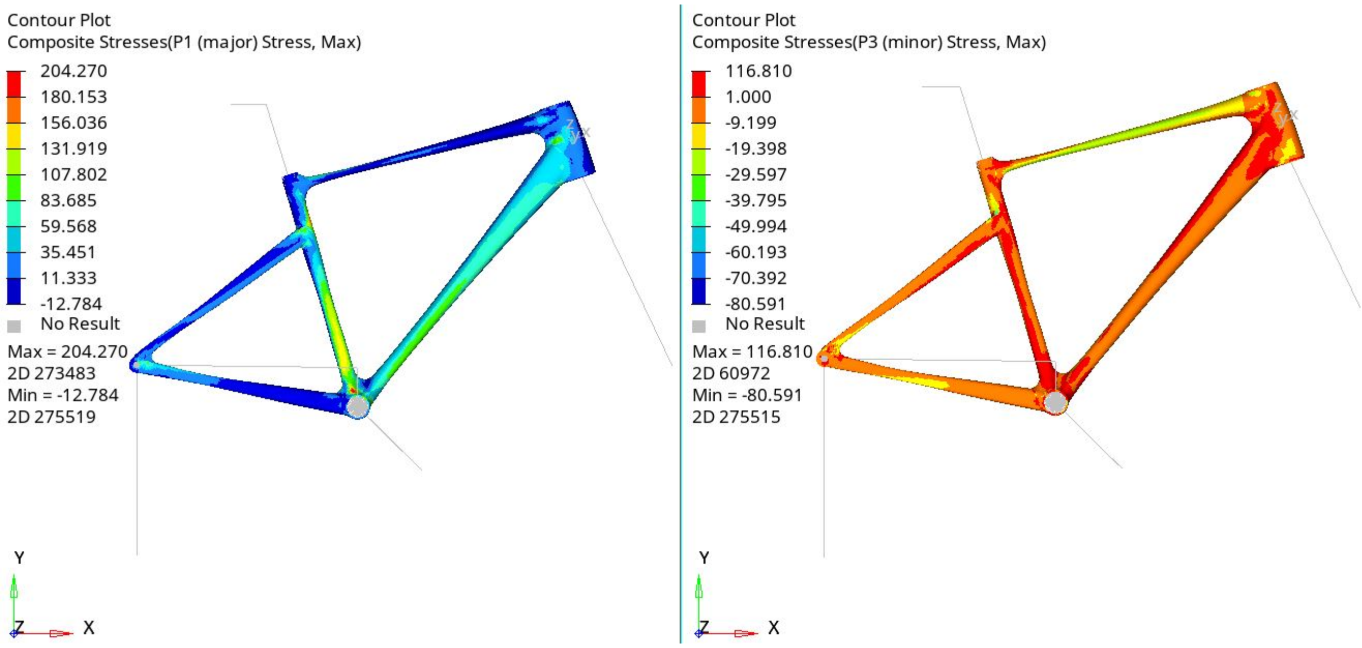


Figure V.12: Composite stressP_1 and P_3 - super-plies

Considering stresses, in composites Von Mises is not the best value to look at, but it is better to focus on $P_1$and P_3. These are the stresses along the different directions: P_1 can be used to see the biggest tensile stress flow direction, seeing it as an upper bound estimate for the highest tensile stress in that region; for what concerns P_3 it shows instead the critical compression stress. Any region that has a minimum (most negative) P_3 stress that is positive must be a tension dominated region.

This first analysis can already give some information about the loading conditions and the behavior of the different plies, but the optimizer will take care of properly show the best way to set the material: doing this process “manually” would be very complicated.

Factors that will affect the composite optimization are:

- Part Geometry
- Ply Geometry
- Material Data
- Mesh Data
- Material Alignment Information
- Lay-up sequence
- Z-Offset Information
- Drape Information

Each one of these factors will contribute to the optimization results: this latter will try to maximize performance and minimize the opportunity for part failure.

V.2.2 Free-size optimization

The goal of optimization as a whole is to make something as effective as possible, avoiding waste and maximizing performances.

The first step will provide us with a general idea of the importance of the different layers and their orientation. For this phase it is necessary to use the super-plies laminate previously created. The stacking sequence can be random since the "Laminate option" should be used with the "Smear" option [14]. The smear option removes the effect of stacking sequence from the problem.

Another change into the setups of the model refers to substituting the TSAI failure theory in the composite property to STRN, which is the maximum stain theory.

It is now possible to create the Design Variables for the optimization:

>Analysis > optimization > free-size > create

Here there will be some parameters to insert. First of all, the *mindim* will require to insert the minimum width of a ply section. Being the dimension of one element 3 mm, a *mindim* of 9 has been chosen. In a similar way the program will ask for the minimum and maximum laminate thickness.

To define the ply group manufacturing constraints the box *BALANCE* will be checked (it will give symmetric results for 45° and -45° orientations) and the *entity type* will be set as *STACK*.

The second step consists into defining the responses of the optimization. The objective function in the optimization will refer to the responses.

>Analysis > optimization > responses

There will be two responses in the optimization:

- Response "mass": this will allow to see if the final mass satisfies the requirements.

By setting ***Analysis > optimization > dconstraints*** we'll be putting an upper bound to the mass of the frame. The value chosen is of 900 g.

- Response "weighted compliance": compliance is the reciprocal of the stiffness and by minimizing it the stiffness will be maximized.

This will take into account the different load-steps and will make a weighted compliance of the three. It has to be considered that the same weight at different single compliance does not lead to a uniformly distributed weighted compliance [14]. The compliances are taken from the analysis output file:

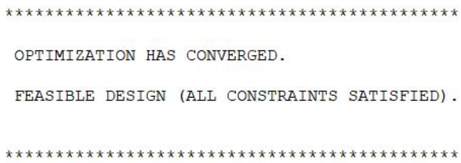
Subcase	Compliance	Epsilon
1	8.841623E+03	2.988059E-10
2	4.491734E+03	1.506789E-11
3	2.774856E+03	1.024111E-10

Figure V.13: Compliances

The first load case will be driving the determination of the minimum weighted compliance. We'll be giving to all of them a weight of 1, since they are not too far from one another as values.

The response WCOMP will be the optimization objective to minimize: ***Analysis > optimization > objective***

Finally, the control cards section must have an updated OUTPUT - card with the keyword FSTOSZ (free-size to size), to ensure the transition of design-information to the size - optimization [14]. Now, by inserting *optimization* as the run option the optimization can start.



```
*********************************************

OPTIMIZATION HAS CONVERGED.

FEASIBLE DESIGN (ALL CONSTRAINTS SATISFIED).

*********************************************
```

Figure V.14: Convergence message

Results clearly give an overview on the parts of the frame that need to be more or less loaded. At first sight it is very clear that the down-tube and the seat-tube are the ones that need the highest thickness, as well as the lateral sides of the bottom bracket and of the head-tube. The rear has a smaller section and can have thinner walls while still being able to bear the load in the right directions. It must be noticed that the rear stay must be able to bend vertically to dump vibrations and make it more comfortable for the rider when hitting bumps. This is also one of the reasons why the unidirectional fiber can well fit on that tube following its direction.

The underlying image represents the element's thickness as a whole.

