ECAM
Brussels Engineering School

CONCEPTION ET DIMENSIONNEMENT DU CARÉNAGE DE L'ÉOLIEN GEMINI

HAUTE ÉCOLE LEONARD DE VINCI

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RÉSUMÉ

RESUMÉE

This Project comes when the idea of taking care of the pollution in cities was using wind turbines on buildings was born. There is a concentration of energy when the wind passes through the corners of buildings. GEMINI members validated the idea and efficiency of installing a wind turbine on the corner of a building to transform that wind into electrical energy. Using a specific fairing and structure the wind turbine is able to increase its efficiency.

This Project starts after this validation process finishes. Once the effect is approved to be reached, it is the time to design more accurately the structure where the rotor and alternator will be located and how to concentrate this air to pass through the rotor.

Following the guideline VD 2225 to create an accurate design and to evaluate the different options managed, a first final design is obtained. There is still time to do a tunnel test and to iterate again the process, doing it the performance of the result would increase even more.

After the design is decided, in this stage of the Project it is considered to do two different simulations using CAD software, SolidWorks. A static analysis and a frequency analysis will take part in the later sections of this document.

It is proved that the final design is useful for the utilities required, but it will be desirable to repeat a couple of iterations and to do some other prototypes to be tested before starting to produce the final product.

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Abstract :

Étude, modélisation et dimensionnement de la structure et du carénage du projet éolien GEMINI. Ce travail prend en compte les différents efforts et vibrations engendrés par le vent sur le dispositif. Il comporte également une étude comparative sur les différentes solutions techniques permettant de moduler et superposer les carénages avec un positionnement sur la solution retenue. L'ensemble de ce travail a été réalisé sur base du cahier des charges fourni par GEMINI.

Codification :

12.4 Énergies renouvelables

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MEMORY

1. INTRODUCTION

Wind power production is the technology of converting the energy in the air movement to usable mechanical energy, and subsequently electrical energy. This project is intended to be the continuation of another one from a student of this same school named GEMINI project.

Figure 1.1. GEMINI Project

GEMINI is a start-up who proposes a new solution to produce durable energy innovating the use of wind turbines. The idea is to install mini wind turbines with a special fairing on corners of buildings using the Venturi Effect.

According to the Venturi Effect there is a big concentration of energy on corners of buildings that could be used to create clean energy to empower those buildings. That concentration of energy increases in the high points of buildings, it means this concept is perfect for big and modern cities.

In the previous stage of this project, other team validated the idea of GEMINI wind turbines using software simulation. They determined the right shape and the elements required to the correct operation of the whole turbine.

In this stage of the project, the idea is to finish the design according to urbanistic regulations and other design standards. It will be necessary to determine all the materials that are going to be used. The final design is going to be ready to build and put in place to test it.

All the designs are made using SolidWorks from Dassault Systèmes. SolidWorks is a solid modelling computer-aided design (CAD) and computer-aided engineering (CAE) computer program. It uses parametric feature-based approach to create models, this characteristic is very important for this project because it lets us change all parameters in a short time to iterate options until the final design. We are using the simulation add-in for doing the static analysis, vibration analysis and fatigue analysis.

Chapter 2 considers the theoretical aspects of this thesis essential for the reader to understand all concepts of wind turbines and design standards.

Chapter 3 is considered the development stage. All the methods and tools used are described and explained in detail.

Chapter 4 present the conclusion of the presented work, along with suggestions regarding modifications and further work and analysis in the area of the topic.

2. THEORETICAL BACKGROUND

This chapter consider important theoretical aspects of the thesis. It starts with an introduction to the environmental aspects of wind turbines. Next section covers the aerodynamic aspect of wind turbines from a generic view. Then a brief study of the techniques used in software analysis.

2.1. Wind: General Concepts

2.1.1. Definition

It is considered important for the understand of the current project to explain the concepts of wind, wind energy and wind power.

Figure 2.1. Wind in nature

Wind is a form of solar energy. Winds are caused by uneven heating of the atmosphere by the sun the irregularities of the earth's surface and the rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover.

Wind utilities have been used for many years, ancient mariners used sails to capture the wind and farmers used windmills to pump water. But today the use of wind turbines that generate electricity from the breeze is growing day by day, their use has increased more than 25 percent per year (Renewableenergyworld.com, 2017).

This wind flow is forced to pass through wind turbines to generate electricity. Wind turbines convert the kinetic energy in the wind into mechanical power that can be used for specific tasks or a generator can covert this mechanical power into electricity to power homes, businesses, schools, etc. The power in the wind depends on the wind speed and is proportional to both the wind speed cubed and the rotor area. The general formula for this kinetic energy, in its unperturbed state is given in Equation 2.1.

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A \cdot v_w^3 \qquad [2.1]$$

Where

ρ: Density of the air

A: Area of the turbine blades

v_w: Wind speed

The actual kinetic energy that can be extracted is considerable lower. There are other factors like blade design, generator and rotor used, friction as well as other electrical losses.

In a more generic way, one of the most interesting characteristics of the wind is that the energy contained in its power is proportional to its curve of speed. So, if the speed of the wind is doubled, the wind turbine energy is multiplied 8 times. The result of this point means that very little variations of the wind speed are transformed in very big variations of the energy generated.

The different fluctuations affecting wind power could be sorted:

- Micrometeorological with duration from shares of second about several minutes.
- Mesometeorological with duration from several minutes till several hours.
- Synoptic with period of fluctuations about 4 days, caused by cyclones and anticyclones.
- Global, from a week about one month.

- Interannual variability, connected with fluctuations of radiating balance of the Earth and activity of the Sun.

The smaller the fluctuations, the bigger the effect on quality of the electric power produced by wind turbines. For the purpose of this project we are especially interested in the three first cases of fluctuations, the ones that affect more directly to the consumers. The variability of parameters of wind, wind turbines are recommended to be used in the productions permitting discontinuation of electricity supply, so our wind turbines are only a source of support for the regular energy systems.

2.1.2. Wind Turbines

The history of windmills amounts more than 2000. They have been used basically for grinding grain or pumping water. After 1920, windmills started to be used for wind power conversion.

Existing systems of wind turbines are divided into three classes:

- Horizontal-axis rotors (HAWT): direction of the Windstream is parallel to the axis of wind wheel rotation. The rotation plane is perpendicular to a wind direction (Figure 2.2)

Figure 2.2. Horizontal-axis wind turbine

- Vertical-axis rotors (VAWT): the axis of wind wheel rotation is vertical, so the Windstream is perpendicular to axis of wind wheel rotation (perpendicular to surface of the earth). They work irrespective of the wind direction, the most common one is the Savonius Rotor, and there are others like the Darrieus Rotor (Figure 2.3).

Figure 2.3. Savonius and Darrieus wind turbines

VAWT have advantage over HAWT because they do not have to turn when direction of wind changes, so they could work in all the scenarios. This makes a big difference between them, even if the HAWT have the constructive possibility to produce bigger power, rather light weight relative to unit of power.

2.2. Venturi Effect

2.2.1. Definition

The Venturi Effect is the reduction in fluid pressure that results when a fluid flows through a constricted section of a pipe. It's named like that because of Giovanni Battista Venturi, an Italian physicist.

As the fluid velocity in the throat is increased there is a consequential drop in pressure. The fact that a pressure drop accompanies an increased flow velocity is fundamental to the laws of fluid dynamics (Figure 2.4).

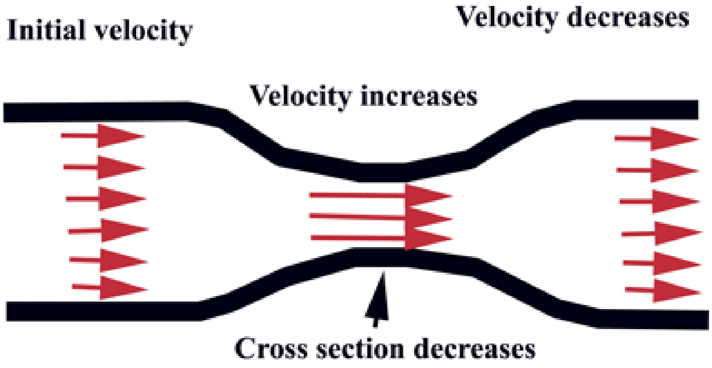

Figure 2.4. Venturi Effect demonstration

2.2.2. Application

The effect Venturi is used in multiple applications, but in this project, it is necessary to explain the increase in fluid speed due to converging and diverging passages between perpendicular buildings.

Observing and analysing the structure of most of big cities in the world, it is obvious that a common characteristic emerges, the urban canyons, similar to natural canyons. An urban area consists of buildings that form the urban surface that repeated is actually the urban canyon. Different heights, lengths, building spacing form geometrically different urban canyons that require different approach. The urban canopy layer is the layer of air from ground to roof level in an urban area and because it affects the temperature, the air quality and the wind speed, it contributes to the wind funnel (or channelling) effect. Generally, the funnel effect is where two adjacent surfaces squeeze the air between them, resulting in an increase in wind speed (Figure 2.5).

Passages between buildings can be responsible for increased wind speed near ground-level that can cause wind nuisance for pedestrians. Several types of passages between buildings can be distinguished, including passages between parallel buildings placed side-by-side, passages between parallel shifted buildings and passages between perpendicular buildings. Depending on the wind direction, the passage in the latter category can be called a “converging passage” or a “diverging passage”. The term Venturi-effect is typically associated with converging passage.

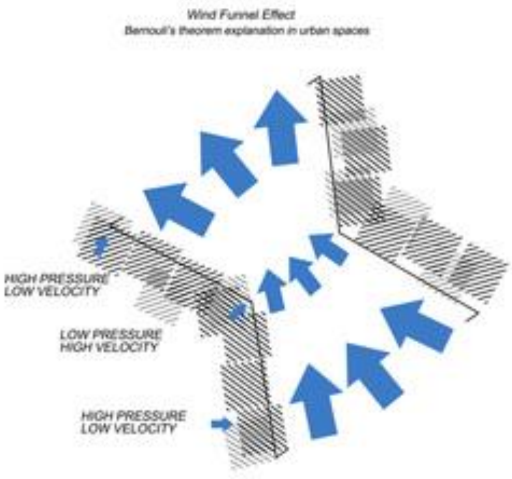

Figure 2.5. Wind funnel effect

We will not describe more precisely how the Venturi effect works because in the previous stage of this project it has been already validated that this effect could be used by our wind turbines to produce energy.

2.3. Computational Fluid Dynamics

Computational fluid dynamics (CFD) are fluid mechanics that uses numerical analysis and data structures to solve and analyse problems that involve fluid flows. Initial experimental validation of such software is performed using a wind tunnel with a required final validation coming in full-scale testing for example.

The primary approach when there are turbulent flows, where the range of length scales and complexity of phenomena involved is extremely difficult to resolve, is to create numerical models to approximate unresolved phenomena.

This type of software is needed to manage how wind works in front of a building, but for the purpose of this project is not very important, as we manage the wind like an approximation of a constant force pushing the structure of the wind turbine. In the previous stage of the project the other team has already studied how turbulences and the boundary layer affect the final result of wind conversion.

2.4. F.E.M. (Finite Elements Method)

The finite element method (F.E.M.) is a numerical method for solving problems of engineering and mathematical physics. The idea is to simplify a structure to facilitate the structural, stress and other sort of analysis.

FEM cuts a structure into several elements, then reconnects elements at "nodes" as if nodes were pins or drops of glue that hold elements together. After this process is done, it results in a set of simultaneous algebraic equations.

2.4.1. The Method

The number of degrees-of-freedom (D.O.F.) for the F.E.M. is finite, contrary to the continuum calculus, where those D.O.F. are infinite.

Engineering phenomena studied, like elastic or thermal problems, fluid flow, electrostatics, are expressed by governing equations and boundary conditions in order to accurate the problem. When the problem is faced, the user normally knows all the equations that determine its elastic deformation or thermal behaviour, but it is not possible to solve it by hand, and there is where the F.E.M. approximations have sense.

When approaching these problems, it is possible to determine properties ([K]) and their actions ({F}), but it is not possible to determine the behaviour ({u}) during the process. It is possible to assimilate those properties ([K]) with their actions ({F}) (Equation 2.2, Table 2.1).

$$[\mathrm{K}]\{\mathrm{u}\} = \{\mathrm{F}\} \qquad \Longrightarrow \qquad \{\mathrm{u}\} = [\mathrm{K}]^{-1}\{\mathrm{F}\} \qquad [2.2]$$

Table 2.1. F.E.M. Properties

	Property [K]	Behaviour {u}	Action {F}
Elastic	Stiffness	Displacement	Force
Fluid	Viscosity	Velocity	Body Force
Electrostatic	Dielectric permittivity	Electric potential	Charge

This approach is similar for all the procedures, but when the geometry of the entire domain is very complex to make the algebraic equations it is needed something more. There is where F.E.M. has importance. The whole domain is divided into a number of small and simple elements (finite elements), where adjacent elements share the D.O.F. at connecting nodes. Each finite element has its own algebraic equations and then they are all put together to solve them, obtaining unknown variables at nodes.

FEM uses the concept of piecewise polynomial interpolation, by connecting elements together, the field quantity becomes interpolated over the entire structure. The help of a big computer gives the user the possibility of doing this interpolation for very big and complex geometries.

2.4.2. F.E.A. (Finite Elements Analysis)

The properly analysis of the F.E.M. is called finite elements analysis (F.E.A.) and it always follows same procedure, it does not matter the software chosen to do the analysis. In the first stage, the user needs to build a finite elements model, with this pre-process, the computer can conduct the numerical analysis to obtain the final results, those are examined by the user to postprocess them and take decisions. This procedure is the same one used for this project.

The first thing to do is selecting the analysis type between structural static, modal, transient dynamic, buckling, contact and thermal analysis among others. After that, and depending of the software used, it is necessary to choose between 2D or 3D elements type; the 2D analysis uses linear calculus, they represent a very simplified process and they are not very used by modern software, the 3D elements requires a quadratic analysis, they could be truss, beams, shells, plates or entire solids. Once the type of elements is chosen is required to set the material properties of all the elements.

At this point is already possible for the user observe the big amount of data it is necessary to manage, and to realize it is not possible to do it by hand if there are more than three or four complex elements.

After defining all properties, it is the moment to make nodes and build elements by assigning connectivity, this process is more commonly known as meshing. The mesh process is a critical part of the analysis, and it is because of that there are specific software to do it, even though modern 3D modelling software reaches high quality meshes with minimal effort. Once the mesh is defined the user needs to apply boundary conditions and loads to the domain, setting the correct nodes to apply those loads.

Everything is checked by the F.E.A. software before solving it. If the domain is very complex, the solution could take hours to be made, and it is required a high-performance computer.

Once the solver is over, it is possible to see results for every variable which has been chosen in the beginning of the process, for example, displacements, stress, strains, natural frequencies or time history.

Even if the process is not very complicated to do for the user, it is remarkable that there are errors inherent in the F.E.A. during the analysis, the most common are:

- The geometry is simplified, so the results are not exactly validated for the initial domain. Even if the meshing process is accurately done, the final geometry used for the analysis is not the same as the initial one. The ideal situation is to have the smallest mesh parts, but the smaller the parts, the more complexity takes the analysis, so it is important to set correctly the mesh. With modern software is possible to use different sizing mesh process, where the mesh elements would be smaller where there are loads and constraints (Figure 2.6).

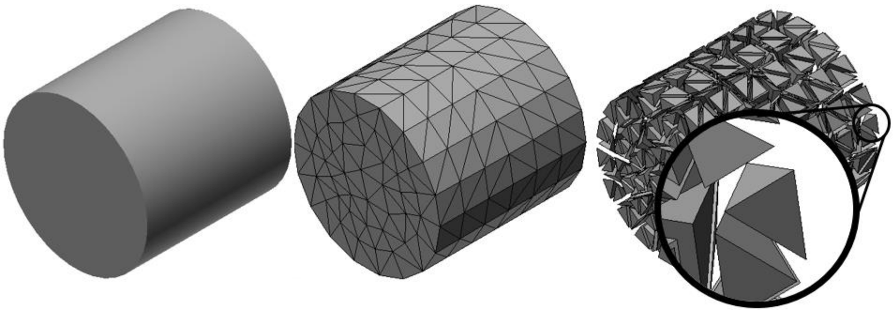

Figure 2.6. Meshing process detailed

- Field quantity is assumed to be a polynomial over an element, which is not true. In case of a deformation, the real deformation appears in a continuous way, but with F.E.A. it changes a lot depending to the properties of the analysis, it could be a linear element (the simplest one), a quadratic element or a cubic element, attending de degree of the polynomial used by the software.

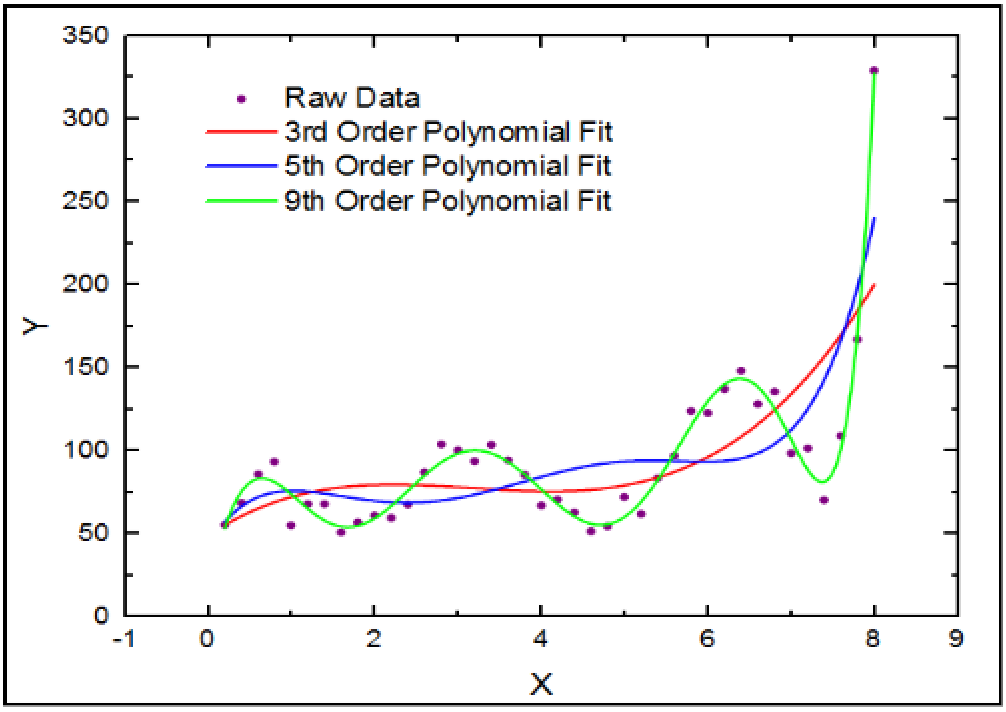

Figure 2.7. Differences between the three approximations

- ✗ Integration techniques used are often very simple, like Gauss Quadrature for example, so the results are just an approximation to reality, and it is not possible to expect the exact same behaviour in the real world. In the same order, computer carries only a finite number of digits, so it is not possible to reach the perfect accuracy of a continuous problem.
- ✗ There is an unavoidable mistake when the properties of the different finite elements change a lot in a small portion of the domain, for example, if there is a very large stiffness difference between two elements of the mesh, the computer has problems to solve it, so the results are not very reliable.

3. DEVELOPMENT

In the third chapter, it is explained the development of the project itself, from where it comes and where it needs to continue after the resolution, explaining every step done in the process.

3.1. Background

This project started one year ago with the Belgian start-up "Projet GEMINI", so the first thing to do was to search all the previous documentation they have already done last year.

They have tested that adding a wind turbine with an outside deflector on the corner of a building it is possible to increase the amount of wind that pass through it.

Using computational design, they have modelled the fairing profile that could increase 500% of the wind power (JANSSENS, 2016). They also thought about the orientation of the building, considering in Belgium there is usually south-west wind.

For decide if everything is useful to export it, they did a wind tunnel test, but it didn't go as planned because of a wrong adapted probe.

In terms of interests for this current project, they have designed the correct fairing shape and they chose the initial correct dimensions required to reach the wind power utilities, using the external fairing, two deflectors and the principal structure. The parameters of study were external fairing radius, stablished after all in 2 meters; the angle of the external fairing, stablished in a maximum of 107º, which means a maximum of 1 metre along the building side; rotor size of 0,75 meters; internal deflector radius of 0,5 meters, as shown in the Figure 3.1.

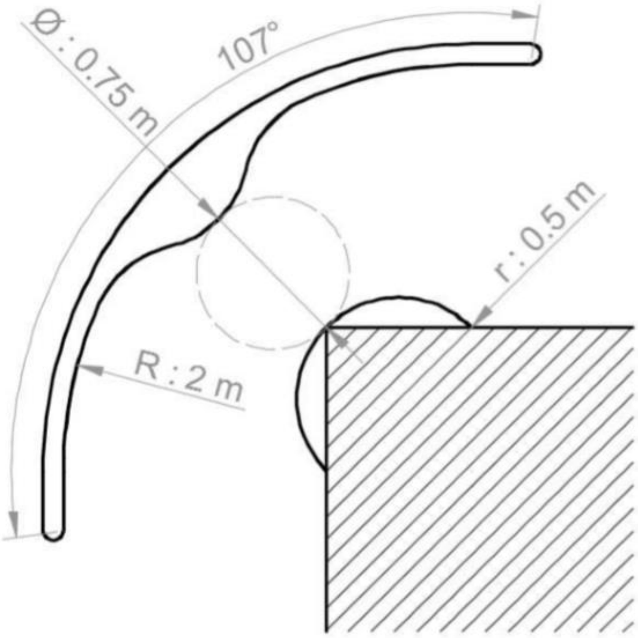

Figure 3.1. Settled dimensions

Once the final shape is designed, it is necessary to determinate the way it will be fixed on the building, choosing a system and the materials to make it affordable.

Just before starting the process of design, the responsible of the project made a background statement where it was possible to see the idea to follow, with the criteria and other important aspects to give importance (Figure 3.2).

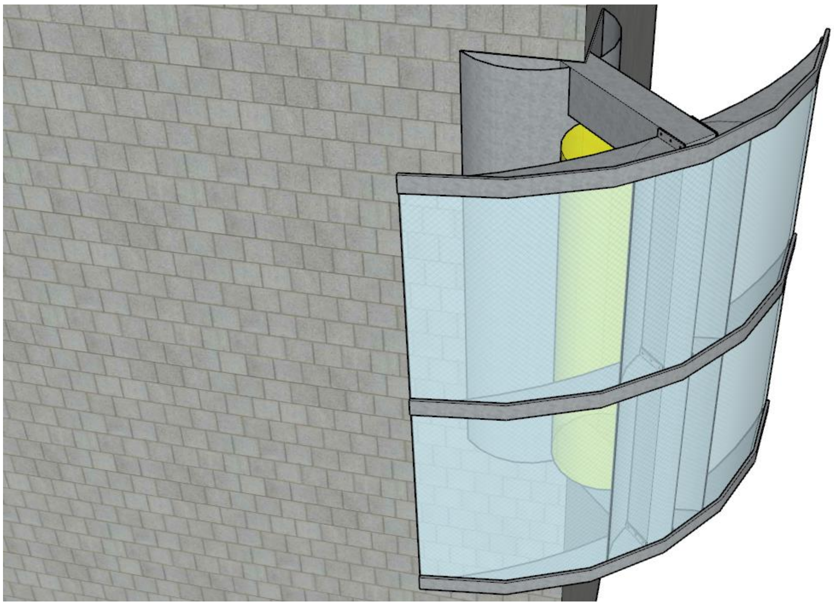

Figure 3.2. Final design idea by GEMINI Project members

With the concept settled, the next point it is to study all aspects that determine the right design to fix the wind turbine to the building corner.

3.2. Design Criteria

Following the natural design process, it is convenient to choose some aspects that will improve the final design. Some of them will finally be just desires, but others will be requirements and there will need to be implemented in the final design.

There will be some aspects that affect only to one part of the complete assembly, but there will also be some aspects that affect it entirely. First, it is important to note all of them, and when all of them are defined, it will be the time to classify them between desires or requirements and their specifications.

All those aspects have been completed and validated by the urban regulation current plan.

3.2.1. Environmental Impact

The environmental impact means the possible adverse effects caused by development, industrial or infrastructural project or by the release of a substance in the environment.

For this project, the possible environmental impact is focused in two levels, noise pollution and landscape integration.

3.2.1.1. Noise Pollution

The wind turbine works very close to windows where people could live, so it is very important to always respect the noise limits for a comfortable life inside the buildings and outside them. The properly design concentrate the aerodynamic turbulences to make them pass through the rotor, so the level of waves in the area is bigger than usual and the noise pollution can happen (Figure 3.3).

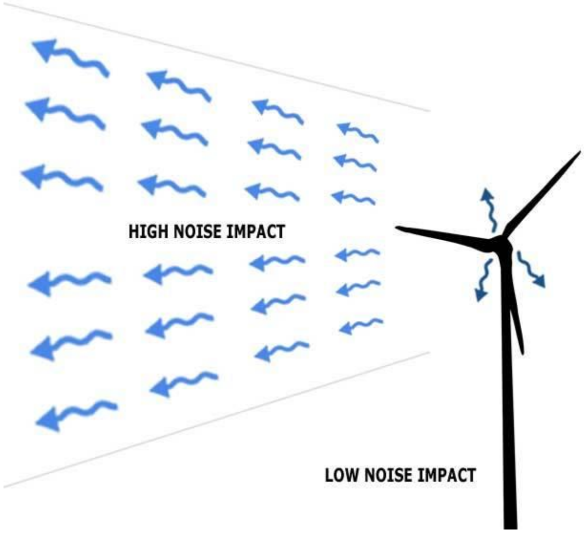

Figure 3.3. Noise pollution

3.2.1.2. Landscape Integration

In terms of landscape integration, it is remarkable that our wind turbines will be placed in the heart of cities and villages, so it is necessary to respect urban regulation plans to keep safe the urban style.

3.2.2. Architectural Integration

This point is similar to the one noted above, but this time is more focused in terms of integration with the building where the wind turbine will be placed. The architectural integration is very important to make a profitable wind turbine, where all materials and shapes need to be in concordance to the building, but at the same point all the wind turbines will be identical, so the design becomes a critical point of the whole project. If the design is wrong or not very accurate, the options of selling it could disappear.

It is very important to respect the naturality of the building, for example, if the external fairing is too large and the windows of the building are placed close to the corner where the wind turbine it would be placed it is basic to keep the light level that pass through them, so it would be necessary to use a glass fairing. This point will be decisive in the choose of materials for the wind turbine (Figure 3.4).

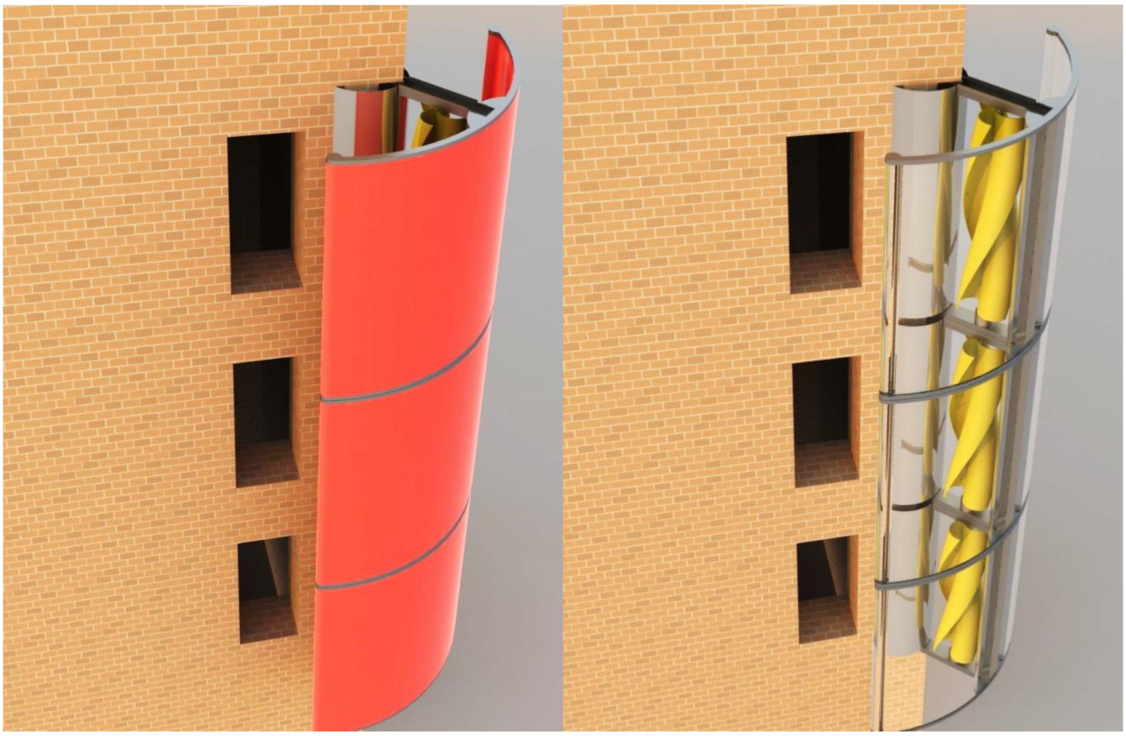

Figure 3.4. Effect of the wind turbine on building windows

3.2.3. External Aggressions Protection

As it is desired the wind turbine would be a durable item, with the less maintenance tasks. It does be important to make a design which could resist all environmental aggressions, vandalism and other unexpected events.

3.2.3.1. Weather Aggressions

In order to avoid weather aggressions, it is necessary to do a design where the water can not stay blocked up because there are many wires and electronic devices that could reduce their time of useful life if they stay wet for a long time. A solution could be the use of an inverted U profile design or designing strategic holes along the structure for the water evacuation following the latest technology of morphology optimization (Figure 3.5). Other options could be the use of specific paintings or coatings that help the drying process.

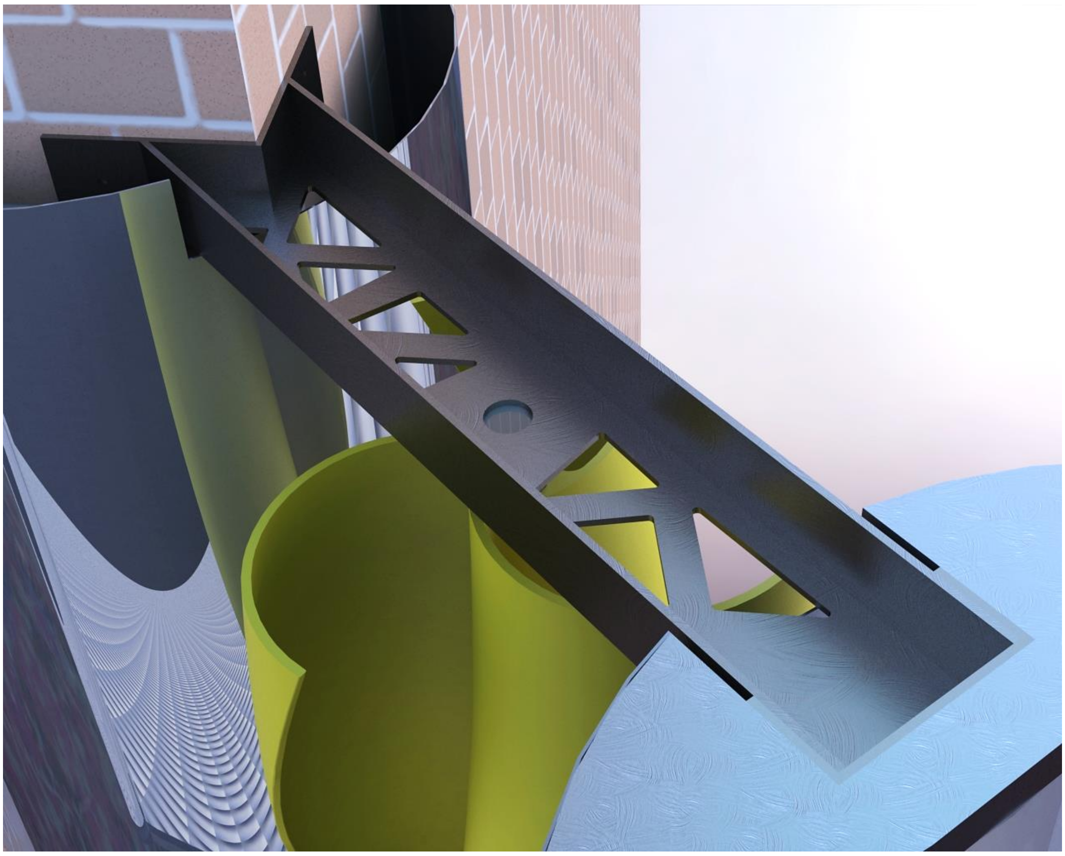

Figure 3.5. Holes optimization to evacuate water

3.2.3.2. Animal Crashes

The wind turbines will be placed on the building with a certain height, so there is a risk for the animals to crash into the fairing or even worse, to crash into the rotor. That issue is critical for the two sides of the problem. If there is a big risk for the animals to crash and die with the use of the wind turbines, the options to sell hem will decrease, and this risk is also basic for the design process attending the desire of a durable device that won't need mayor maintenance tasks. One possible solution is to install nets on both sides of the external fairing (Figure 3.6) and rounding corners to decrease the damage in case of imminent crash (Figure 3.7).

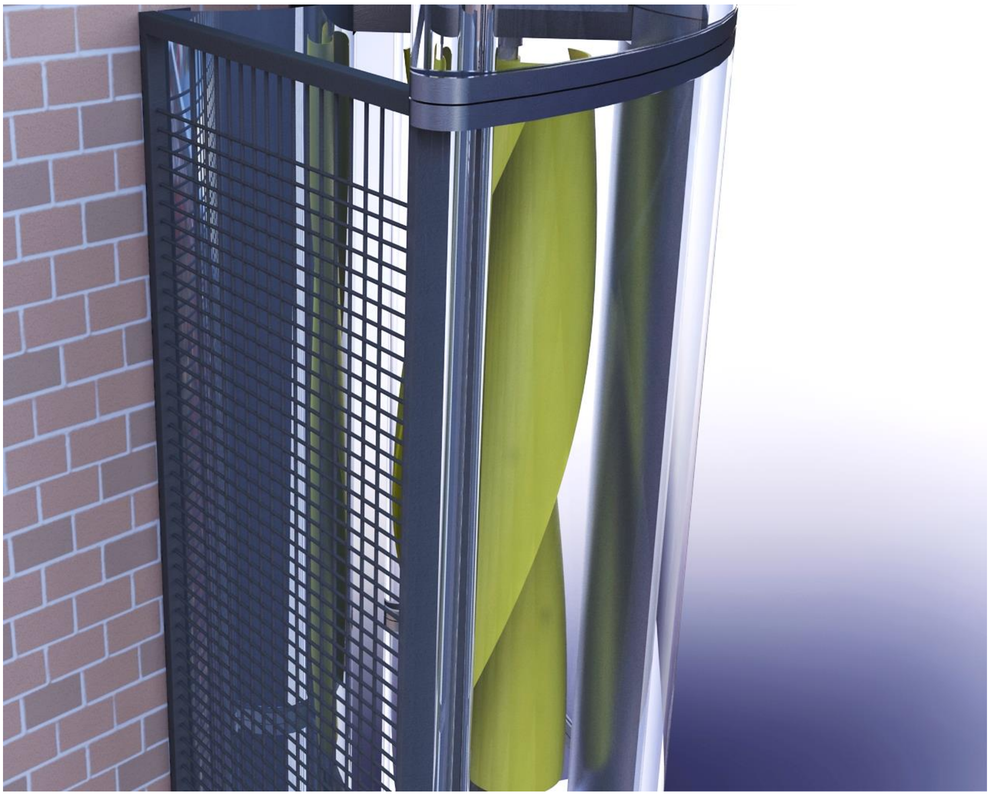

Figure 3.6. Net add-in

Figure 3.7. Rounded corner

3.2.3.3. Vandalism

Even if the wind turbine will be placed with a certain height, it becomes important to keep it safe from possible actions of vandalism. It is important to attend the possibility of people throwing things. The possible solutions is similar to the animals crashes, it would be necessary to install a net in both sides of the wind turbine, with a net size correctly designed to not penalize the air flow but enough small to avoid the entrance of non-desiring objects.