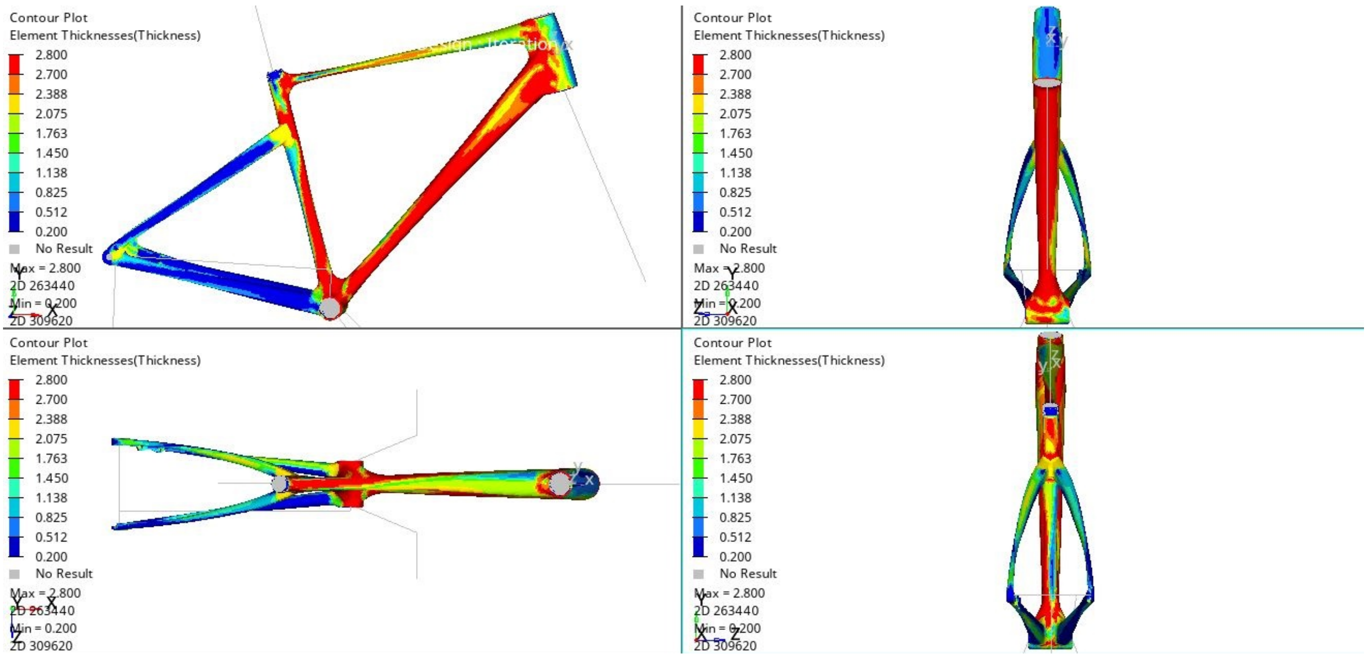


Figure V.15: Free-size ply overall thickness optimization result

This first result can already give a good idea of the critical zones of the frame.

The optimization allows to look also at the different orientation thicknesses. These will provide some information about the fiber orientation that provides the higher structural contribution. There will be four main orientations: -45, 45, 90 and 0°. The 0° orientation seems to be the most important one and the one that needs to be thicker. It follows the 90° and then the 45 and -45° (which are specular one to the other). It was possible to see already in the first analysis results how the tubes were tension dominated. This makes the 0° orientation one of the best ways to make the fiber work properly. Also in the rear stay the 0° orientation is the one providing the best support to the structure. These results are compliant to what bike manufacturers say nowadays about frame fabrication: for them , unidirectional fiber has become one of the best ways to create a stiff and light-weight structure for their bikes [18].

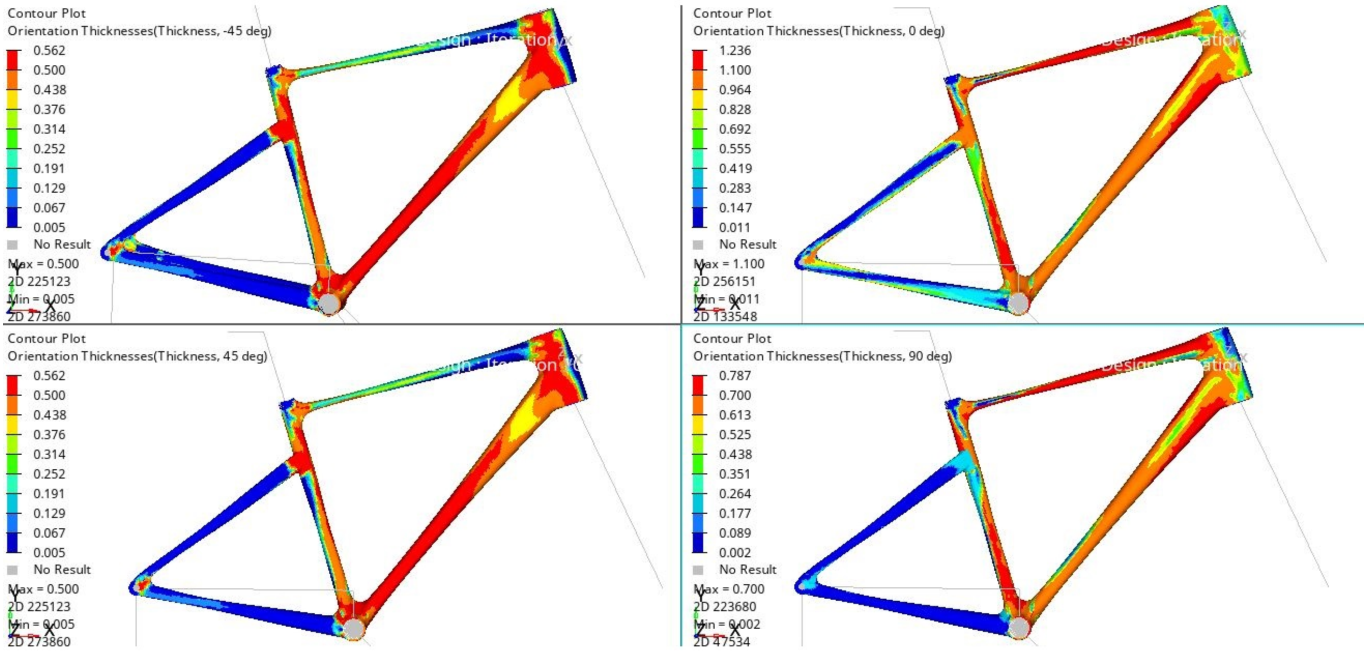


Figure V.16: Free-size orientation thickness

Finally, the different plies as well can be singularly observed to make some considerations. On the top and down-tube the thicker ply is the twill at 90°, reinforced with the UD 0° ply as well. It is possible to notice how the 200T 0° represents only an aesthetic layer and doesn't provide a great structural support. On the rear stay the UD 0° provides the most of the support, while on the rear stay pin also some 400T 45° is necessary.