3.2.4. Structural Impact

This design point is basic to reach a great final design. It is vital to avoid or to buffer vibrations, efforts transmitted to the building and fatigue effects.

If everything is avoided, the design becomes perfect, but the problem is that it is barely possible to obtain this result. The correct behaviour would be to buffer the biggest quantity of those effects.

For this point the correct chose of forces, joints and a good design of profile dimensions becomes critical. Luckily it is possible to test the majority of these effects using CAD software and iterating the results until the best solution.

3.2.4.1. Vibrations

Most part of the vibrations generated appears because the wind turbine is spinning all the time, creating vibrations in the axe and transmitting them to all other parts of the assembly. It is also considered important to do an analysis of the natural modes of vibrations generated to avoid them and make the assembly works in other frequencies. Those natural modes of vibrations are the critical points to avoid because a long-term use of the turbine in those modes could become in a catastrophic failure and all the consequences associated; if the wind turbine is placed in a certain height, that failure could mean a drop of all the elements over someone walking on the street.

The complete buffer of those natural modes of vibrations is not reachable, so it is necessary to install anti vibration systems in joints, fasteners and other correct places of the assembly.

3.2.4.2. Efforts on the building

Even if this part of the design is not critical on this stage of the project, it is always something to remember when we are thinking on how to do it.

The design needs to distribute all the efforts along the building. The complete assembly could reach more than 100 kg, so the efforts to the building can not be transmitted just by two simple attachment elements.

It is remarkable again that our design needs to be adaptable to every building with minimal changes, so the restrictions of a weak building are also applicable to the whole design in order to avoid undesirable crashes or failures.

To have an easier maintenance, it is considered important to install fasteners instead of concrete screws. The different types of concrete screws considered are detailed in the Annex Document.

3.2.5. Modularity

The original idea is to make a modular design where it would be possible to put one wind turbine (around 3 meters tall) above the previous one using an easy and fast system, where there will not be a lot of duplicated elements. If this point is achieved, the final result will appear like one only wind turbine all along the corner of the building, but it will not be necessary to design the number of wind turbines in previous stages, they will all fit together without big changes between designs.

The use of modules in product design simplifies manufacturing activities such as inspection, testing, assembly, purchasing, redesign, maintenance, among others. Those models add versatility to product update in the redesign process. However, the connection can be a limiting factor when applying this rule.

After thinking more about the design, it increases the possibility of having at least two designs, one for the buildings where there will be only one wind turbine, and other one attending more precisely the modularity desire.

3.2.6. Easiness of assembly

While thinking in our design, it is important to remember the concepts of design for manufacturing and assembling. A big reduction of costs would be reached is the design is accurate to this methodology.

There are many factors to attend, here the most important for our project are remarked:

- Reduce the total number of parts: this one is a great opportunity for reducing manufacturing costs. Less parts implies less purchases, inventory, handling, processing time, development time, equipment, engineering time, assembly difficulty, etc. Some approaches to part-count reduction are based on the use of one-piece structures and selection of manufacturing processes such as injection moulding, extrusion, precision castings, powder metallurgy, among others.
- Use of standard components: they are less expensive than custom-made items. The high availability of these components reduces product lead times and their reliability factors are well ascertained.
- Multi-functional parts: there can be elements that besides their principal function have guiding, aligning, or self-fixturing features to facilitate assembly, inspection, etc. There also can be elements shared between different components, these parts can have the same or different functions.
- Design for ease of fabrication: select the optimum combination between the material and fabrication process to minimize the overall manufacturing cost. Excessive tolerance or surface-finish requirement are common problems to avoid.
- Minimize assembly directions: all parts should be assembled from one direction. If possible, the best way to add parts is from above, in a vertical direction, parallel to the gravitational direction, because gravity effects help the assembly process.

- Maximize compliance: it is necessary to include compliance in the part design and in the assembly process, like tapers or chamfers; and moderate radius sizes to facility insertion.

3.2.7. Easiness of installation and uninstallation

Installation and uninstallation process have costs related. In order to reduce those costs, it is basic to pay attention in the design process to the factors affecting the easiness of installation and uninstallation. As it is a device to be installed after the building is already in place, there is a preference to has the ability to be installed by a human person instead of a crane.

As it is a 3 meters structure to be placed in the corner of a building it is very difficult to reach an easy positioning for the installation process, but there can be factors to follow in order to simplify it, like assembling just some parts in factory for an easy transportation to the installation place, or if it is more conveniently to assembly it in two separated times or days. Reaching a minimum of operations and with the less changes of directions is also considered very important for this stage.

3.2.8. Easiness of maintenance

The reliability is a desire for every mechanical design, but even if everything go as planned, components have a life cycled determined and there is a requirement to change them following brands schedule.

As the wind turbine has an important electronic and electric part it is important to focus the effort of facilitating maintenance on this part, electronics are usually more sensitives to failures or errors that need to be repaired on place, so if it possible those parts need to be accessible in an easy way. The installation of easy accessible screws and nuts is important here to reduce times and costs of maintenance tasks.

3.2.9. Compatibility

The previous stage of this project was a collaboration between GEMINI members and Philéole, electrical enterprise in charge of all electronics. For the future, it is desirable to do a design compatible with other rotors, the most desirable is to have a structure compatible with all brands, this is not possible, so maximizing this compatibility becomes important.

Factors like designing specific parts for the assembly of the rotor to the main structure are needed to have in consideration. If there is only a plate or another kind of small and simple system to attach the rotor to the main structure it would be easy to design others simple systems depending the rotor used.

3.2.10. Production Objective

It is necessary to always remember the purpose of the wind turbines, they will need to access the electrical current of a private apartment in a building where the electrical current was already designed. There are different permissions and regulation to follow for not disturbing the previous line.

3.3. Design Elements

The main part of this project is to design how to fix the wind turbine to the building attending all the previous criteria and information. This design will have different parts, some of them al more critical than others to the correct performance of the wind turbine.

Once every element is described it will be the time to apply the criteria and eventually to choose the final design.

Above this section, a first concept of the wind turbine made by GEMINI members was shown (Figure 3.2), so here there will be possible to differentiate each element for the analysis (Figure 3.8).

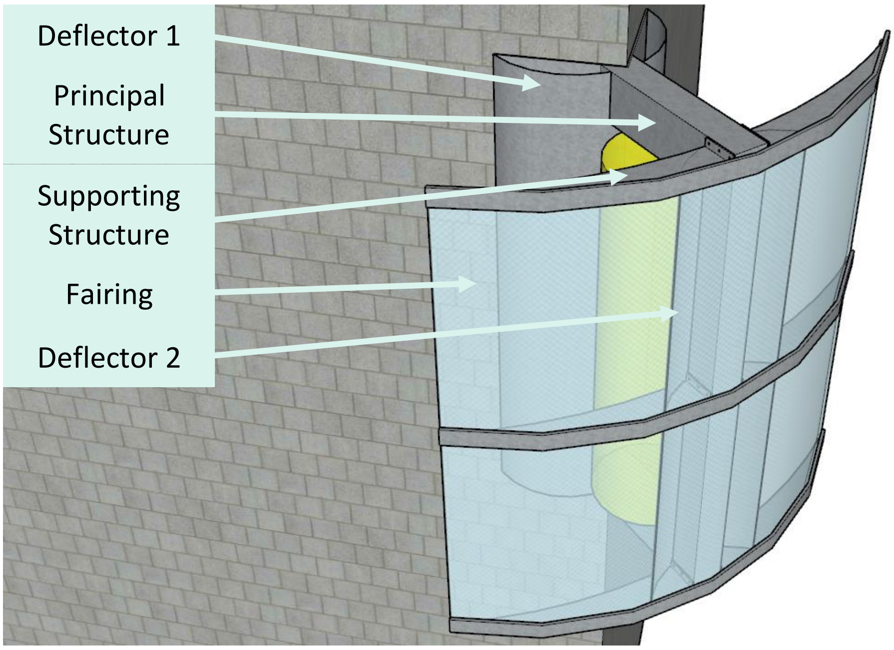

Figure 3.8. First concept of the wind turbine made by GEMINI members

3.3.1. Principal Structure

The principal structure acts like the spinal column of the whole design. Through it all the efforts produced by each element will be transmitted to the building (Figure 3.9).

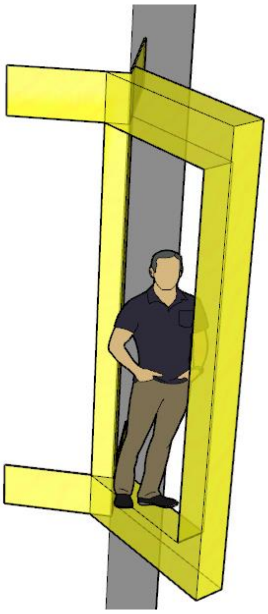

Figure 3.9. First concept of the principal structure

Here there is a list of the efforts to support by the principal structure:

- Vertical loads:
    - Rotor: the main vertical load is the rotor of the wind turbine, it depends of the rotor used, but at least it will need to support without failure or damage the mass of the Philéole rotor used.
    - Human Person: assembling, installing and maintenance tasks will be made by a human being, and considering that the wind turbine is three meters height, that human being could even walk along the bottom profile. Furthermore, the load of a human person is useful to use like a safety factor for every analysis, the effects of other occasional loads will be buffered if we consider in the design process an extra vertical load of 75 kg.
    - Other components: the other components of the fixation assembly will represent a smaller load, but for our analysis it will be presented like a requirement charge to take in count.
- Horizontal loads:
    - Wind: that is the most important load of all the horizontal ones. It is obvious if the wind turbine is made to take the advantage of the wind power conversion, the main structure needs to stay in perfect shape whatever the wind conditions are. With the rotor mass, this is the most important load to analyse.
    - Unexpected loads: bird crashes or other unexpected loads will represent the other part of horizontal efforts. Those efforts will happen just a few times, or even they won't happen, but it is necessary to note them in the analysis to avoid undesirable failures of the structure.
- Torques:
    - Vertical Axis: this is one of the biggest effort to buffer. The rotor is always spinning, so there is a torque generated all over the axis and transmitted to the structure. Depending of the amount of

wind this torque will be directly increased, so it is necessary to design the worst scenario to avoid undesirable effects.

    - Fairing: because of the impact of wind into the fairing, another toque is generated, it is less important than the previous one, but we can not forget about it.

The wind turbine is three meters tall to be able to install the attachment legs where there is a floor, using this parts of the building the efforts transmitted to the building are partly buffered.

The elements to take care about the most in the design process of the principal structure are:

- Fixing system to the building
- Joint elements for these other parts of the wind turbine:
    - Supporting Structure
    - The two existing deflectors
    - Brake system
    - Alternator
    - Rotor
- Place for wires of the rotor and alternator
- Modularity with next principal structure

3.3.2. Deflectors

There will be two deflectors. Those elements are made to concentrate the biggest percentage of wind passing through the rotor with a result of an increase of the wind energy converted.

In the previous stage of the project, the related to GEMINI project members, it has been already validated the existence of this two deflectors and its shape, so the design process here it is only dedicated to the fixing system of both deflectors to the assembly.

3.3.2.1. Internal Deflector

The internal deflector is stuck to the building. As it was said, the design has been already validated, and it consists of a vertical cylinder with a ¾ of radius section.

It is easy to see that rounding the corner of the building the flow of wind passing through the rotor is increased, so its function is critical for the good performance of the wind turbine (Figure 3.10).

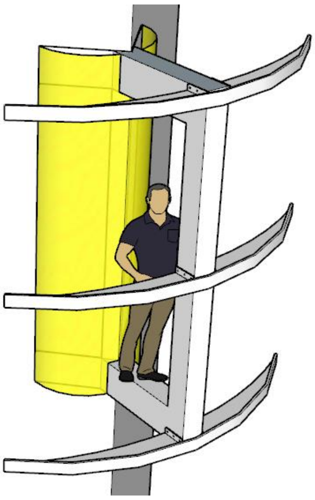

Figure 3.10. First concept of the internal deflector

There will be loads applied to it, but as it is considered stuck to the building, those efforts could be not taken in consideration. Instead, other factors like water and air tightness between the deflector and the building are important.

The connection points to pay attention during the design process for the internal deflector are:

- Principal structure
- Modularity with next internal deflector

3.3.2.2. External Deflector

The external deflector follows same rules than the internal one, it is a vertical cylinder, but this time with a smaller section (Figure 3.11).

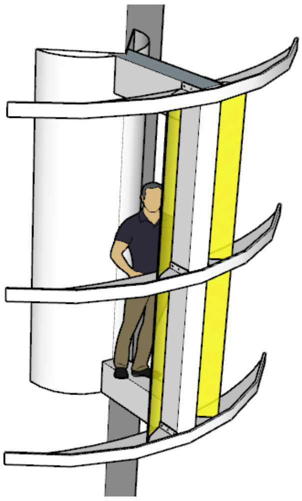

Figure 3.11. First concept of the external deflector

Loads and efforts are also negligible; and problems of water and air tightness take their importance, but with a smaller impact than the internal deflector because it is easier to modify the design of the fairing with evacuation canals.

The connection points to pay attention during the design process for the internal deflector are:

- Principal structure
- Supporting structure
- Modularity with next external deflector

3.3.3. External fairing

This element needs to be accurately designed in order to increase the acceptance of the wind turbine by all customers and users. If a good designed is reached and the aesthetic factors are attended, the wind turbine will not cause a big visual impact for the neighbours of the building where it will be installed or for the pedestrians.

3.3.3.1. Supporting Structure

This supporting structure is meant to be the ribs to harden the external fairing. It will be connected to the main structure using screws and rivet nuts in order to ease the assembly process for thin profiles.

It is composed of three identical elements, two of them place in both extremes of the principal structure and another one in the middle (Figure 3.12).

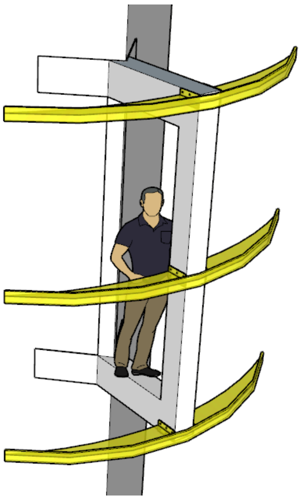

Figure 3.12. First concept of the supporting structure

The main loads this part will need to support are:

- Horizontal loads: there will be an important part of wind effort pushing the supporting structure. This load is transmitted to the principal structure like a torque (already described).

The connection points to pay attention during the design process for the supporting structure are:

- Principal structure
- External deflector
- Fairing

3.3.3.2. Fairing

Finally, there will be an external fairing, which is going to be critical for the final wind turbine. It will be the element everyone see, so it needs to be accurately designed attending beauty and architectural factors.

Aesthetic factors are important, but it is also remarkable that this part will concentrate a big amount of wind flow, both internal and external wind flow will affect the fairing.

Noise pollution also affects this element, as it is the most external element it needs to be designed to buffer the more noise possible. It will be possible to do it if the radius and materials are well chosen (Figure 3.13).

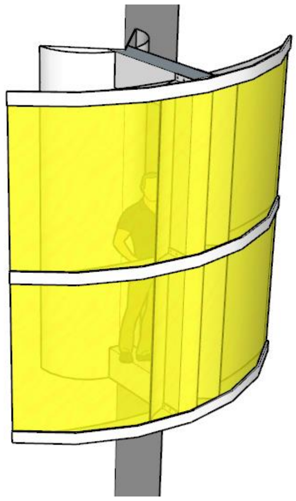

Figure 3.13. First concept of the fairing

The main loads this part will need to support are the same of the supporting structure, but in a lower quantity:

- Horizontal loads: there will be an important part of wind effort pushing the supporting structure. This load is transmitted to the principal structure like a torque (already described).

The connection points to pay attention during the design process for the fairing are:

- Principal structure
- Supporting structure

3.4. Methodology

There is a design methodology for mechanical projects, so after all the design criteria and the elements have been described, it is time to follow every step to arrive to a good solution.

In this section, this design methodology will be introduced and the steps will be described in depth.

First of all, there is an initial approach to the project and the problem to be solved. This part has been already done in the previous sections. As a summary, it is possible to present the *black box* of the problem, where the inputs and the outputs are settled in order to present what does the problem need to do (Figure 3.14).

Figure 3.14. Black box of the wind turbine structure

It is very important to do this *black box* to realize what would receive more attention during the process design. Once this point is done, it is time to evaluate the design criteria we have described before using a list of demands. The concept is to create a list where all these parameters are evaluated as desires or requirements. This first approach is not meant to be mandatory and it could be changed during the design process. On this step, the coordination between the parts interested in the final product is very important, because everyone has his own opinion about which parameters are mandatory or which ones are only desirable (Table 3.1).

Table 3.1. List of demands

Requirement/Desire	Description
Requirement	Noise pollution, focusing on the concentration of wind through the wind turbine and the noise generated
Requirement	Landscape integration, focusing on the respect of all urban regulation plans
Requirement	Weather aggressions, attending on the country (Belgium), it is mandatory to avoid all the bad effects of the weather
Requirement	Buffer vibrations, for avoiding failures
Requirement	Buffer efforts transmitted to the building, for avoiding failures
Desire	Architectural integration, focusing on the concordance with every building
Desire	Animal crashes, focusing on the installation of a net
Desire	Vandalism, focusing on the installation of a net
Desire	Modularity, focusing on the attachment elements to make possible the installation of one or more wind turbines in the same time
Desire	Easiness of assembly, resulting in a reduction of costs
Desire	Easiness of installation and uninstallation, resulting in a reduction of costs
Desire	Easiness of maintenance, resulting in a reduction of costs
Desire	Compatibility, focusing on the advantage of using different brands and types of rotors

Once every parameter is identified and classified, it is time to sort the inputs and outputs with the relevant parts involved in the function of the wind turbine. This is showed with a functional analysis and it is useful in the design process to accurate which parameters will need to be studied before with just a visual exposure. After this analysis, it will be time to start thinking about the different options we could have to eventually arrive to the best final design (Figure 3.15).

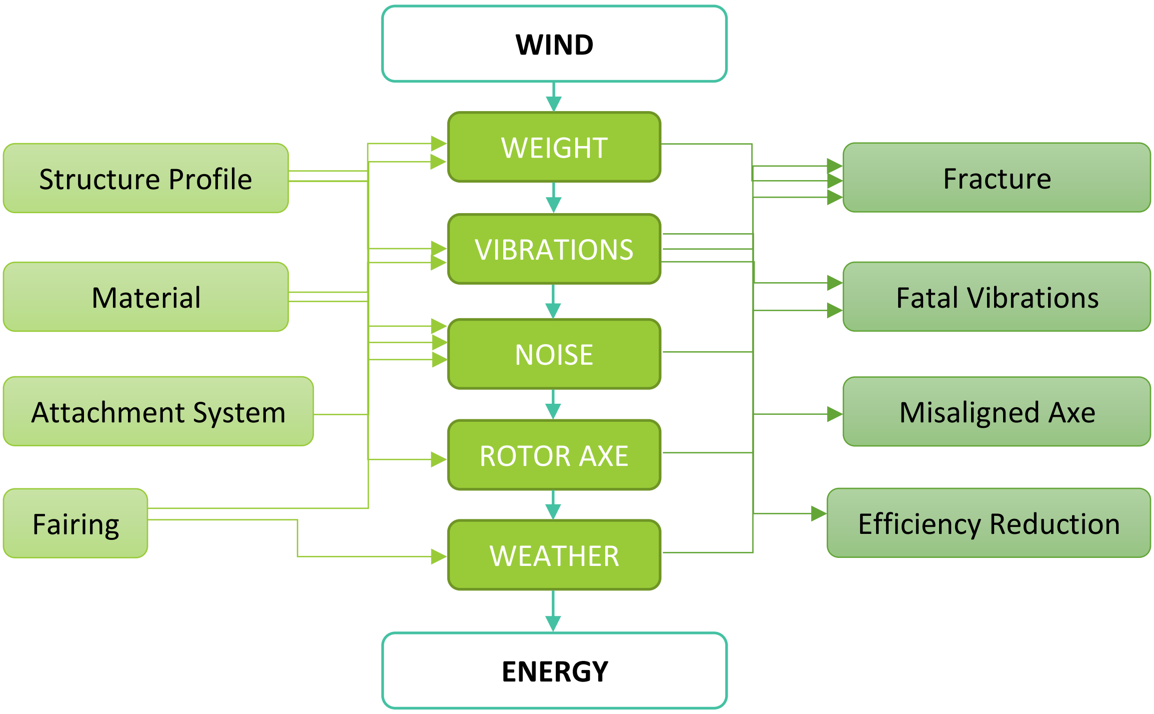

Figure 3.15. Function Analysis

Right now, it is possible to focus the design process on the parameters that affect the most to the final design performance and to start describing the different possibilities designed.

3.5. Design Options

This section will be dedicated to explain de different options that were designed. After doing it, an evaluation of them is placed in order to choose the best one for each element.

The whole designed needs to be focused on the principal structure, because it will support all the biggest efforts, either internal of the design itself or external (already described in the sections above).

3.5.1. Principal Structure

First, it will be necessary to decide the parameters of the principal structure to make it light and tough enough to support every load. After developing the structure, there are two domains were the characteristics could change to modify its response, those are the profile chosen for the bars and the system used to fix the structure to the building.

Every aspect associated to the different options will be described deeper and the right choice will be identified in the final part of this section.

The first concept given by the GEMINI members is taken as a bottom point for the final design, so there will be three bars stuck to the building by two fixing points, and there will be another element between the two fixing pats to reinforced the structure, it could be seen in the Figure (3.16).

Figure 3.16. Initial principal structure

Once the basics are settled it is time to present the different options.

3.5.1.1. Structural Profile

It is preferable to choose standard profiles, they will be cheaper and for managing stocks or logistics everything will be easier. So this will be our specific requirement at this point.

The first option was to use just one square profile, but it was dismissed because it is impossible to accomplish the desire of compatibility with this system. If the client wants to install two GEMINI wind turbines, he will need two double each element of the principal structure. Furthermore, there is no possibility of water evacuation if the profile is closed, so the electronics could be damaged in case of rain.

So, the problem is now to search two profiles and to combine them together to create a final combination that results in just one profile. At least this effect needs to be visually effective to the final users.

There are four options considered:

- Two U profiles overlapped and inverted with another U profile inverted acting like a cap (Figure 3.17)

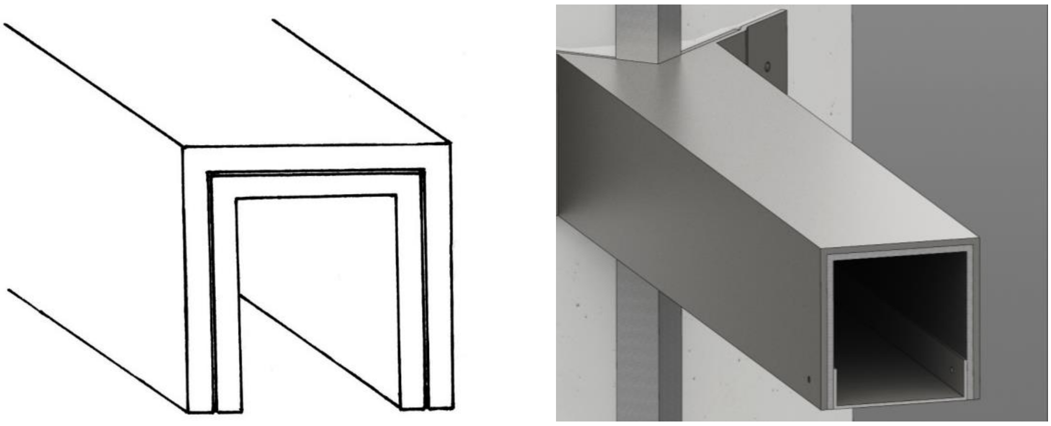

Figure 3.17. Two U profiles sketch

- One U profile inverted and one T profile inverted (Figure 3.18)

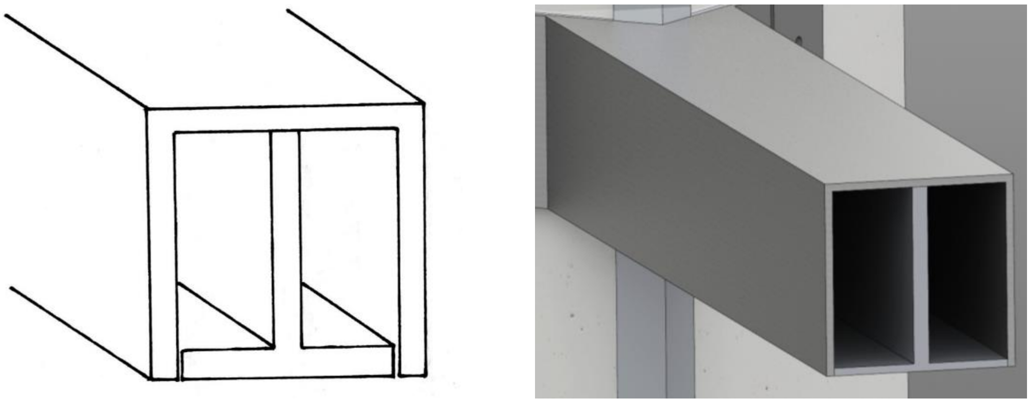

Figure 3.18. U profile - T profile sketch

- One U profile inverted and one H profile (Figure 3.19)

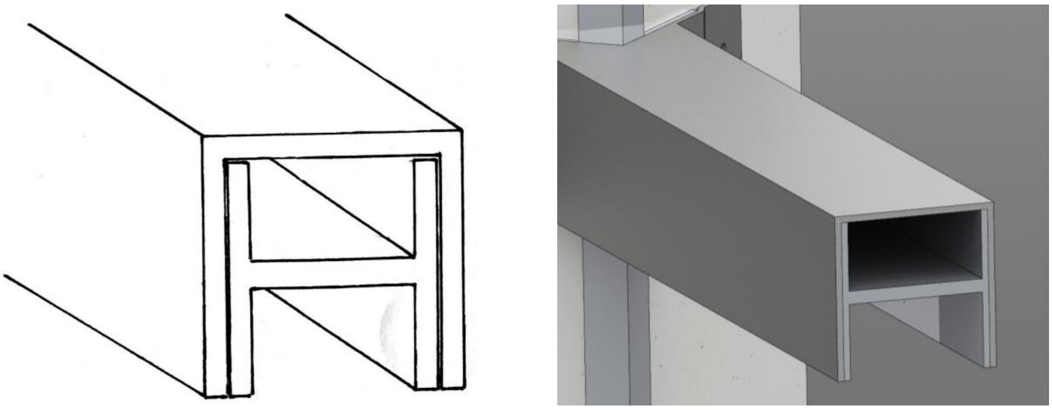

Figure 3.19. U profile - H profile sketch

- Two U profiles opposed to each other with a H profile in between to buffer vibrations and keep both U profiles well positioned. (Figure 3.20)

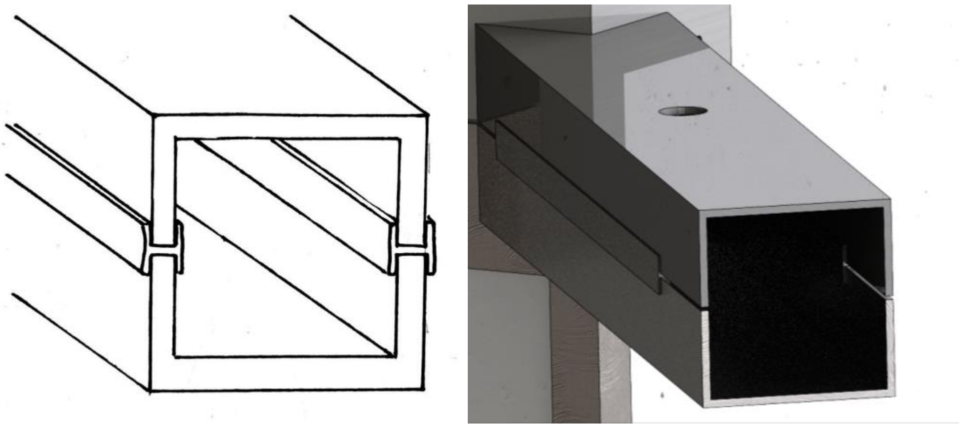

Figure 3.20. Two opposed U profiles sketch

The final design will be chosen at the end of this section to continue with the design process workflow used.

3.5.1.2. Attachment Elements

This part is critical because they transmit all the efforts to the building, and even more important, there will be the only connexion between the building and the whole wind turbine, so in case of failure these parts would have the highest possibilities to be responsible of it. It is desirable to increase the toughness of this part as much as possible.

This part is also critical in order to make de design modulable, because they represent the extremes in both sides of the structure, so they will be the connexion between one structure and the one installed above.

After studying every option, there will be three options considered:

- Z attachment: both pats are joined as a puzzle, it is easy to understand how they work in the Figure 3.21.

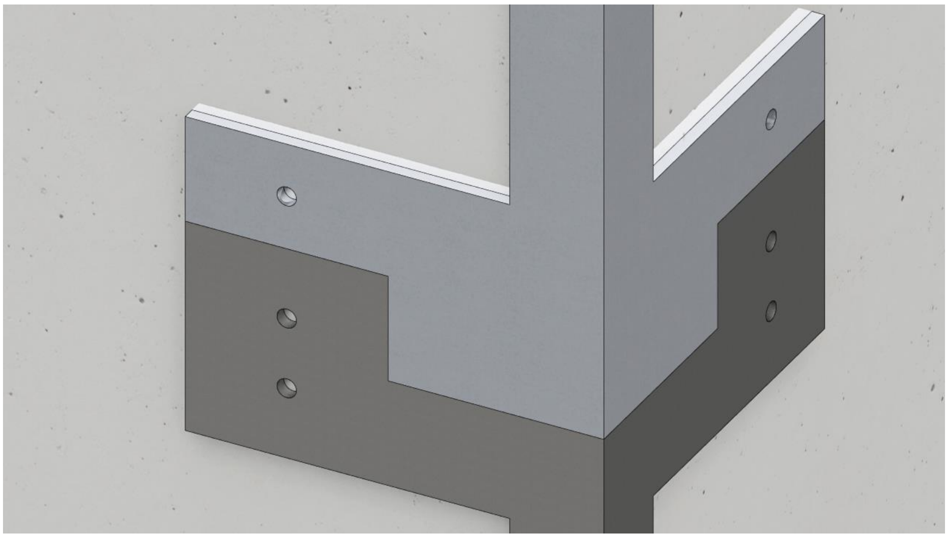

Figure 3.21. Z attachment sketch

- Overlapped attachment: in this one the wind turbine that is supposed to be installed above will overlap the related below it. It is also easier to understand the principle with the Figure 3.22.

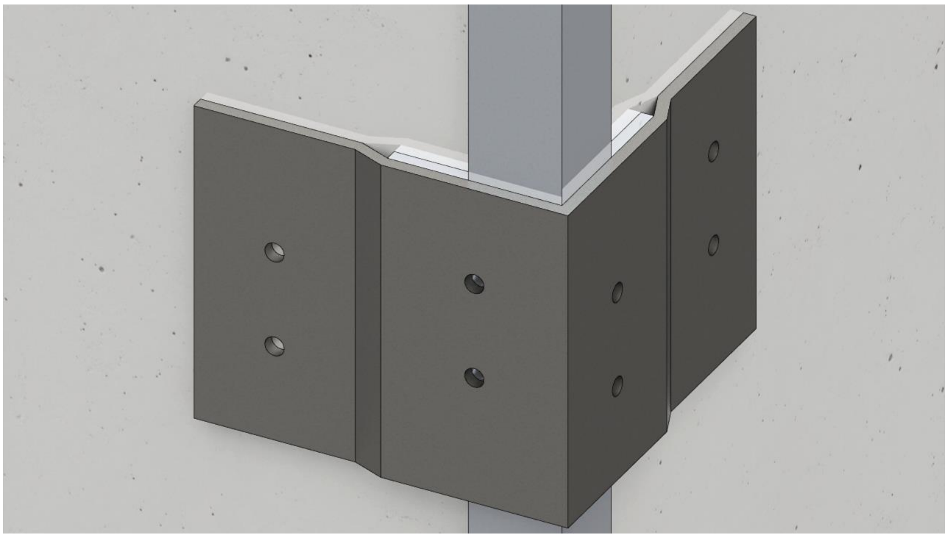

Figure 3.22. Overlapped attachment sketch

- Simple but half-height attachment (Figure 3.23).

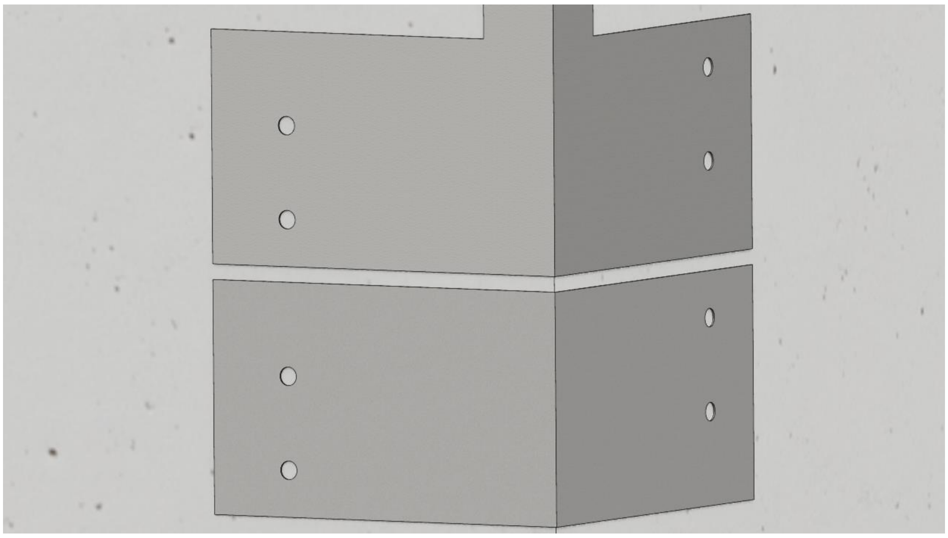

Figure 3.23. Simple half-height attachment sketch

The final design will be chosen at the end of this section to continue with the design process workflow used.