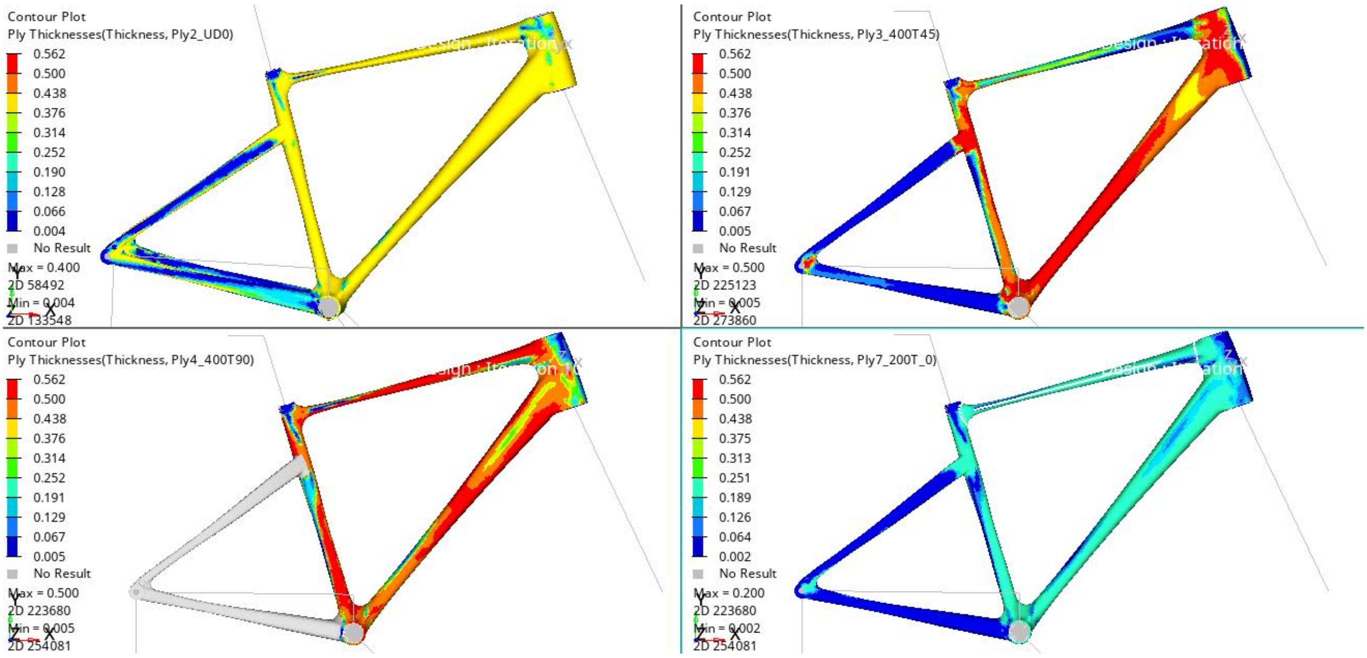


Figure V.17: Free-size single ply thickness

As shown, free-size optimization already gives the most information about where there is need of material and how to set it down. Still, it doesn't deal with manufacturing constraints. If the component under study has a very simple geometry, though, a "manual decision" on how to set the plies could be already done thanks to this important step. For the frame we'll continue with further help from the optimizer.

V.2.3 Size optimization and final layout

In this step of the optimization the goal is to consider manufacturing constraints and to obtain manufacturable ply thicknesses. In fact, not all thicknesses are manufacturable and there is need to properly set the plies down in a feasible way.

File > Import > Solver Deck

In the *.fem* file it is possible to notice how some things have now changed:

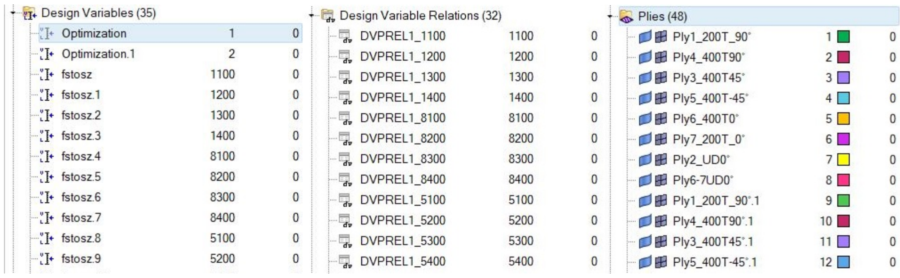


Figure V.18: Changes after free-size optimization

For the design space plies with appropriate element-sets are created.

The plies with a new ID have the following meaning:

Example: PLYS_1100

1 - first design variable defined in free-size

1 - second ply (orientation in previously defined laminate)

00 - third shape of the ply - bundle

The sets of plies are optimized without a lot of elements, but they have very complex shapes and elements that are not attached to the frame anymore. This will require some cleaning before running the second part of the optimization.

The thickness information of the single orientations was transferred as follows by the FSTOSZ information as ply-shapes for the following size-optimization. For example, it is possible to see the UD 0° in Figure V.19:

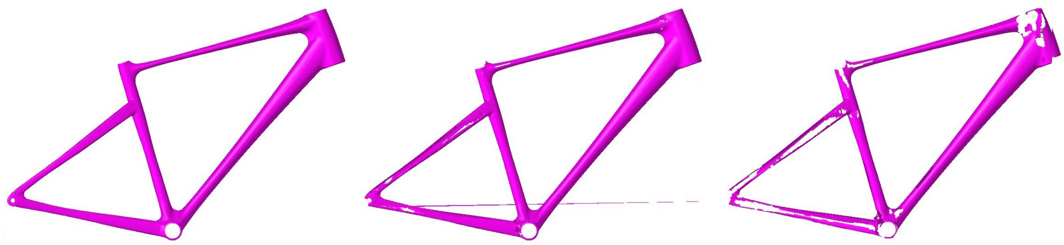


Figure V.19: Ply shape 1 - 2 - 4

The next step consists into cleaning up these shapes by deleting unnecessary elements or adding them to complete the plies geometries. It is time consuming and the goal is to make them look more manufacturable to ameliorate the following optimization step, which will take into account all the parameters to allow a possible lamination of the frame. Furthermore, not only the shape of these plies has some issues, but the thickness as well is very small. Size optimization will be helpful to have a thickness that is a a multiple of the one of the plies we have in the real world.

Figure V.20: New edited plies

Now, the upper bound of the shape thickness of each *design variable* must be updated with, for example, 0.0 as lower and 0.4 as upper bound.

This is what has been done:

Ply	Design upper bound [mm]	Ply	Design upper bound [mm]
fstosz	0.2	fstosz.16	0.5
fstosz.1	0.2	fstosz.17	0.5
fstosz.2	0.2	fstosz.18	0.5
fstosz.3	0.2	fstosz.19	0.5
fstosz.4	0.2	fstosz.20	0.5
fstosz.5	0.2	fstosz.21	0.5
fstosz.6	0.2	fstosz.22	0.5
fstosz.7	0.2	fstosz.23	0.5
fstosz.8	0.5	fstosz.24	0.4
fstosz.9	0.5	fstosz.25	0.4
fstosz.10	0.5	fstosz.26	0.4
fstosz.11	0.5	fstosz.27	0.4
fstosz.12	0.5	fstosz.28	0.4
fstosz.13	0.5	fstosz.29	0.4
fstosz.14	0.5	fstosz.30	0.4
fstosz.15	0.5	fstosz.31	0.4

Table V.10: Upper bound update

For each ply it is then necessary to fill the right spot with the manufacturable thickness, depending on the different fabrics we have to laminate. This value must be modified for each ply as in Table 28:

Ply	TMANUF	Ply	TMANUF
PLYS_1100	0.2	PLYS_5100	0.4
PLYS_1200	0.2	PLYS_5200	0.4
PLYS_1300	0.2	PLYS_5300	0.4
PLYS_1400	0.2	PLYS_5400	0.4
PLYS_2100	0.4	PLYS_6100	0.16
PLYS_2200	0.4	PLYS_6200	0.16
PLYS_2300	0.4	PLYS_6300	0.16
PLYS_2400	0.4	PLYS_6400	0.16
PLYS_3100	0.4	PLYS_7100	0.16
PLYS_3200	0.4	PLYS_7200	0.16
PLYS_3300	0.4	PLYS_7300	0.16
PLYS_3400	0.4	PLYS_7400	0.16
PLYS_4100	0.4	PLYS_8100	0.2
PLYS_4200	0.4	PLYS_8200	0.2
PLYS_4300	0.4	PLYS_8300	0.2
PLYS_4400	0.4	PLYS_8400	0.2

Table V.11: Manufacturing thickness

What now has become the main goal is to see how many plies of each ply shape and of which thickness are required to satisfy strength and manufacturing requirements [14].