3.5.2. Fairing

The external fairing is another element susceptible of changes, depending on which factors we rather follow. It will change the weight and the stiffness of the whole assembly, so the whole behaviour will change too.

The first option is to put a complete clear plastic fairing as seen as in the Figure 3.24.

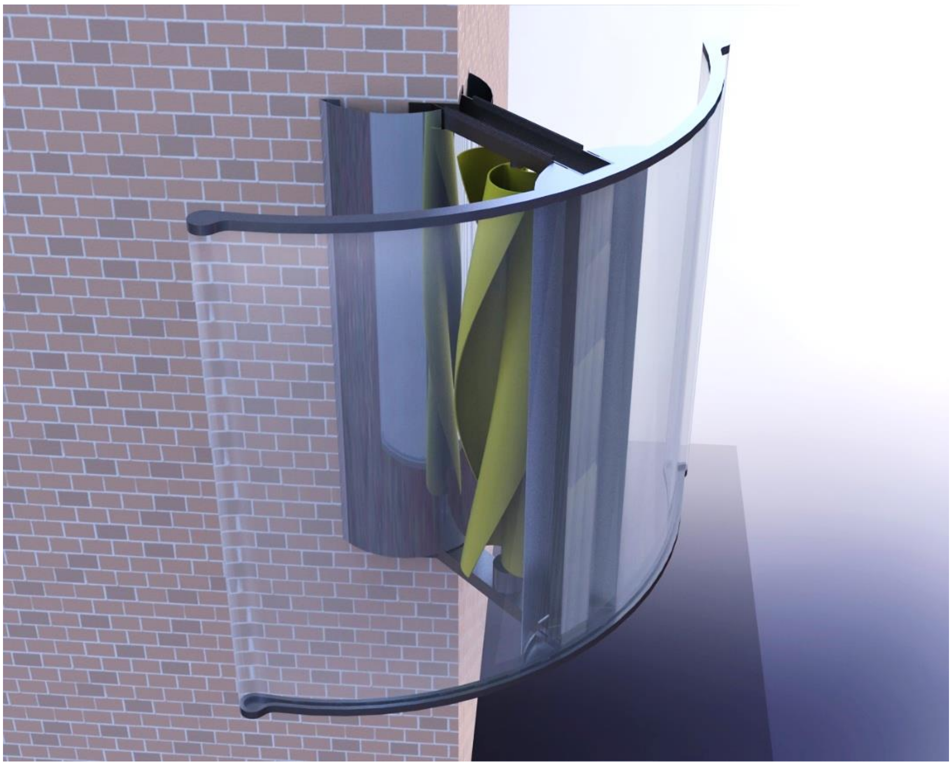

Figure 3.24. Whole plastic Fairing

The second option is to use half-half of the total height in order to increase the toughness of the structure if needed (Figure 3.25).

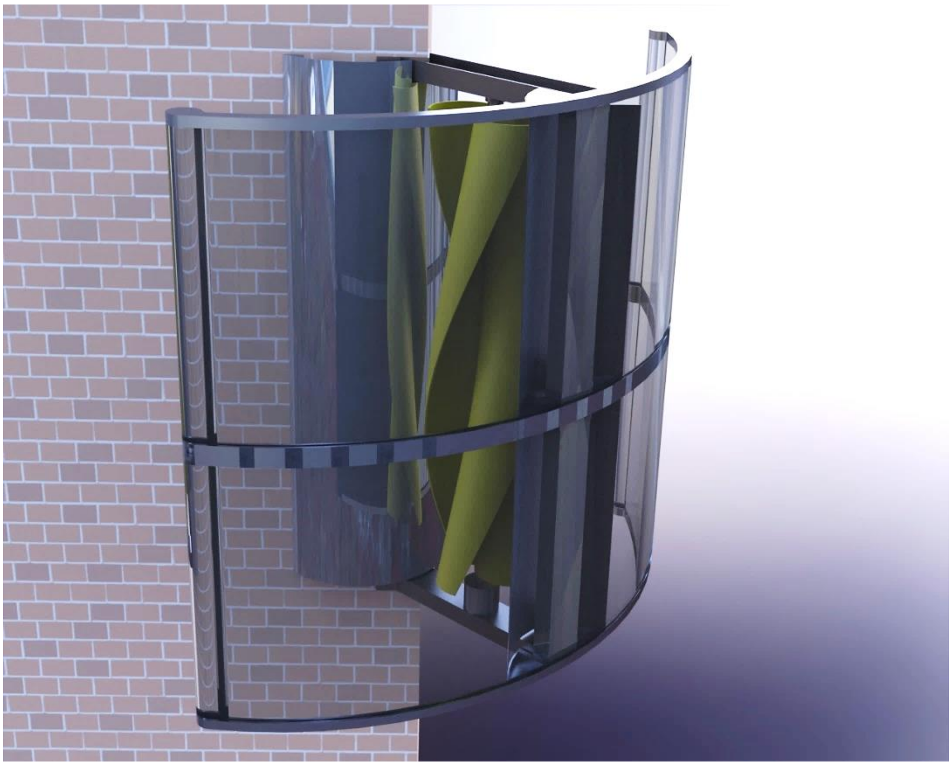

Figure 3.25. Half-Height Fairing

Finally, there is another option more advanced, using an open fairing. This design is too complex to test with a regular computer, so to design it, it would be necessary to contact and pay a professional engineering design enterprise.

3.5.3. Deflectors

Last element susceptible to changes are both deflectors. It is searched a way to attach them easy and fast, so the first idea is to do a complete deflector but letting space for the principal structure.

If an easier way to install it is searched, it is possible to install a partial height deflector, where just one side goes the whole height. It is easier to understand the design by seeing the Figure 3.26. This option increases the easiness of assembly a lot.

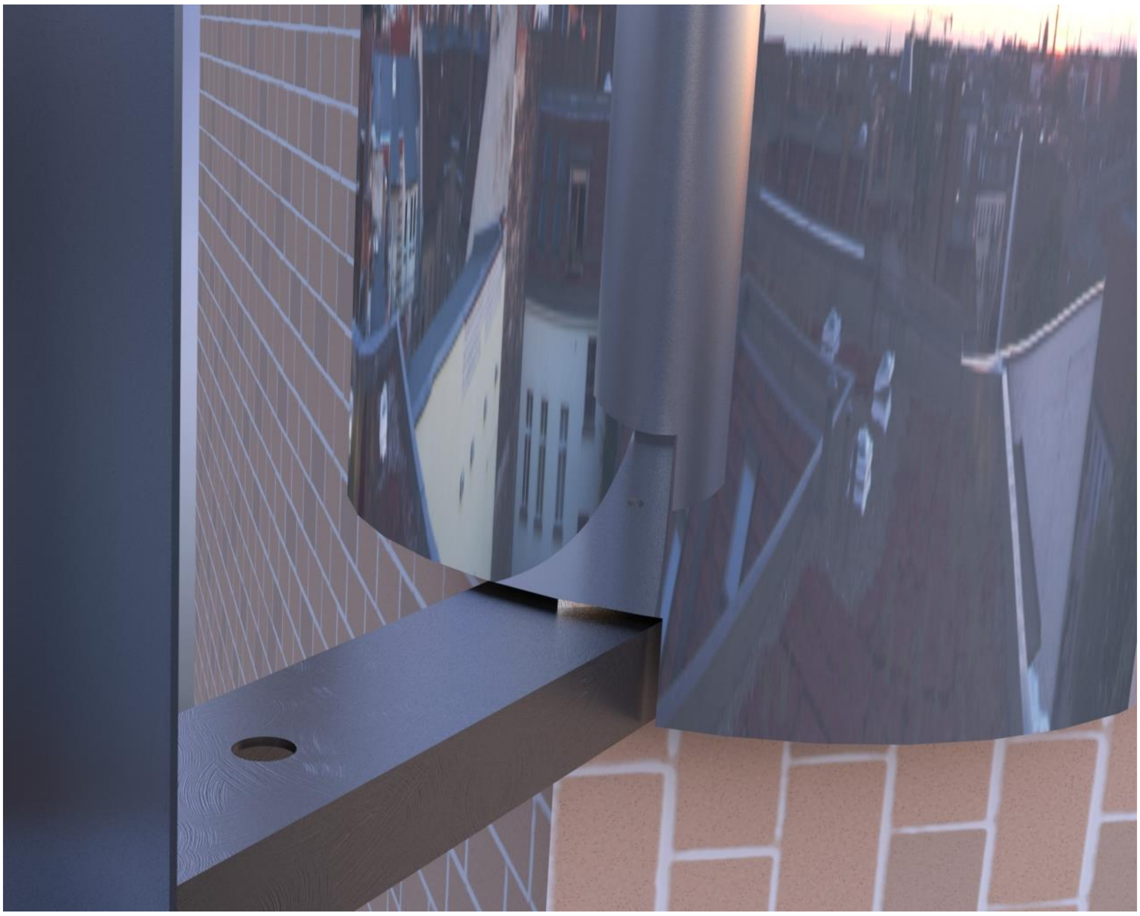

Figure 3.26. Detail of the deflector different height

3.5.4. Final Considerations

Once every option is described, it is time to choose the right one for each element.

In the Table 3.4 is described from 0 to 4 how good each option is for each element following the guideline VD 2225, with the rules applicable noted in the Table 3.2.

Table 3.2. Guideline VDI 2225 criteria

Guideline VDI 2225	
Points	**Description**
0	No satisfactory at all
1	Almost not satisfactory
2	Sufficient
3	Good
4	Very good

To apply the method, it is necessary to assign a ponderation for each factor, it is possible to see ours in the Table 3.3.

Table 3.3. Ponderation for each factor

Description	Ponderation (g_i)
Weight	30%
Cost	25%
Toughness	10%
Durability	20%
Easiness of Installation	15%

The final value for each factor is also determined by the guideline VD 2225, attending this equation:

$$G_{wj} = \sum_{i=1}^{n} g_i \cdot w_{ij} \quad [3.1]$$

Knowing that:

G_{wj}: final value for the variables

g_i: ponderation of factors

w_{ij}: value of the variable j, attending the criteria i

Table 3.4. Different designs evaluation

Description	Value					Final Value (G_{wj})
	Weight 30%	Cost 25%	Toughness 10%	Durability 20%	Easiness of Installation 15%	
Principal Structure Profile:						
2 U Profiles overlapped	1	3	1	2	1	**1,7**
U – T Profile	3	3	3	2	1	**2,5**
U – H Profile	3	3	2	2	3	**2,7**
2 U profiles with H profile	4	3	3	2	2	**2,95**
Principal Structure Attachment:						
Z Attachment	4	3	4	3	2	**3,25**
Overlapped Attachment	1	2	2	2	1	**1,55**
Simple Half-Height Attachment	4	3	3	3	4	**3,45**
Fairing:						
Whole Fairing	2	3	3	2	4	**2,65**
Half-Height Fairing	2	2	4	2	3	**2,35**
Open Fairing	4	0	3	2	2	**2,2**
Deflectors:						
Partial height	4	3	3	3	4	**3,45**
Entire height	3	3	4	3	2	**2,95**

It is easy to see right now which one is the right option for every element in the assembly.

There is still the possibility of changing some decisions if after the iterations of the design and the simulations there is some choice that does not work.

In case of changes for the final design, it is important to repeat this process but this time writing the mistakes and the bad values modified.

3.6. Materials

In this section, the materials used for the wind turbine are described. There are plenty of materials used in industry right now, but our requirements and desires will contribute on the election of the best ones.

The material selection is one of the foremost functions of effective engineering design as it determines the reliability of the design in terms of industrial and economical aspects. A balance between material selection and the design process itself are required to obtain a great and profitable result.

There will be different factors determining the choice of one material from the from another one, these factors can be sorted in categories:

- Material properties: it means the expected level of performance from the material. They could also be classified:
  - Mechanical properties
  - Fatigue strength
  - Young's Modulus
  - Poisson's ratio
  - Hardness
  - High or low temperature behaviour
  - Density
- Material cost and availability: the material is supposed to be priced appropriately and to have multiple sources.
- Processing: the processes used to do the final design are also supposed to be considered here, as they were also important in the design criteria. Those could be casting, machining and welding ability of the material studied.
- Environment: the effect that the service environment has on the part, vice versa; and the effect that processing has on the environment.

The different chosen materials are described and assign to their related elements in the following sections.

3.6.1. Stainless Steel

Stainless is a term coined early in the development of these types of steels for cutlery applications. It was adopted as a generic name for these steels and now covers a wide range of steel types and grades for corrosion or oxidation resistant applications.

Stainless steels are iron alloys with a minimum of 10.5% chromium. Other alloying elements are added to enhance their structure and properties such as formability, strength and cryogenic toughness. These include metals such as:

- Nickel
- Molybdenum
- Titanium
- Copper

Non-metal additions are also made, the main ones being:

- Carbon
- Nitrogen

The main requirement for stainless steels is that they should be corrosion resistant for a specified application or environment. The selection of a particular type and grade of stainless steel must initially meet the corrosion resistance requirements. Additional mechanical or physical properties may also need to be considered to achieve the overall service performance requirements.

The characteristics of stainless steel, notably its corrosion resistance, aesthetic appearance and mechanical properties, make it ideally suited for many architectural applications. Optimum performance is achieved by taking into account these characteristics when designing in stainless steel.

Main factors affecting the performance of the stainless steel are:

- Grade: the grade has a major influence on its performance and needs to be matched to the environment.

- Surface finish: this has an equally important role in determining corrosion resistance. Poor quality polished finishes can lead to disappointing performance of stainless steel.

There is another really interesting aspect about stainless steel. As designers, it is important to believe in sustainable development, and this material is theoretically 100% recyclable and its long-term life makes it an ideal environment performer. The main alloying elements of stainless steel are all highly valuable and can easily be recovered and separated from other materials.

Main characteristics of the stainless steel used are showed in the Tables 3.5 and 3.6.

Table 3.5. Mechanical Properties of stainless steel

Grade	Name Designation	Tensile Strength (MPa) min	Yield Strength 0.2% Proof (MPa) min	Elongation (% in 50mm) min
AISI 304	X5CrNi18-10	515	205	40

Table 3.6. Physical Properties of stainless steel

Grade	Density (kg/m^3)	Elastic Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)
AISI 304	8000	193	0.29	86

Talking about our wind turbine, the principal structure will be made of stainless steel. This part will need to resist the highest level of efforts, torques and vibrations, so it is considered to be made of a high performance material, to make it the most rigid element in between the fairing and the building and enough flexible to absorb the torques of the rotor and alternator.

3.6.2. Aluminium

Aluminium is a silvery-white metal and it represents the 13th element in the periodic table. It is the most widespread metal on Earth and the third most common chemical element on our planet after oxygen and silicon. It was discovered 200 years ago. Aluminium was first used in quantity for building and construction in the 1920s. The applications were primarily oriented toward decorative detailing and art deco structures. After the Empire State Building were built with aluminium in 1930 its use started to grow faster.

One of the most recognized characteristics is that aluminium is the most energy efficient and sustainable construction material. The estimated recycled content of aluminium building materials used today is between 50 and 85 percent.

The most important aluminium performance properties could be sorted following the next list:

- Durability: aluminium alloys are weather-proof, corrosion-resistant and immune to the harmful effects of UV rays.
- Design flexibility: aluminium allows extrusion, rolling, sawing, drilling, riveting, screwing, soldering process among others.
- High strength-to-weight ratio: thanks to the metal's inherent sturdiness, aluminium structures can be very narrow and the material's light weight makes it easier to transport and handle on site.
- Hundreds of surface finishes.
- Low maintenance: this is a major cost advantage over the lifetime of a product.

Primary smelter aluminium is pure and, as such, has a relatively low strength. For extrusions and other manufactured components, the material is alloyed to improve its strength, although even the most heavily alloyed wrought aluminium is still 92% pure.

There are two series of alloys widely used in construction:

- 5000 series work-hardened magnesium alloys
- 6000 series heat-treatable magnesium silicone alloys (those ones are more extrudable and, therefore, offer greater scope for complex shapes).

The typical properties for aluminium are showed in the Table 3.7.

Table 3.7. Physical properties of aluminium

Density (kg/m^3)	Elastic Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)
2689.8	68.3	0.34	27

Finally, the mechanical properties of different aluminium alloys are represented in the Table 3.8 to help the choice of the right material.

Table 3.8. Mechanical properties of selected aluminium alloys [aalco®]

Alloy	Tensile Strength (MPa)	Yield Strength 0.2% Proof (MPa) min	Elongation (% in 50mm) min	Shear Strength (MPa)
1000 series	115	105	10	70
2000 series	365	290	15	220
3000 series	155	140	9	90
4000 series	160	135	3	
5000 series	230	190	13	135
6000 series	260	170	19	170
7000 series	510	435	5	350

This material looks very interesting for the wind turbine. Deflectors and the support structures will be made of an aluminium alloy. Using this material, the loads transmitted to the principal structure are reduced without losing a lot of the mechanical properties required for those parts.

3.6.3. Other materials

At this point is important to give a look to the elements that are not defined yet. There is only one element without material definition, it is the external fairing. In a first place, this element will be done in aluminium alloy, but attending to the list of requirements and desires, the search of a better material is considered.

In order to keep the architectural integration, it will be interesting to find a transparent material. With a transparent material, the light will not be interrupted as much as it is with an aluminium fairing. The visual impact of the whole wind turbine is reduced and if the design and material is well done and balanced, the wind turbine could become a good accessory to the corner of buildings in every city.

So, the research is limited to find a transparent material valid for the wind turbine external fairing, the results are presented below.

3.6.3.1. Polycarbonate (PC)

Polycarbonate plastics are a naturally transparent amorphous thermoplastic. Although they are made commercially available in a variety of colours, translucent or not; the raw material allows for the internal transmission of light nearly in the same capacity as glass.