The analysis allows to get a result where the useless plies are taken away and it is possible to calculate the correct thickness for each ply and material. Furthermore, it is now necessary to shape each ply taking into account its manufacturable. Some elements are added and some removed to make "rectangular shapes" that could easily be cut. There are then other software, such as Laminate Tool, that automatically create a ply shape to be cut and a ply-book with the instruction to laminate. Sometimes the process can be long and there might be a lot of pieces to set in the right place.

The last step consists into defining the correct order of the plies. There are some general rules that give the best possible cohesion between the different layers: first, it is always better to alternate the angle orientation of the fibers, in order to make a composite as homogeneous as possible; second, the plies that have smaller shapes should be laid under the bigger ones, because the latter covers them making delamination less luckily to happen. Unidirectional fibers therefore need to be separated one by the other with a twill fabric, for example, and structural fibers need to be covered by the other layers, receiving less damage from the outside. In general, unidirectional fibers with a good layup can be set with more precision and have better performances, while twills can be better for localized strengthening and to avoid the internal complex layers to delaminate.

The plies sequence is here shown:

Material	Thickness	Orientation
CF200T2HS	0.2	90°
CF380T2HS	0.4	45°
CF200UDIM	0.16	0°
CF380T2HS	0.4	90°
CF380T2HS	0.4	-45°
CF380T2HS	0.4	0°
CF200T2HS	0.16	0°
CF200UDIM	0.16	0°
CF380T2HS	0.4	45°
CF200UDIM	0.16	0°
CF200UDIM	0.16	0°
CF200UDIM	0.16	0°
CF380T2HS	0.4	-45°
CF200T2HS	0.2	90°

Table V.12: Plies sequence - carbon fiber

It can be seen that there are sixteen layers, each one made by a certain material with a certain thickness. It is important to note that each one of them doesn't cover the whole frame, but it is shaped in a different way and will be manufactured and placed following that scheme.

On Hypermesh it is possible to check the different thicknesses over the frame: the final result has a maximum of 2.96 mm in the connection between the rear stay and the seat tube and on the lower part of the head-tube. The down-tube as well is pretty thick, reaching 2.4 mm in its upper part. The rear stay is much thicker than in optimization results, but in order to avoid unnecessary displacement the range goes from 1.2 to 2. Still, this part of the frame needs to deform a little when hitting bumps or jumping, without being too stiff. Extreme stiffness is sometimes related to frame brittle fractures experienced by cyclists.

Figure V.21: Plies thickness

Unidirectional fiber represents the core of the frame and it is the one giving the major structural contribution and it is a great choice in term of the frame's weight. After the optimization the frame is much lighter and it passed from being 1.37 kg to 0.947 kg. It has a major displacement compared to the frame with super-plies, but only with a difference of 4 mm. The maximum composite failure index is 0.625 in the three sub-cases and this guarantees a good margin even when talking about fatigue. Of course, this failure index is slightly higher than in the over-thick frame, but not that much, since the goal of optimization is therefore removing the material only where it is not needed.

Total frame's weight	0.947	kg
Maximum composite failure index	0.625	\

Table V.13: Frame weight after optimization, with final layout

Here it is shown, for example, the failure index of the single plies.

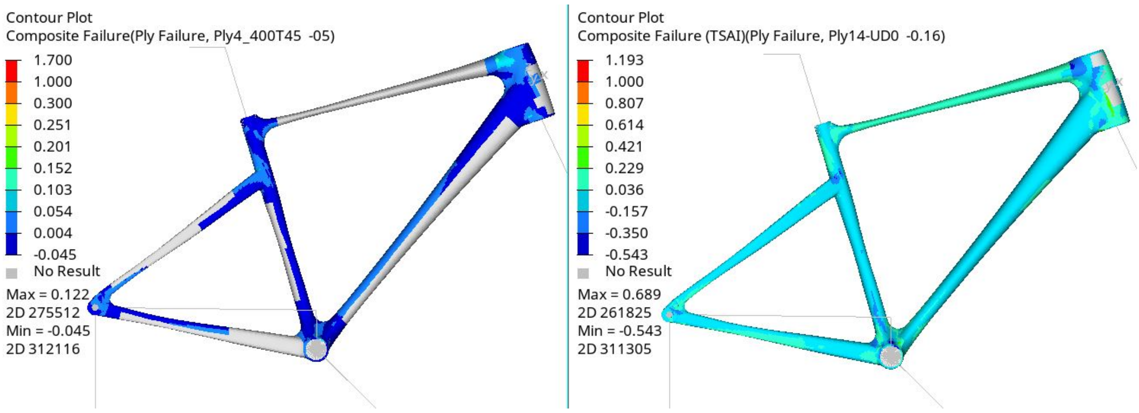


Figure V.22: Plies failure index, 400T 45° and UD 0°

Stresses are very low and this is normal since in the free-size optimization the goal has been maximizing stiffness.

This carbon frame is in line with what exists on the market nowadays. Manufacturers have made frames that weight 0.700 kg as well, but that's by making everything very extreme. Dealing with a gravel bicycle for amateurs this result can be already satisfying and it guarantees the proper performances and comfort. Something that is in any case very important in the cycling and composite world is testing: this would be a great step to analyze how the numerical results match the real behavior of the component.

V.3 Natural fiber frame

Carbon fiber has very powerful properties and it guarantees one of the best performances when talking about strength-to-weight ratio. Nonetheless, its production cycle, its use and its end of life represent an issue because of the CO2 emissions related to it and the impossibility to recycle wastes. The research into natural fiber is more and more interesting and in this dissertation the bicycle frame will be modeled and sized using the hemp fiber reinforced composite. What can be already predicted looking at the data-sheet of the materials is that the thickness of the component will need to be much higher than the one of the carbon frame and the weight could therefore raise as well. Still, the goal can be getting as close as possible to its mechanical characteristics and dynamic behavior under loads and constraints, analyzing the possibility to have a more sustainable and performing bicycle frame.

The process to make all the simulations follows step by step what has been previously introduced and it starts by entering into the program the material physical properties and by laying down a super-plies laminate for the first free-size optimization. The loads and constraints will remain the same as in the previous section. The laminate will be laid down as follows: N110BioUD.

	Thickness	Material	Orientation	Components
Super-ply sequence	0.9	N110Bio	45°	all
	0.7	N110BioUD	0°	all
	0.7	N110BioUD	0°	all
	0.9	N110Bio	-45°	all
	0.9	N110Bio	45°	all
	0.7	N110BioUD	0°	all
	0.69	N110Bio	-45°	all

Table V.14: Hemp fiber frame's super-plies laminate

Total frame's weight	5.30	kg

Table V.15: Frame weight with super-plies, hemp

The super-plies sequence ends up having a very thick and heavy frame. The over-thickness has been chosen in order to have a frame with a composite failure index minor than one and this required ultra-thick layers. Still, it can be seen that the maximum composite failure index is not low and in the connection between the rear stay and the seat tube can be almost critical. The expectation will be that the optimizer doesn't take off much material from that area, but keeps it pretty thick. Again, as in the carbon frame, the front stay is more stressed than the rear one, but some attention needs to be paid on the rear pin holes.

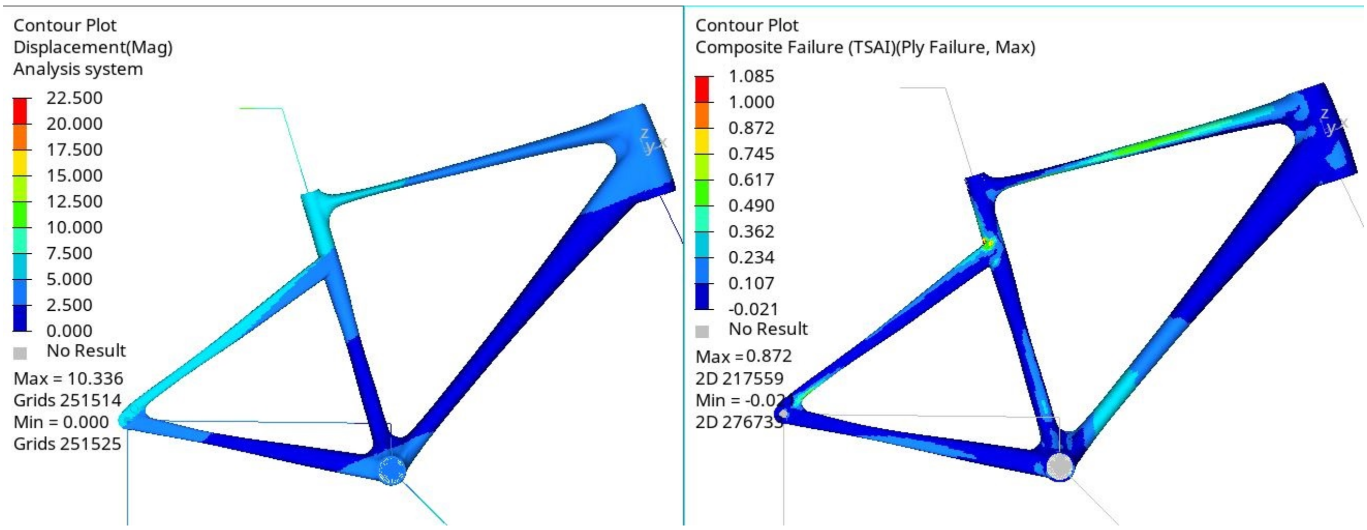


Figure V.1: Displacement and composite failure index, hemp fiber

Seen the heaviness of the frame it has been decided to set as mass constraint 2 kg on the total frame for a first optimization. Only looking at the analysis results is in fact difficult to expect it to weight about 1 kg or less, especially with such a high failure index when the frame is that thick. The objective will be again to maximize the stiffness response and all the steps to achieve a good free-size optimization are exactly as in the carbon fiber frame section. A further attention must be paid in the hemp fiber frame due to the minor testing performed on such a material compared to all the knowledge gathered through the years when using carbon fiber.

The free-size optimization is therefore run and the results follow below:

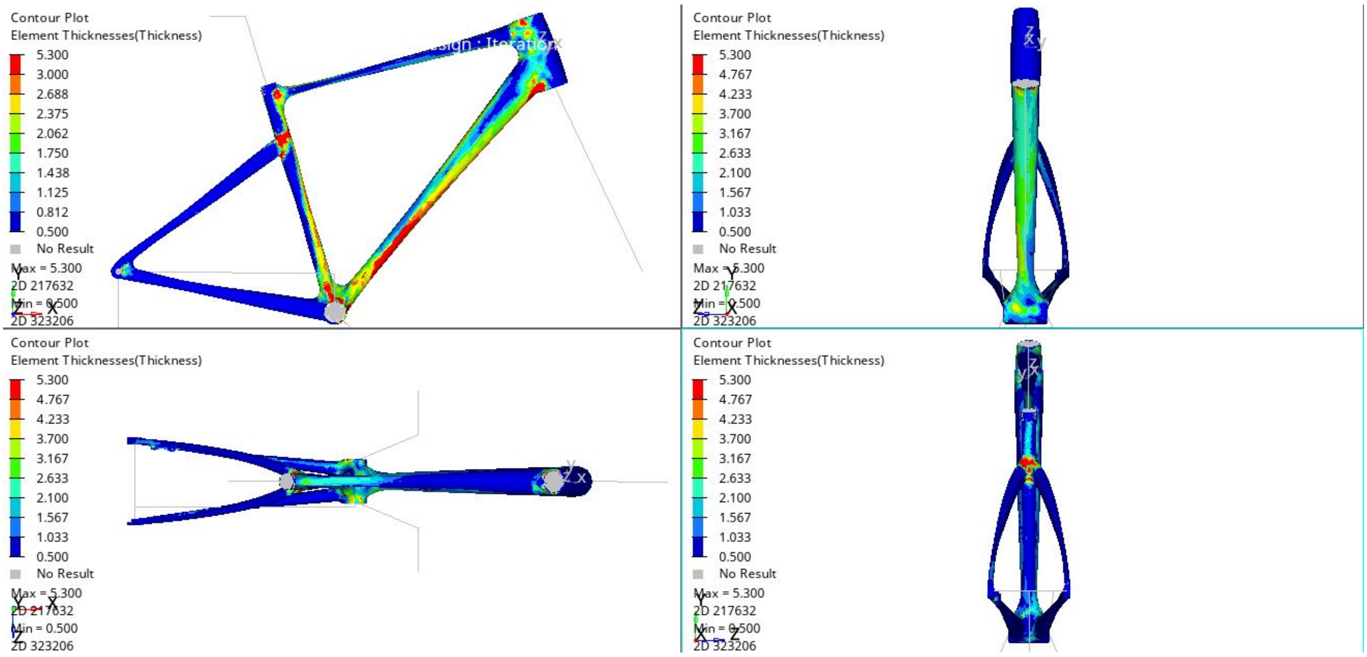


Figure V.2: Free-size ply overall thickness optimization result, hemp

As expected, the frame is very much thicker than the carbon frame one, having a range from 0.5 to 5.3 mm. Even the 5.3 mm needs to be taken carefully into account, because that's the maximum thickness of the over-thick frame used for the optimization: the solver can only subtract material, and presenting areas with a value of 5.3 mm could also mean that over there there might be need of thicker plies. The "thickness distribution", a part from the thickness values themselves, is pretty similar to the carbon frame, showing more material on the front triangle (such as top-tube, seat-tube and down-tube) and less on the rear stay.