Figure 3.27. Polycarbonate in building structures

Polycarbonate polymer are used to produce a variety of materials and are particularly useful when impact resistance and transparency are a product requirement, like the wind turbine fairing. Another interesting feature of PC is that it is very pliable. It can typically be formed at room temperature without cracking or breaking, similar to aluminium sheet metal.

Main properties of this material are represented in the Table 3.9.

Table 3.9. Mechanical properties of PC

Chemical Formula	Melt Temperature (ºC)	Tensile Strength (MPa)	Bend Strength (MPa)
$C_{15}H_{16}O_2$	288-316	59	93

3.6.3.2. Ethylene tetrafluoroethylene (EFTE)

Ethylene tetrafluoroethylene is a fluorine-based plastic. It is designed to have a high corrosion resistance and strength over a wide temperature range. It has a relatively high melting temperature, excellent chemical, electrical and high-energy radiation resistance properties.

The importance of EFTE in architectural structures is growing, using it to covers and plastic windows where light is important.

It is a self-cleaning material due to its non-stick surface, and it is also recyclable.

Figure 3.28. EFTE in building structures

3.6.3.3. PET Glycol-modified (PETG)

Polyethylene terephthalate (PET, PETE, PETG) is a plastic resin of polyester family that is used to make products with thermoforming process requirements. It can be injection moulded or sheet extruded.

PETG can be semi-rigid to rigid, depending on its thickness, and it is very lightweight. The main virtue of PETG is that is fully recyclable. It is strong and impact-resistant.

Figure 3.29. PETG in building structures

3.7. Static Analysis

Once every element is defined and the materials are chosen it is the time to start de final design in order to make all the analysis possible to verify it and to make the necessary changes if they are needed.

The final design is the one represented in the Figure 3.30.

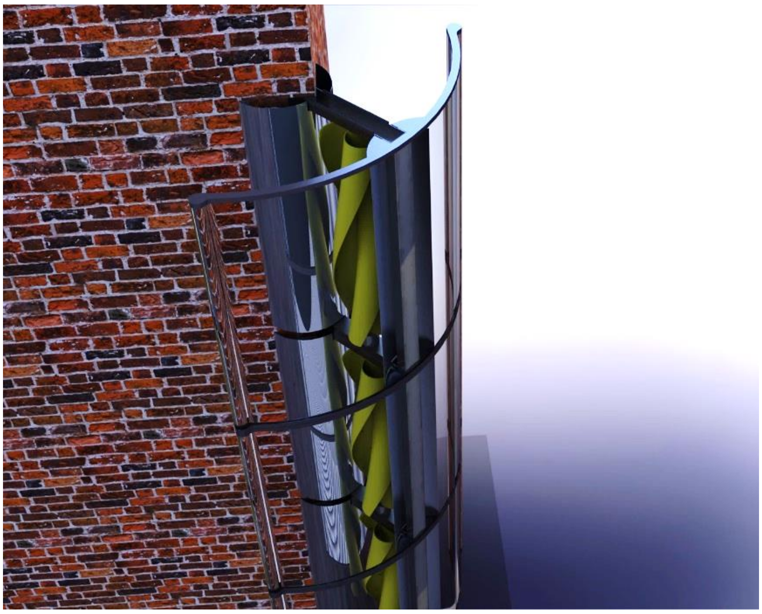

Figure 3.30. Final design

3.7.1. First approximation

First of all, there will be a demonstration of how the SolidWorks simulation works and why we do believe in the results. It was explained in the FEM and FEA sections how the method works, but now we show how the results are approximately the same when the simulation is done using SolidWorks Simulation and when it is done by hand-made traditional calculus.

SolidWorks Simulation is a very useful tool to analyse complex geometries and assemblies, so to prove how it works there are several simplifications in the original model. The principal structure is made of three U profiles made of stainless steel and they are 200 mm wide. After researching catalogues to find the standard size of this profile, we have found three different U profiles, UPE, UPN and U, but there isn't any U profile 200 mm wide, so the options to choose are UPE 200 and UPN 200.

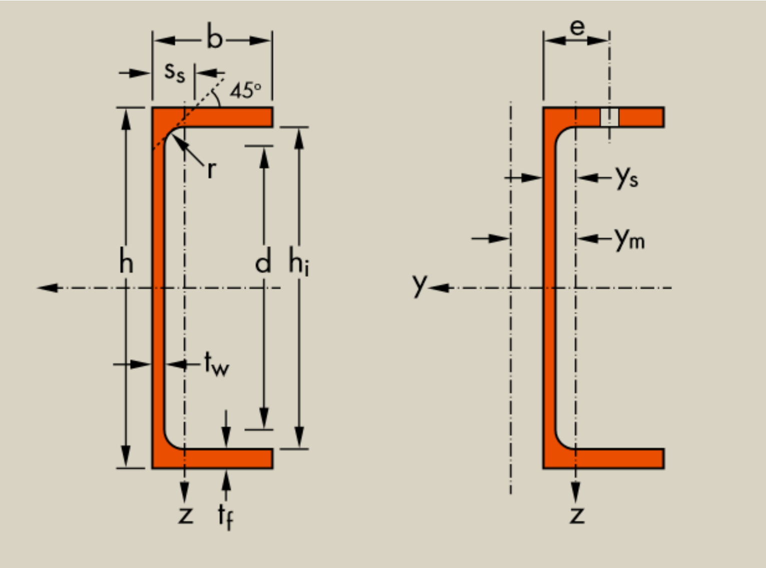

Figure 3.31. UPE Profile dimensions

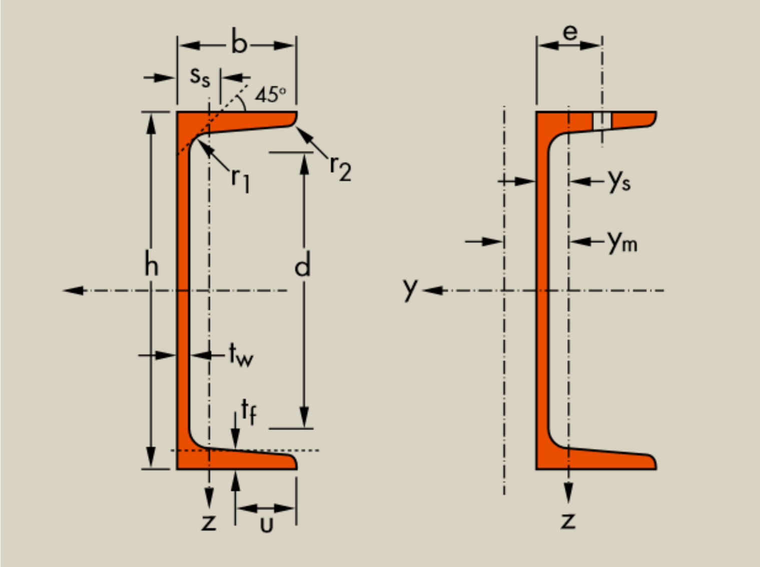

Figure 3.32. UPN Profile dimensions

Table 3.10. Profiles properties for the principal structure

Designation	Dimensions (mm)					Section Properties			
	h	b	t_w	t_r	A (mm^2)	I_y (mm^4)	W_y (mm^3)	I_z (mm^4)	W_z (mm^3)
UPE 200	200	80	6	11	2900	19100000	191000	1870000	34500
UPN 200	200	75	8,5	11,5	3220	19100000	191000	1480000	27000

These are the properties required for the hand-made calculus, knowing that:

$$W_y = \frac{2 \cdot I_y}{h} \quad \text{and} \quad W_z = \frac{2 \cdot I_z}{h} \qquad [3.2]$$

The first step is to define the problem like the Figure 3.50.

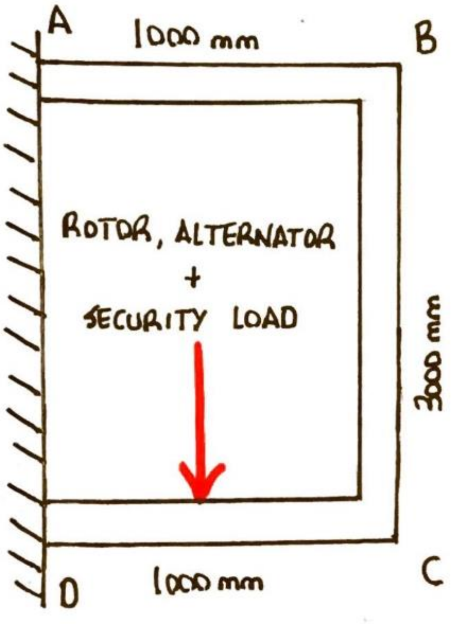

Figure 3.33. Diagram of the initial situation

Once our structure is defined, it is time to draw the bending moment diagram (Figure 3.51), obtained from a porches and beams annex. The load applied in the middle of 1619 N is consequent of the wind turbine mass and a security factor of 75 kg. This security factor is actually the load of a human being walking on the wind turbine structure, there are some install and maintenance tasks where it is desirable for the structure to resist the load of someone walking on the structure.

$$\text{Load: } 90\text{kg} + 75\text{kg} = 165\text{kg} \quad \longrightarrow \quad 165\text{kg} \cdot 9{,}81\, {}^{\text{m}}\!/_{\text{s}^2} = 1619\text{N} \qquad [3.3]$$

There is another simplification, there are two bars of 1000 mm and the other one is going to be three times approximately, 3000 mm, all of them with the same section and material properties.

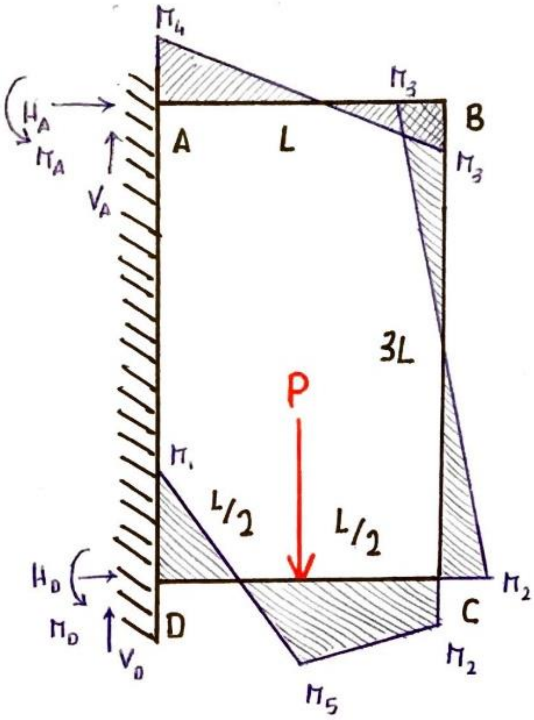

Figure 3.34. Blend moment diagram

The bending moments associated to the diagram are:

$$M_1 = \frac{PL}{4}\left(1 + \frac{3+2k}{4(k+2)} - \frac{3k}{2(6k+1)}\right) \quad [3.4]$$

$$M_2 = \frac{PL}{8}\left(\frac{3k}{(6k+1)} - \frac{k}{2(k+2)}\right) \quad [3.5]$$

$$M_3 = \frac{PL}{8}\left(\frac{3k}{(6k+1)} + \frac{k}{2(k+2)}\right) \quad [3.6]$$

$$M_4 = \frac{PL}{4}\left(1 - \frac{3+2k}{4(k+2)} - \frac{3k}{2(6k+1)}\right) \quad [3.7]$$

$$M_5 = \frac{PL}{4} - \frac{M_1}{2} + \frac{M_2}{2} \quad [3.8]$$

Knowing that k is:

$$k = \frac{I \cdot L}{I \cdot 3L} = \frac{1}{2L} \quad [3.9]$$

The final results for the bending moments are:

M_1 = 490,76 Nm
M_2 = 23,13 Nm
M_3 = 63,61 Nm
M_4 = 166,96 Nm

$M_5 = \quad 170{,}94\ \text{Nm}$

As it is shown in the diagram, the most solicited locations are the A point and the point where the load is applicated.

Using the UPN profile, the results for the section dimensions in our problem are:

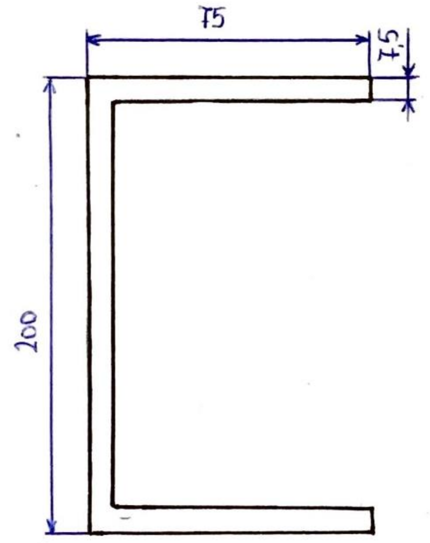

Figure 3.35. Section of the used beam

$A = 2672\ \text{mm}^2$

$I_z = 1312245{,}28\ \text{mm}^4$

$W_z = 34993{,}21\ \text{mm}^3$

The main objective is to calculate the equivalent stress and compare it with the result from the software. The Von Misses equivalent stress is defined like:

$$\sigma_{\text{equiv}} = \sqrt{\sigma^2 + 3 \cdot \tau^2} < \sigma_{\text{admiss}} = \frac{\sigma_{\text{ys}}}{\text{SC}} \qquad [3.10]$$

Where:

σ: normal stress

τ: shear stress

σ_{admiss}: admissible stress limit

σ_{ys}: yield stress

SC: Security Factor

First, it is necessary to calculate the normal stress following the equation:

$$\sigma_n = \frac{M}{W_z} \qquad \text{for } M_1 \text{ and } M_5 \tag{3.11}$$

$$\sigma_{n1} = \frac{497600 \text{ Nmm}}{34993{,}21 \text{ mm}^3} = \mathbf{14,02\ MPa} \tag{3.12}$$

$$\sigma_{n5} = \frac{170935 \text{ Nmm}}{34993{,}21 \text{ mm}^3} = 4{,}88 \text{ MPa} \tag{3.13}$$

After, it is necessary to calculate the shear stress following the equation:

$$\tau_{shear} = \frac{\text{Load}}{\text{Area}} = \frac{1619 \text{ N}}{2672 \text{ mm}^2} = 0{,}606 \text{ MPa} \tag{3.14}$$

Finally, we can calculate the equivalent stress:

$$\sigma_{equiv} = \sqrt{14.02^2 + 3 \cdot 0{,}606^2} = \mathbf{14,06\ MPa} \tag{3.15}$$

The point here is to compare those results with the results obtained from the SolidWorks Simulation. All the simplifications done for this verification are also made to the software model, so the principal structure is simplified in order to be compared more accurately (Figure 3.36).

Figure 3.36. Simplification for the approximation analysis

A punctual load is applied in the middle of the bottom beam, simulating the load of the rotor and alternator plus the load of a human being. The pats are considered fixed to the building. The simulation is run and the results are:

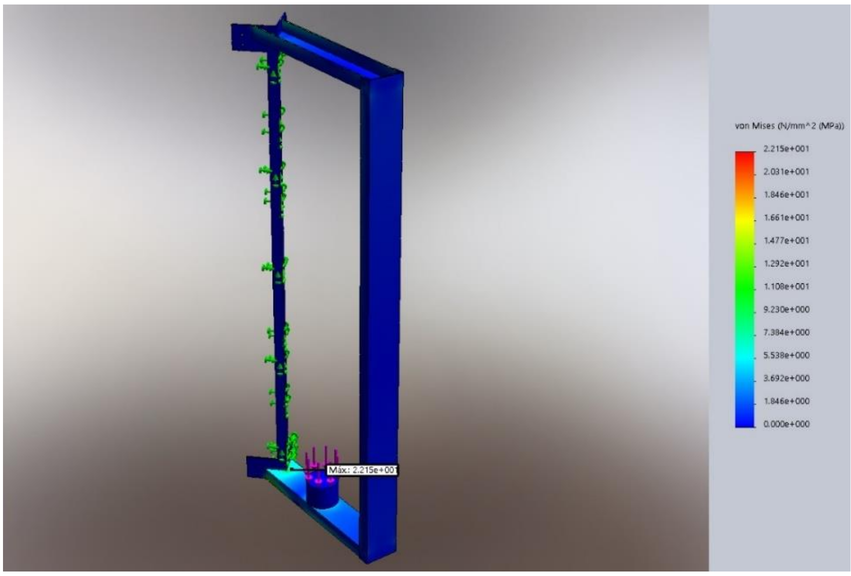

Figure 3.37. Von Mises equivalent stress

The Von Mises equivalent stress is higher than ours (**22,15 MPa**), so the problem now is to discover why is it different. It is considered as the addition of the normal stress and the shear stress, so each one is needed to be verified (Figure 3.38 and Figure 3.39).