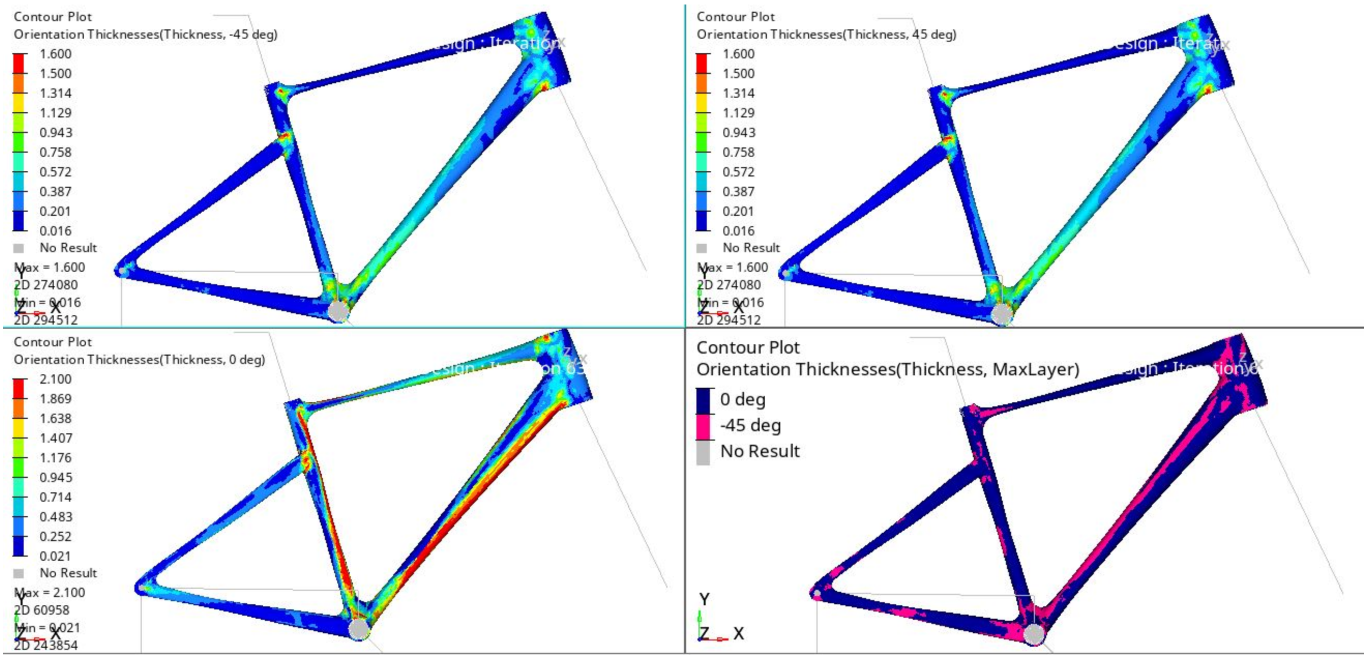


Figure V.3: Free-size orientation thickness, hemp

Another useful graph is the one describing the contribution of each orientation angle of the plies to the final structural behavior. As for the carbon fiber frame the unidirectional fiber seems to withstand the most part of the load and it therefore needs to be thicker than other angles. the 45° fiber seems to be very useful instead on the top part of the down-tube. The frame in the fourth quadrant of Figure V.3 is represented showing the orientation that has the thicker layer in every area. It is possible to see that in almost all the tubes the 0° orientation is thicker, while on the bottom bracket, the head-tube and the upper part of the down-tube the 45° withstand more load. It is important to make all of these considerations before proceeding in the following steps of the optimization.

Again, it is then necessary to look at manufacturing constraints and plies thickness and this is done by the size optimization.

The first step will deal with the plies cleanup: the optimization returned 28 plies with more or less elements and these need to be prepared for the next phase. Again, before running the last optimization the thickness bounds and the manufacturing constraints are set into the model:

Ply	Design upper bound [mm]	Ply	Design upper bound [mm]
fstosz	0.5	fstosz.14	0.5
fstosz.1	0.5	fstosz.15	0.5
fstosz.2	0.5	fstosz.16	0.5
fstosz.3	0.5	fstosz.17	0.5
fstosz.4	0.4	fstosz.18	0.5
fstosz.5	0.4	fstosz.19	0.5
fstosz.6	0.4	fstosz.20	0.4
fstosz.7	0.4	fstosz.21	0.4
fstosz.8	0.4	fstosz.22	0.4
fstosz.9	0.4	fstosz.23	0.4
fstosz.10	0.4	fstosz.24	0.5
fstosz.11	0.4	fstosz.25	0.5
fstosz.12	0.5	fstosz.26	0.5
fstosz.13	0.5	fstosz.27	0.5

Table V.16: Upper bound update, hemp

Ply	TMAN	Ply	TMAN	Ply	TMAN	Ply	TMAN
PLYS_1100	0.43	PLYS_2400	0.37	PLYS_4300	0.43	PLYS_6200	0.37
PLYS_1200	0.43	PLYS_3100	0.37	PLYS_4400	0.43	PLYS_6300	0.37
PLYS_1300	0.43	PLYS_3200	0.37	PLYS_5100	0.43	PLYS_6400	0.37
PLYS_1400	0.43	PLYS_3300	0.37	PLYS_5200	0.43	PLYS_7100	0.43
PLYS_2100	0.37	PLYS_3400	0.37	PLYS_5300	0.43	PLYS_7200	0.43
PLYS_2200	0.37	PLYS_4100	0.43	PLYS_5400	0.43	PLYS_7300	0.43
PLYS_2300	0.37	PLYS_4200	0.43	PLYS_6100	0.37	PLYS_7400	0.43

Table V.17: Manufacturing thickness, hemp

The results of the optimization show how in certain areas of the frame a lot of plies are necessary and, as seen in the element thickness in Figure V.2, some reach the maximum thickness of 5.3. The plies sequence proposed has in fact 18 layers, where the last 9 concentrate in the area of the connection between the rear stay and the seat tube. The bottom bracket and the down-tube are pretty thick as well.

Material	Thickness	Orientation	Material	Thickness	Orientation
N110BioT	0.43	45°	N110BioUD	0.37	0°
N110BioUD	0.37	0°	N110BioT	0.43	45°
N110BioUD	0.37	0°	N110BioUD	0.37	0°
N110BioT	0.43	-45°	N110BioUD	0.37	0°
N110BioUD	0.37	0°	N110BioT	0.43	-45°
N110BioT	0.43	45°	N110BioT	0.43	45°
N110BioUD	0.37	0°	N110BioT	0.43	-45°
N110BioT	0.43	-45°	N110BioT	0.43	45°
N110BioUD	0.37	0°	N110BioT	0.43	-45°

Table V.18: Plies sequence - hemp fiber

In this configuration those areas have a maximum thickness of 5.3 mm, but by running a structural analysis it is possible to see how those areas are very much stressed. It could be therefore useful to start again from the first step of the free-size optimization, by making the initial super-plies thicker. However, since the issue seems to be restricted to that area it might be possible as well to run some manual iterations adding more material on certain delicate zones and seeing when the result seem acceptable. This has been performed on the frame, adding one step at the time layers especially of the twill fabric N110BioT (as suggested by the orientation results after the free-size optimization) around the entire connection between rear stay and seat tube and adding some material as well on the down-tube and bottom bracket. This process ended up having the following updated sequence of plies, ending up with a laminate of 29 plies:

Material	Thick.	Orient.	Material	Thick.	Orient.	Material	Thick.	Orient.
N110BioT	0.43	45°	N110BioT	0.43	45°	N110BioT	0.43	45
N110BioUD	0.37	0°	N110BioUD	0.37	0°	N110BioUD	0.37	0
N110BioUD	0.37	0°	N110BioUD	0.37	0°	N110BioT	0.43	90
N110BioT	0.43	-45°	N110BioT	0.43	-45°	N110BioUD	0.37	0
N110BioUD	0.37	0°	N110BioT	0.43	45°	N110BioT	0.43	-45
N110BioT	0.43	45°	N110BioT	0.43	-45°	N110BioUD	0.37	0
N110BioUD	0.37	0°	N110BioT	0.43	45°	N110BioT	0.43	45
N110BioT	0.43	-45°	N110BioT	0.43	-45°	N110BioUD	0.37	0
N110BioUD	0.37	0°	N110BioT	0.43	45	N110BioT	0.43	-45
N110BioUD	0.37	0°	N110BioT	0.43	-45	\	\	\

Table V.19: Plies sequence updated - hemp fiber

The result obtains something that is very different from the carbon fiber frame, at least looking at the thicknesses of the frame in the various points. The weight of the component is below the 2 kg, but still pretty high:

Total frame's weight	1.87	kg

Table V.20: Frame weight after optimization, with final layout, hemp

The range of thickness in the component varies from 1.97 mm to 10.09 mm, which looks something very big. This might look unusual, but not surprising, since hemp fiber's physical properties are very different from the ones of carbon fiber. The natural fiber reinforced composite behaves in a similar manner when talking about material orientation, but structurally it needs to much more support of material. The major thickness is experienced, as anticipated, in the connection between the rear stay and the seat tube. As it is possible to see in Figure V.5 (where the section of the frame in the connection is shown), there is need of many layers supporting the rear stay connection and it is important also to constantly keep under an eye the manufacturable of the component. In fact, if the frame became too thick, the inner section could become too small and very difficult to be laminated. Still, looking at the result in this specific case the frame looks manufacturable and man layers will need to be set in that area, paying attention to allow the saddle tube to be inserted into the seat-tube, regulating the seating height of the rider.