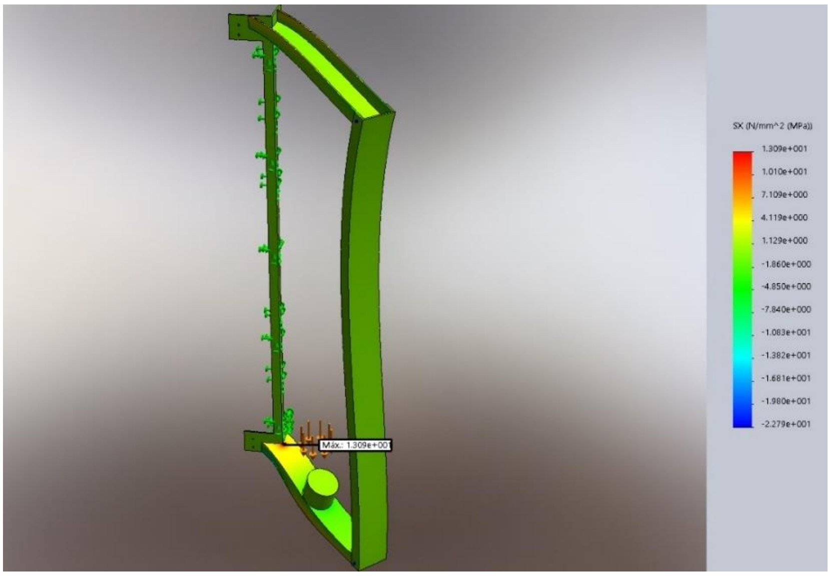

Figure 3.38. Normal stress of the structure

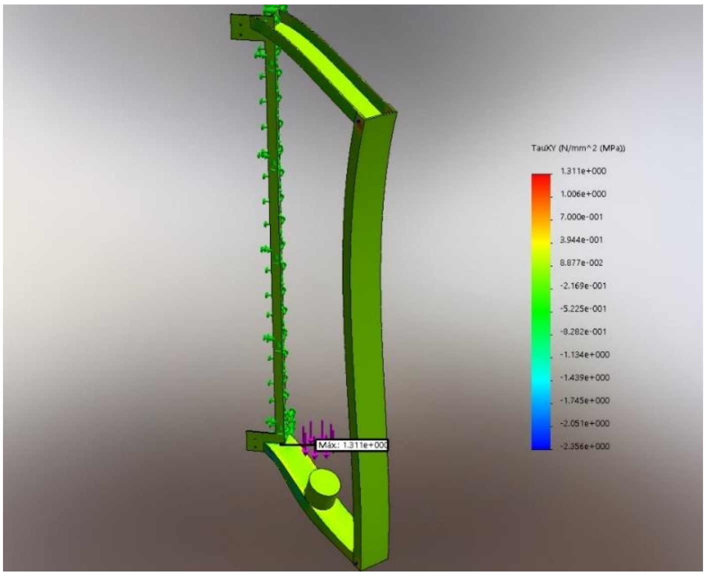

Figure 3.39. Shear stress of the structure

It is easy to see where is the bigger difference, the normal stress is similar to the one hand made, with a value of 13 MPa, but the shear stress has a value of 1,3 MPa, two times the one calculated before. But verifying our analysis, the highest solicited location is where M_1 is placed, the A point. So, it is possible to use the SolidWorks in order to calculate our whole structure, which is very difficult to simulate using traditional calculations.

It is also possible to see that the yield stress noted in the previous chapter is higher enough to support the applied loads, even counting with the security factor. It is seen like a good situation to install the wind turbine, but it is necessary to check if after every element is designed this limit is still higher enough.

3.7.2. Background

Once the software simulation is verified, it is time to prepare the whole simulation. Before, the correct thickness of the profiles needs to be checked, even if the most desirable election is to use a standard profile (7,5 mm of thickness), like we did in the previous demonstration. If we find another profile cheaper or lighter valid for our purpose, it will be the correct one.

After, the other elements are made from these measures, and the simulation is done again to verify that our calculations do not over pass the admissible yield stress of each material for each component.

3.7.3. Union elements and loads

3.7.3.1. Union elements

First of all, the joints and loads need to be settled. We are considering that our structure is fixed to the building, but in this memory, we are not dealing with this fact, so there is a theoretical perfect attachment between the building and the principal structure.

The principal structure has two elements, one with the two horizontal beams welded to the attachment pats and another one vertical beam, joined by screws with rivet nuts. This principal structure is made in stainless steel.

The support structure and the fairing are also attached to the principal structure using screws with rivet nuts, they are very useful for the maintenance tasks. The idea is to use the lower number of screws and nuts, so the design is focused on creating self-oriented elements, those elements are easy to place and they would need the minimum number of screws just for keep them safely attached. That is the idea used to place the fairing respect the support structure (Figure 3.40).

Figure 3.40. Union of support structure and external fairing

The deflectors are also designed to be self-oriented with the minimum number of screws.

Both deflectors and the supporting structure are made in aluminium, and the external fairing is made in transparent plastic.

3.7.3.2. Loads

The loads considered in the following procedures are the security load of a human being, like it was considered in the previous calculations, the proper load of the whole structure mass and the average wind of Belgium, obtained from the official database.

The average wind speed in Belgium is 4 m/s with a maximum of 30 m/s.

The human being load will be placed all along the base beam of the principal structure.

For the wind load, it is more difficult to simulate it, the ideal study starts by a flow simulation, where an equivalent wind load is obtained and it is used to the static or frequency analysis in addition of the other ones. In our case, we are using a direct equivalent load, calculate using the following equations:

$$\mathrm{F} = \mathrm{A} \cdot \mathrm{P} \cdot \mathrm{C_d} \tag{3.16}$$

Where:

$$\mathrm{A} = \text{section affected area} \tag{3.17}$$

$$\mathrm{P} = 0.613 \cdot \mathrm{v}^2 \tag{3.18}$$

$$\mathrm{C_d} = 1.4 \text{ (plane and not very big surface)} \tag{3.19}$$

The power of the wind is calculated using an equation from the American Society of Civil Engineering (ASCE)[1], the 0,613 coefficient comes from common values of air density and gravitational acceleration

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[1] http://www.asce.org

So, if it is considered the whole turbine receiving wind as a plane surface, the load is 404,11N, but if it is only considered the wind affecting one profile, the load per profile is 10.10N.

A remote load/mass affecting all the surfaces in the direction of that load will be used in the simulation process to simplify the calculations.

3.7.4. Procedure

3.7.4.1. Thickness Analysis

The first approach to the final design is made designing the principal structure. Once the U profile was validated, it was time to do the thickness analysis to find the perfect match for our purpose.

In the analysis, the thickness is modified between 2 mm and 10 mm to see the impact of those changes in the response of the structure having in consideration only the weight of the rotor and the alternator. The geometry of the rotor is so complex for analysing using a regular computer, so knowing that simplifying it, it does not affect to our results, there will be the following simplification (Figure 3.41).

Figure 3.41. Model modification for static analysis

All the screen captions are added to the annex, here there is only be showed the final mesh structure in the Figure 3.42 and the final results of maximum values in the Table 3.11.

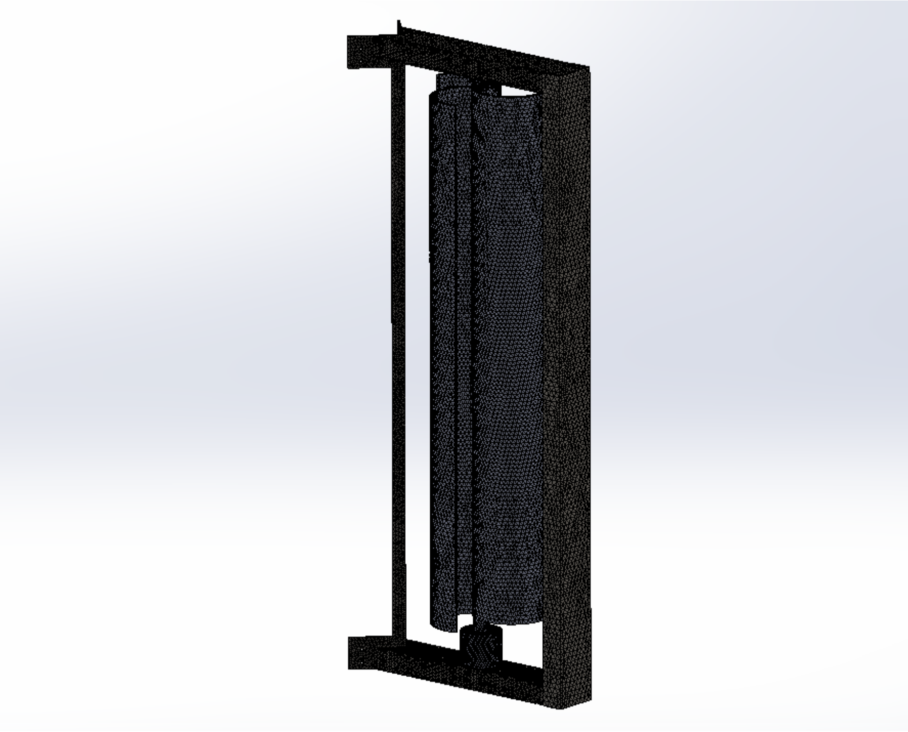


Figure 3.42. Final mesh

Table 3.11. Results of maximum values of the static analysis

Profile dimension (mm)	Von Mises stress (MPa)	Displacement (mm)
2	57,78	0,53
4	31,50	0,34
6	23,35	0,28
8	20,33	0,26
10	17,83	0,21

It is considered important to do a diagram to reflect this variation in a more visual way, to understand how the behaviour changes with the profile thickness.

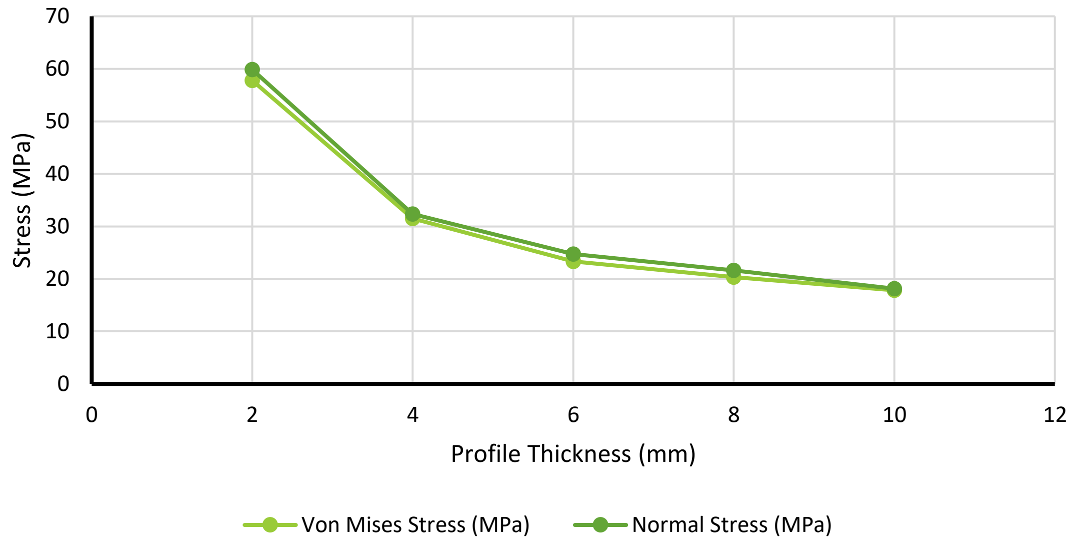


Figure 3.43. Diagram of impact of the thickness in structure behaviour

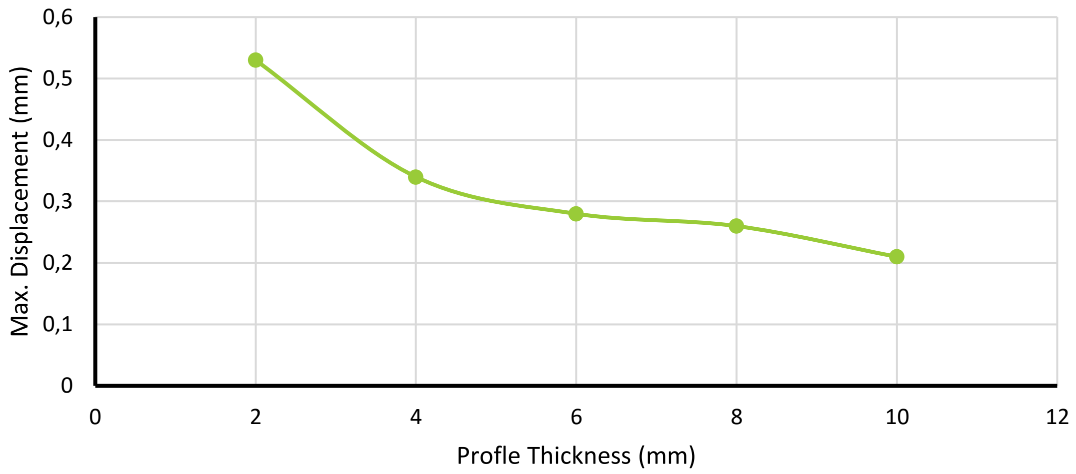


Figure 3.44. Diagram of impact of the thickness in the structure maximum displacement point

It is easy to see the big reduction of the stress or the displacement between 2 mm and 4 mm, this reduction is less important between 4 and 6 and even less important between 6 and 8, where all the standard profiles where placed in the catalogues. So, our plan of using a standard profile is validated for our structure.

It is also possible to observe that even after reducing the simplifications used in the previous demonstration, the results for normal tress and equivalent stress are still coherent with those obtained from handmade traditional calculations.

From now, our profile will be defined with 8 mm thickness.

3.7.4.2. Complete Analysis

The procedure continues by designing the rest of the elements until the fairing is complete. As it is seen in the picture, this is the aspect of our final wind turbines, more precisely in the situation of more than one wind turbine is installed.

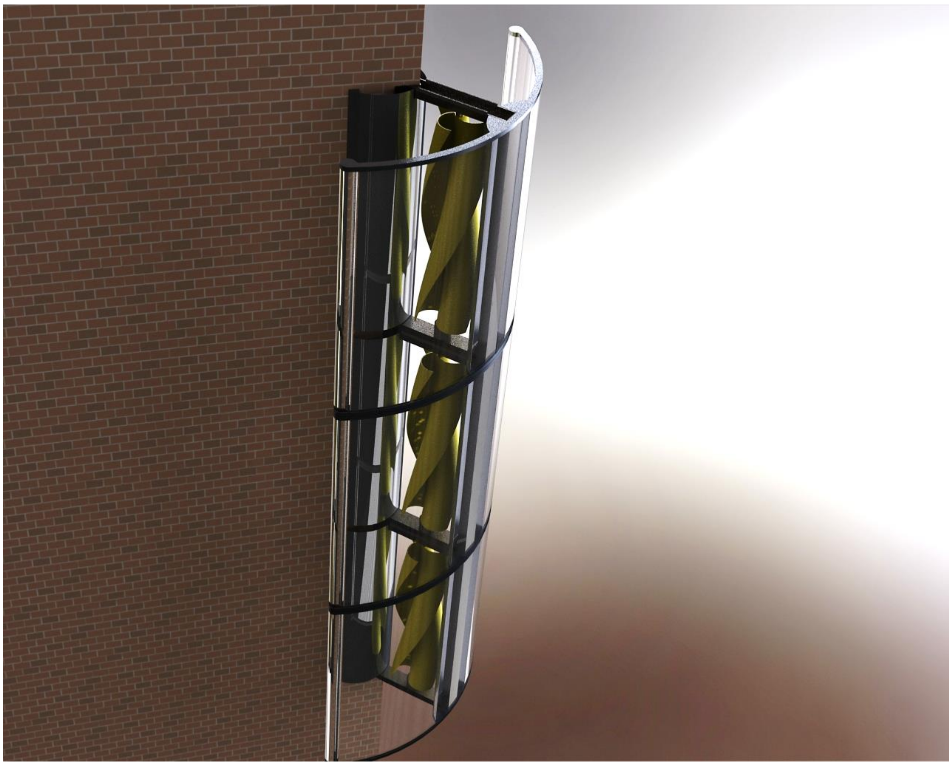


Figure 3.45. More than one wind turbine installed

Even if this situation is possible, the study will be done using only the cases with one wind turbine. After doing the analysis it was considered important to notice the difference between the importance of also run the analysis with at least one more wind turbine assemblied.

The already used simplification of the rotor is used here too, because the complexity of the whole geometry is still very high to run the simulations if the blended rotor is used.

Figure 3.46. Right rotor for simulations

The first step is to assign materials for each element, after that, it is necessary to say where is going to be the fixed part. There will be four fixed surfaces, the four ones touching the building, because if there are less elements to be analysed, there will be less mistakes associated and because in our project we start with the attachment elements settled. Then, it is the moment to add the external loads, the gravity force and the wind force.

Wind load is simulated using a simplification. As we said in a section above, the ideal is to use a flow simulation of the wind passing through the rotor, but we are using the equivalent load we have calculated before (404,11 N) to reduce the complexity of the problem for the software. This load is going to be a remote load affecting every structure from one side, simulating the action of wind (the detailed images of how this loads and fixed parts are settled are described in the Annex 2 Document).

Finally, it is necessary to mesh every element to run the analysis. Once the mesh is done, the geometry is the one shown in the Figure 3.47.

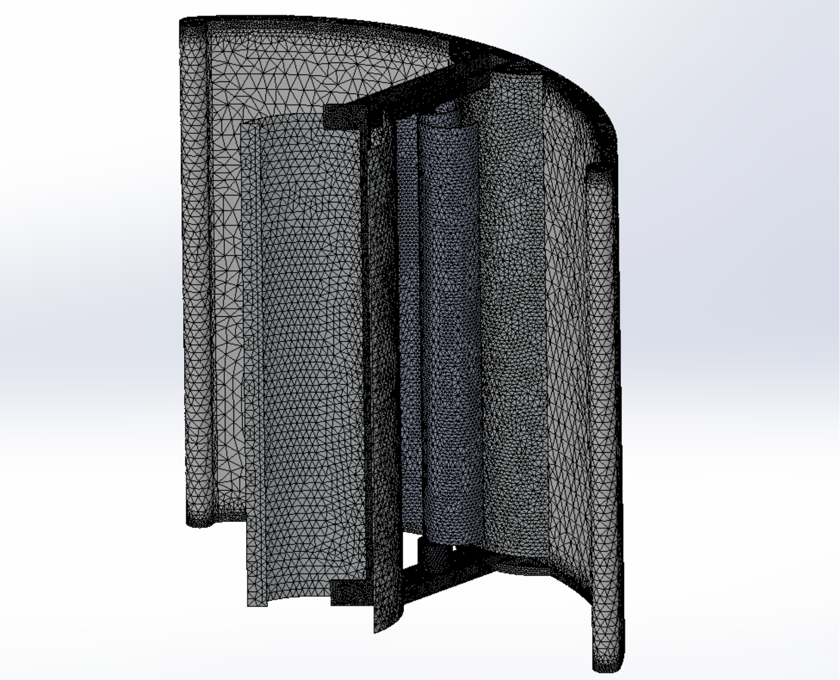


Figure 3.47. The whole turbine structure meshed

3.7.5. Results

Once the parameters are defined and the assembly is correctly meshed, it is the time to run the analysis.