Another aspect to be taken into account is the sudden difference of thickness from the 10.9 mm zone to the 5.58 zone: there the shift will need to be gradual and an inner layer that covers the whole areas is useful to avoid delamination and keep together the different plies.

For what concerns the rest of the frame, instead, the rear stay and the front part of the head-tube are the thinner ones, while the down-tube needs some extra material to have a good factor of safety.

Figure V.4: Thickness with optimized plies

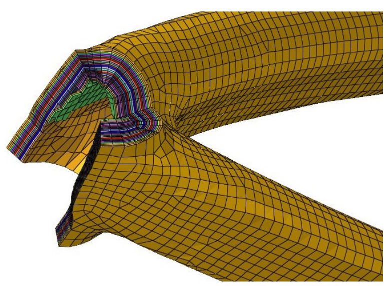


Figure V.5: Ultra-thick zone of the hemp frame

Once all the plies are set in place it is necessary to run again a structural analysis that checks the indexes that predict the component's failure or resistance.

As usual, the three fatigue cases are chosen to make the final considerations on the structural reliability of the frame. Figure V.6 shows the Composite Failure Index obtained on the hemp fiber frame. As it can be seen, the failure index is not very low, especially considering that some margin would be preferable when talking about fatigue. The maximum is in fact 0.87 and it appears on the connection between rear stay and the seat tube, despite all the material set over there. up front close to the head tube there are some elements with an index of 0.75, which is not that low as well, even if more acceptable and the component itself not as ultra-thick as in the rear stay. Still, adding material would increase the weight, bringing the bike to be far from what's on the market nowadays.

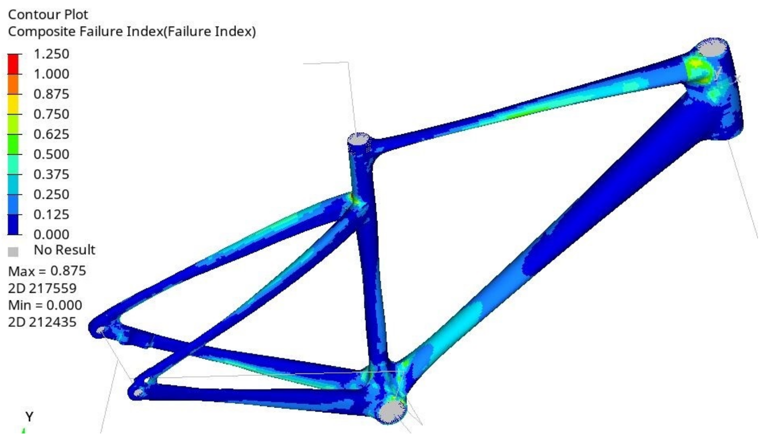


Figure V.6: Composite failure index, hemp

It is also possible to look at the single plies failure index, always calculated with the Tsai-Wu failure criterion. Here as well the UD looks more loaded especially on the rear stay and the top-tube and its index reaches the value of 0.87 close to the rear stay connection and 0.6 on the top-tube; the twill ply at 45° reaches instead 0.747 by the head-tube. These values are acceptable, but a lot of testing would be useful to truly check the frame's behavior. In any case, depending on the different areas some orientations give the most structural contribution to the component.

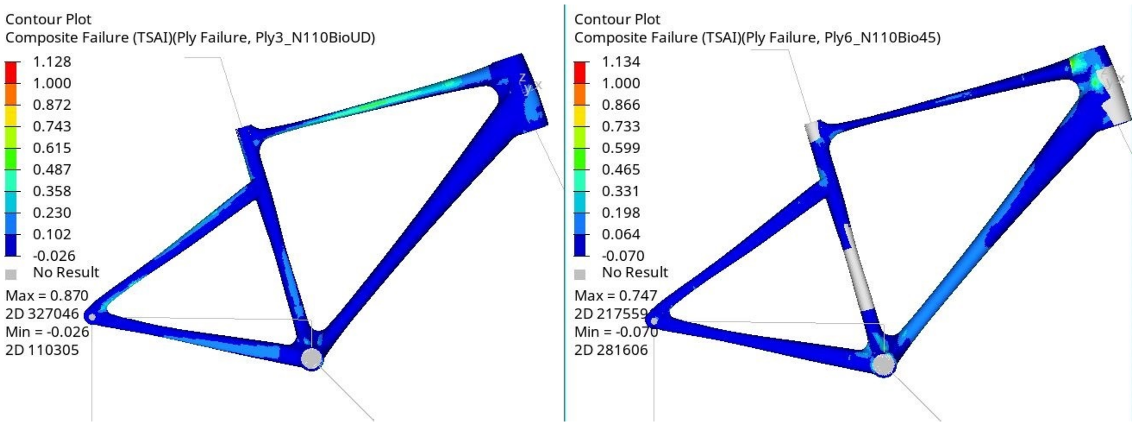


Figure V.7: Plies failure index, 0° and 45°, hemp

What can be seen is therefore a true potential of hemp fiber that might not be ready yet for such structural applications yet. A higher margin would be needed in order to produce the component also due to the wide range of physical properties the hemp takes on when treating it: the scattering of the data of the material is pretty high and it would be good to be cautious adding some more plies also for that reason. For manufacturing constraints, however, attention must be paid onto avoiding oversizing of the rear stay connection section, that risks to end up being completely filled. Still, the failure index in this situation is minor than one and the frame ends up not braking.

Part VI
Technologies

To have a complete overview on the frame production cycle it is interesting to have a look over the technologies used nowadays to build composite made bike frames, specifically the ones with carbon fiber.

Carbon frame production developed in the last twenty years especially because of the increasing demand for it from the market. Seen the great mechanical properties of carbon fiber always more riders choose a carbon frame that, thanks to technological progress, became more accessible even under an economical point of view. Some of the best bicycle frames in the world are nowadays produced in Asia, specifically in Taiwan: at first, as often happens, the production of such components was very expensive and was therefore transferred in Asia, where the market allowed a very cheaper labor. Through the years, experience allowed Taiwan to increase more and more the quality of its products and is nowadays one of the places where they build the best frames in the world (let's think at Giant and Merida). Asian market is now expanding in China and India as well, but it will still take time to reach the quality level needed by professionals all over the world.

Europe has as well its market, but it is usually made up of smaller numbers and oriented towards a major customization of the frame for the customer. Businesses like Lightweight (Germany) make a production very focused on details and quality, but their numbers don't cover of course the broad needs of the demand, satisfied instead by the asian and american industry.

What makes the carbon fiber frame that costly is related especially to the material cost and the production method, which needs to be further explained.

The production of a carbon frame can only have a low level of automation and is currently dependent on human labor. The fibers are in fact manually laid on the mold and the time needed to make a single frame is pretty high. Carbon fiber allows freedom to set the frame stronger in certain places and mix different kinds of fiber to have very precise properties. This might end up in 300-400 fiber cut pieces that will have an exact position and orientation, requiring to the worker a lot of time and precision. Also, customer customization is often required and it doesn't allow for a great in line production.

To understand the production process of a frame it is necessary to have a look at the two main type of products that are found on the market: the *wrapped frame* and the *monocoque*.

In order to be able to make different sizes and to allow customization the easiest and elder solution is for sure wrapping: the different tubes forming the frame are assembled and then glued and wrapped together with some extra carbon fiber.Originally, instead of wrapping, some aluminum junctions were made to link the tubes, but it was soon replaced by carbon wrapping itself. This usually ends up in additional weight to the frame and a loss in the continuity of the fiber, resulting in lower mechanical properties. Ideally, in fact, the frame should be monocoque, a single piece that allows the fibers to spread energy without breaking the different layers. A true monocoque, though, is very difficult to make for many reasons: first, it is not easy to have a technology that allows to take out of the mold an entire frame without braking or ruining it; second, having a single mold of a certain size would make it impossible to play on the different geometries in order to make other sizes of the frame. This would bring costs to exponentially raise and the process to slow down. This is the reason why what today is called "monocoque" is actually an assembly of a monocoque piece formed by the top tube, the down tube and the head tube together with the rear stay.

In a frame production process there are different steps that require a great amount of knowledge and practice:

1. First of all there is the choice of the carbon fiber type and orientation, followed by an optimization that allows to have a proper stratification of all the layers. The fibers are therefore unrolled and impregnated in the right resin (this holds true for prepreg) and cut in the right shape depending on the combination previously defined. Software such as Laminate Tools by SmartCae allows to optimize the cutting, reducing waste, and laying down proper instructions for the application sequence.

2. The carbon sheets assembly requires an exact order placement. The layers are laid around bladders and pre-formers and are later placed into giant molds.

3. The molds are placed into massive heated presses that apply two to ten bars of pressure incrementally over 45 minutes at 170 degrees. In a step called debulking heat and pressure are applied to the outside of the frame, bladders inflate on the inside pushing it outwards. This heats the resin and allows it to flow evenly through the layers, eliminating air gaps.

Figure VI.1: Frame production process, part 1

1. After molding the frame is left to cool down before being removed from the mold. Excess of rein is then mechanically eliminated.

2. The frame is then baked into a giant oven to cure the resin and remove any remaining moisture or air gaps.

3. The surface of the frame is then prepared by sanding it down and the pre-formers and bladders are mechanically removed by hand.

4. The machining process then begins and it takes care of drilling and milling all the little holes and details into the frame.

5. Later the front and rear triangles are joined together by fitting and gluing them together on a special jig that guarantees them to be in the exact orientation.

6. The final steps consists into surface finishing and preparation. Here the final quality of each piece is checked and the frame gets varnished and ready to be painted.

Figure VI.2: Frame production process, part 2

Making a carbon frame is therefore a long and complicated process that enables to reach great performances and satisfy the needs of the bikers of today.

Part VII
Conclusions and final considerations

The bicycle's world is continuously developing and evolving and frames as well. Different developments and studies are performed depending on the cycling field and each discipline boosts a certain aspect of innovation and technology (such as aerodynamics for chrono-bikes, or dynamic for mountain bikes, etc.), but the focus on materials is common to all of them. The goal is in general to maximize performances, which can be related to different aspects depending on the type of bikes, and diminish weight, and therefore effort. Comfort can also play an important role, especially when talking about gravel bicycles. These latter are versatile and when designing there is need to model their behavior taking into account the different loads they can be subjected to. This is what has been done in this dissertation when building the load models stressing the frame. Still, the material aspect of this study has been central into making some important considerations. The frame, after being designed on Solidworks, has been studied and optimized both in the case of a carbon fiber reinforced composite, both a natural fiber reinforced one.

In the first case, the fabrics chosen to lay down the laminate and their data-sheets have been supplied by Micla Engineering: a twill and a unidirectional fabric made of nanotubes additivated carbon fiber. These performing materials have been laid down and optimized thanks to Hypermesh and have given back a very light and stiff frame. The frame, in fact, is more than compliant with the items present on the market nowadays: its weight is 0.93 kg and its failure indexes have enough margin to not risk sudden rupture under the fatigue cases, having their maximum of 0.625. The Figure below shows how the frame places itself in the market when talking about the weight.

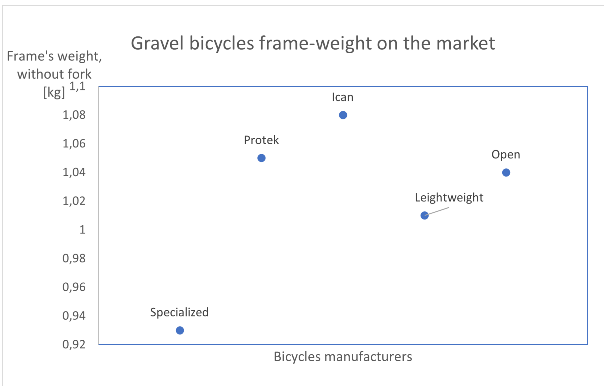


Figure VII.1: Example of gravel bicycle's frames on the market

Something that is anyway still very important for the manufacturers is testing and experimental data would be useful to further check the performance of this kind of frame. It is interesting to notice that the standards used to model the frame for the structural analysis refer to real tests made by manufacturers on such components.

For what concerns the natural fiber frame, hemp has been chosen as one of the most suitable materials studied by now to try on such a structural component. Already on paper it is clear that its physical properties are far from the carbon fiber ones, but if looking at values of the specific Young's Modulus hemp can look almost comparable to glass fiber. With hemp fiber as well two kinds of fabrics were used to make the simulations: a twill and a unidirectional fiber. The laminate has been optimized as for carbon fiber and the results have been displayed.

What's clear is the big difference existing between the two frames. In fact, looking at weight, the hemp fiber's one is 1.87 kg. This value might not seem that high, but it places itself out of the market needs of nowadays. Its structural behavior as well has much less margin to failure than carbon fiber, reaching a composite failure index also of 0.875 in the static case. In order to lower it there would be need to add more material in the connection between the rear stay and the seat-tube, but that zone is already over-thick and would tend to have a completely full section if material was furtherly added. Additionally, that would coincide with a growth of the frame's weight, leading it to not be an appealing component for users. Something that could be done to lower stresses in that area could be, though, to change the geometrical design of the rear stay endings to make the curve over there smoother and the sections wider. Geometry affects as well the structural behavior of the frame and, while carbon fiber allows for some more freedom in design, hemp fiber might need some more measures to be sure the frame withstands all of the loads.

Even though research is making a lot of progress on the natural fibers, hemp fiber might still need some time in order to be applied with confidence on highly structural components. Nonetheless, it showed how it can be anyway possible to create a bicycle frame with it that, if made a little thicker in certain areas, could bear stresses with more margin. It is important to put effort into this kind of applications, especially because of their structural potential and the sustainable aspect of their production. It is true that epoxy is used to laminate such a material, but the factors to be analyzed when looking at the impact on the environment need to take into account also other aspects: natural fiber production results in lower environmental impacts compared to glass fiber production and by incineration it allows to get energy and carbon credits [11]. Research and development are one of the keys to ameliorate the components and production processes of nowdays and the biking industry as well can't wait to be apart of it, providing to designers and engineers the interesting challanges to overcome and components to study.

List of Figures

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