From the analysis, we obtain the Von Mises stress and the displacements generated while the simplification of the wind simulation is happening in the real world (with the gravity effect).

In the Figure 3.48 and 3.49 is possible to see those results coloured.

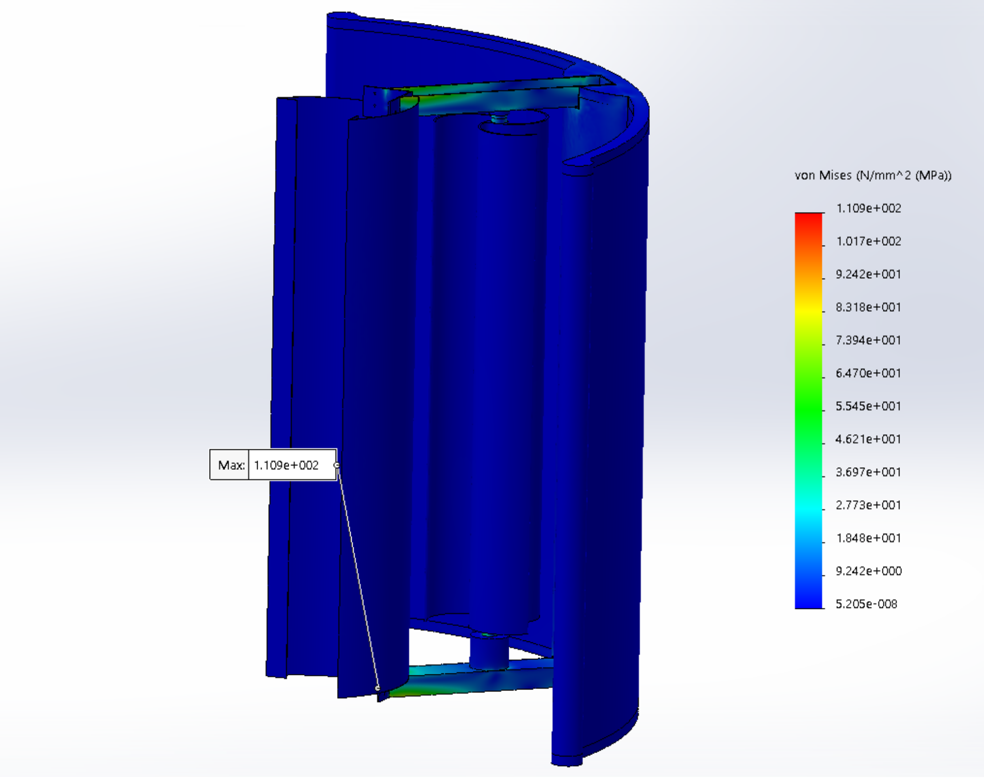


Figure 3.48. Von Mises stress results

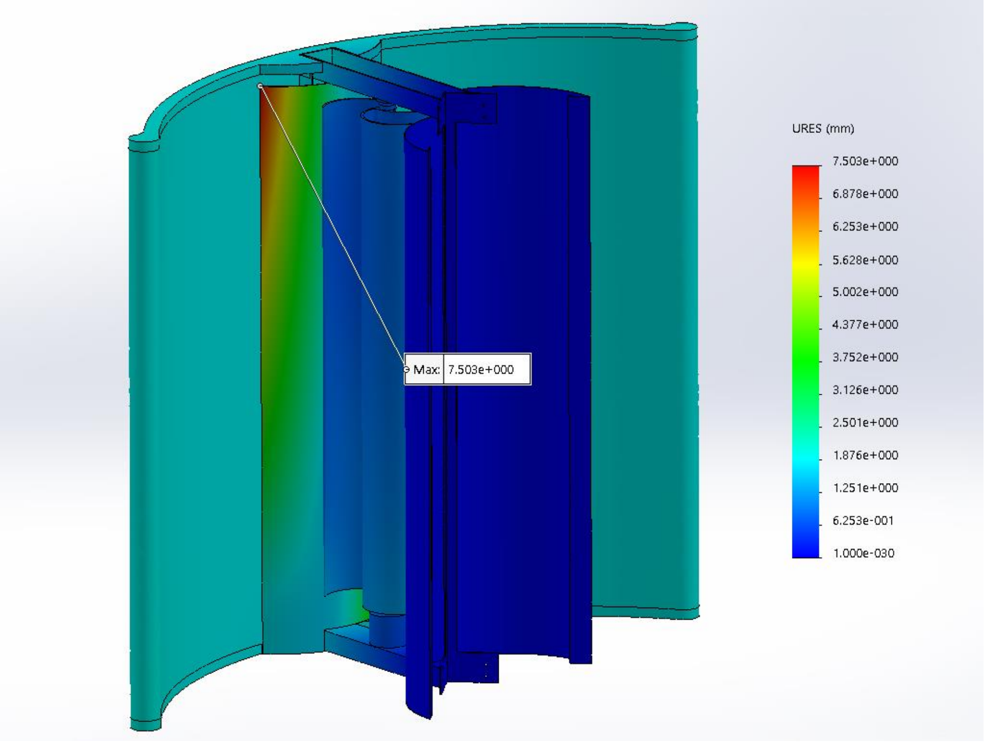


Figure 3.49. Displacements results

The maximal Von Mises stress is 110 MPa, far from the elastic limit or the admissible limit of the stainless steel. Those measures are made using the average value for the wind speed. Then we are using the maximum wind speed to see the difference.

The biggest displacement takes place in the opposite extreme of the wind entrance on the external deflector with a value of 7,5 mm. As we have chosen an open deflector to easy its installation, it is logic that this could happen. Once we see here that this extreme is more solicited than the other parts, the importance of the frequency analysis is growing. If the highest efforts in the modal shapes happen on this extreme, maybe it is necessary to change our choice for this element.

3.8. Frequency Analysis

Every structure has the tendency to vibrate at certain frequencies, called natural or resonant frequencies. Each natural frequency is associated with a certain shape, called mode shape, that the model tens to assume when vibrating at that frequency. When a structure is properly excited by a dynamic load with a frequency that coincides with one of its natural frequencies, the structure undergoes large displacements and stresses. This phenomenon is known as resonance. For undamped systems, resonance theoretically causes infinite motion. Damping, however, puts a limit on the response of the structures due to resonant loads.

It is used to evaluate a structure when it is subjected to dynamic environments. It can help to avoid resonance and design vibration isolation systems.

A real model has an infinite number of natural frequencies. However, a finite element model has a finite number of natural frequencies that is equal to the number of degrees of freedom considered in the model. Only the first few modes are needed for most purposes.

The natural frequencies and corresponding mode shapes depend on the geometry, material properties, and support conditions. The computation of natural frequencies and mode shapes is known as modal, frequency, and normal mode analysis.

3.8.1. Background

For this analysis, there will be some differences. The rotor and alternator will be simulated like a remote load to simplify the complexity of the assembly. There is no way to run the analysis with the whole structure. The simplifications for this study are:

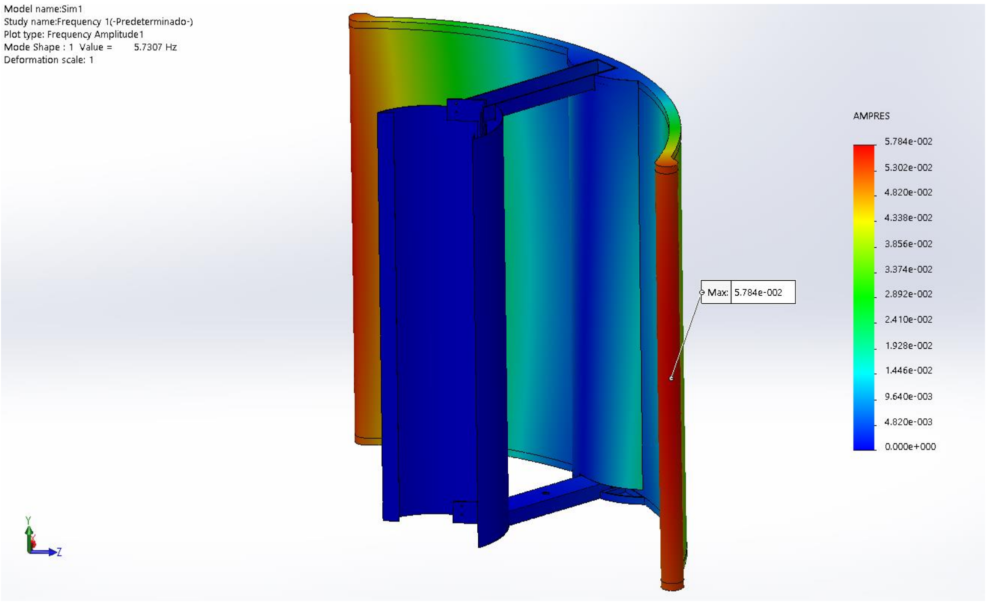
- The rotor and alternator are replaced by a remote mass.
- The wind force is simplified like it was for the static analysis.

The steps are similar to the static analysis, in first place it is needed to assign materials to each element. After that, it is necessary to stablish the fixed parts to the building (same 4 surfaces as before) and the external loads (gravity and wind load as before).

This time, it is needed to select how many modal shapes we want to obtain after the analysis. We want 10 modal shapes, even if only the 5 first have some importance, but it easier to evaluate changes of behaviour.

3.8.2. Results

The meshed model is similar to the one from the static analysis, but this time it has not the rotor and alternator. Once the model is meshed the analysis is ready to be run. The results are showed in the Figure 3.50.



Model name:Sim1
Study name:Frequency 1(-Predeterminado-)
Plot type: Frequency Amplitude1
Mode Shape : 1 Value = 5.7307 Hz
Deformation scale: 1

Figure 3.50. Modal shape 1 results

It is difficult to see the numbers, but the modal shape appears at 5,73 Hz, with a period of 0,1745 seconds. It is a very low firs modal shape, ideally it is searched to find a structure with a higher modal shape to avoid the resonance with the effect of the wind on the structure. Using the colour scale, it is easy to see that the most solicited part in the modal shape are both extremes of the external fairing, as it could have been ideally thought in a first place.

Like the results are not convincible at all, it is considered important to repeat the study but this time using just the principal structure, then adding the support structure and the external fairing, for eventually compare the modal shape with this result.

The results of the principal structure alone are showed in the Figure 3.51.

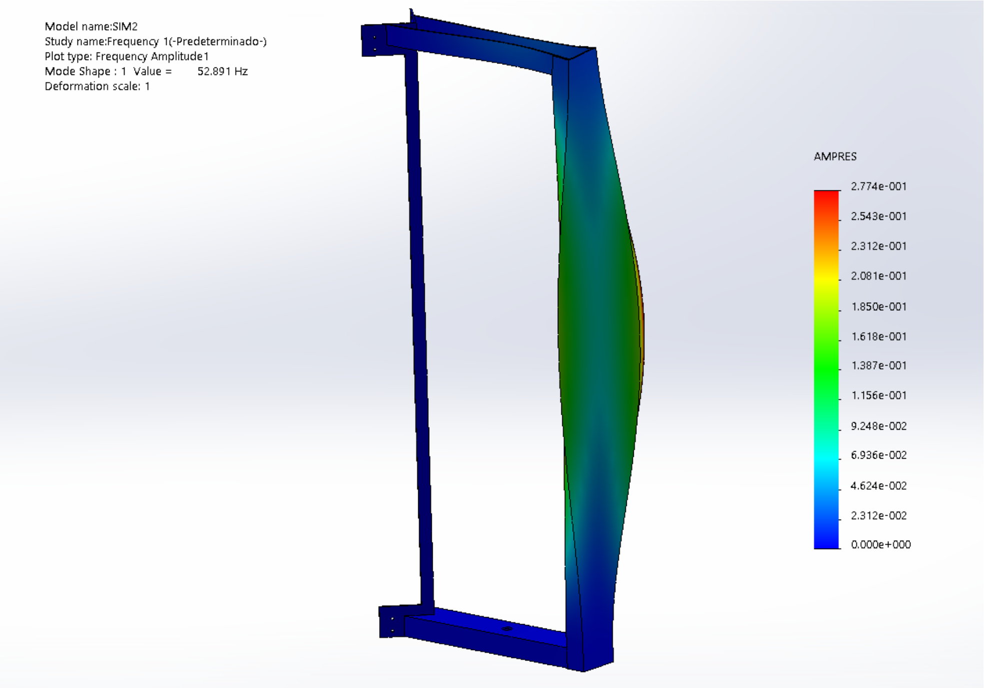


Figure 3.51. Modal shape 1 results of the principal structure

The frequency of this firs modal shape is of 52,89 Hz this time, is so much higher than the first one, so the principal structure is adequate to the design requirements. We are adding now the external fairing with the support structure to see the changes (Figure 3.52).

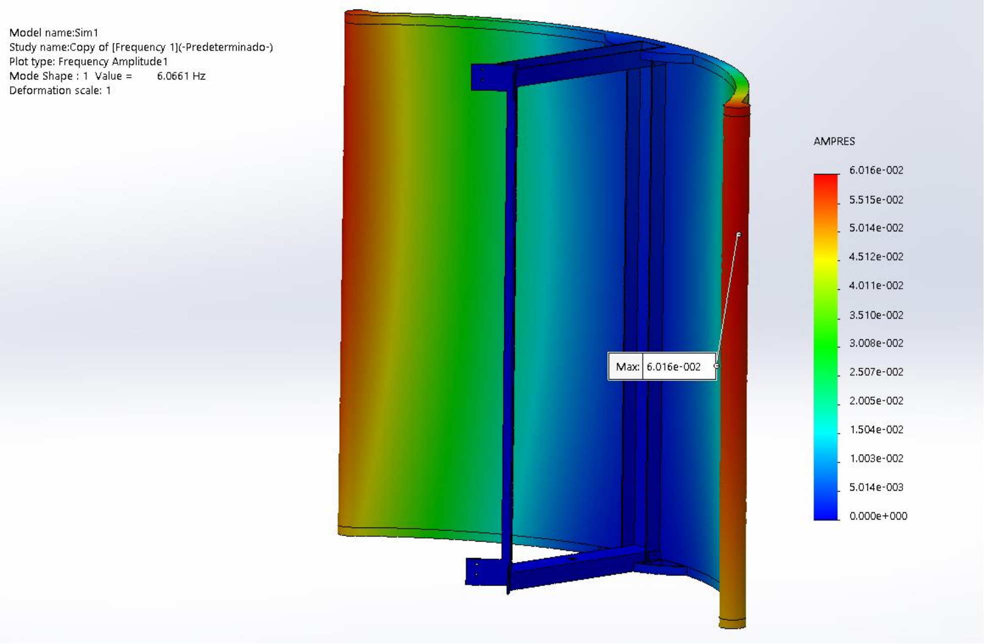


Figure 3.52. Modal shape 1 without deflectors

Without deflectors, the first modal shape drops until 6,06 Hz. It is bigger than the case with the whole assembly, but very much lower than the first modal shape for the principal structure. So, with those results, the next iteration needs to be focused on how to improve the external fairing to increase these modal shapes. The two different ways to increase those modal shapes are increasing the toughness and decreasing the total mass. The biggest element is the external fairing, so this is the element to be analysed deeper.

There is another option, where those low modal shapes appears at low frequencies, and those frequencies appears in resonance with the wind when the speed is slow, so the efforts produced to the structure are not very dangerous.

3.9. Other Analysis

It was considered important to think outside the box, so other works related to the project are also included.

It is the case of a students work assigned by the tutor of this project about the natural frequencies of the external fairing. They modelled a simplified assembly to obtain them and the results are presented in the following section.

On other part, there were two wind tunnels tests during the course of this project, so the results are also presented in the next section.

The modal frequencies of a structure are dependent only on the stiffness of the structure and the mass which participates with the structure, it is not dependent on the load function.

3.9.1. Students Work

The students tried to simulate the modal shapes of the external fairing using Matlab, another powerful software. They started with very simplified assemblies and hypotheses. They followed the next hypotheses:

- The principal structure is perfectly stuck to the wall and is tough enough to buffer the efforts of the rotor and alternator spinning.
- The external fairing is right instead of the curve one.
- The external fairing is only affected by blend loads.

With all these simplifications, the assembly has only one degree of freedom, so there will be only one modal shape.

The conclusion of all of them is that having in consideration all of these hypotheses, the external fairing will not work above the modal solicitation of wind in any case, only if some stiffener elements place on the extreme points of it.

Although considering just one degree of freedom, the modal shape happens in a very low frequency, this low frequency corresponds to a very low speed of wind, so the loads produced on the fairing are weak. There is not a very big danger of catastrophic fracture.

3.9.2. Wind Tunnel

A wind tunnel is a facility that provides a controllable flow field for investigating various flow phenomena and testing aerodynamic models. This tool is used in aerodynamic research to study the effects of air moving past solid objects. The atmosphere is under well-controlled flow circumstances compared to open environment experiments.

This is a very important step in a high performance design. It is crucial to be able to iterate the wind tunnel test every time there is a change in the design.

So, with the information of the previous stage of this project, the GEMINI members decided to do a wind tunnel test in Liège (Figure 3.53).

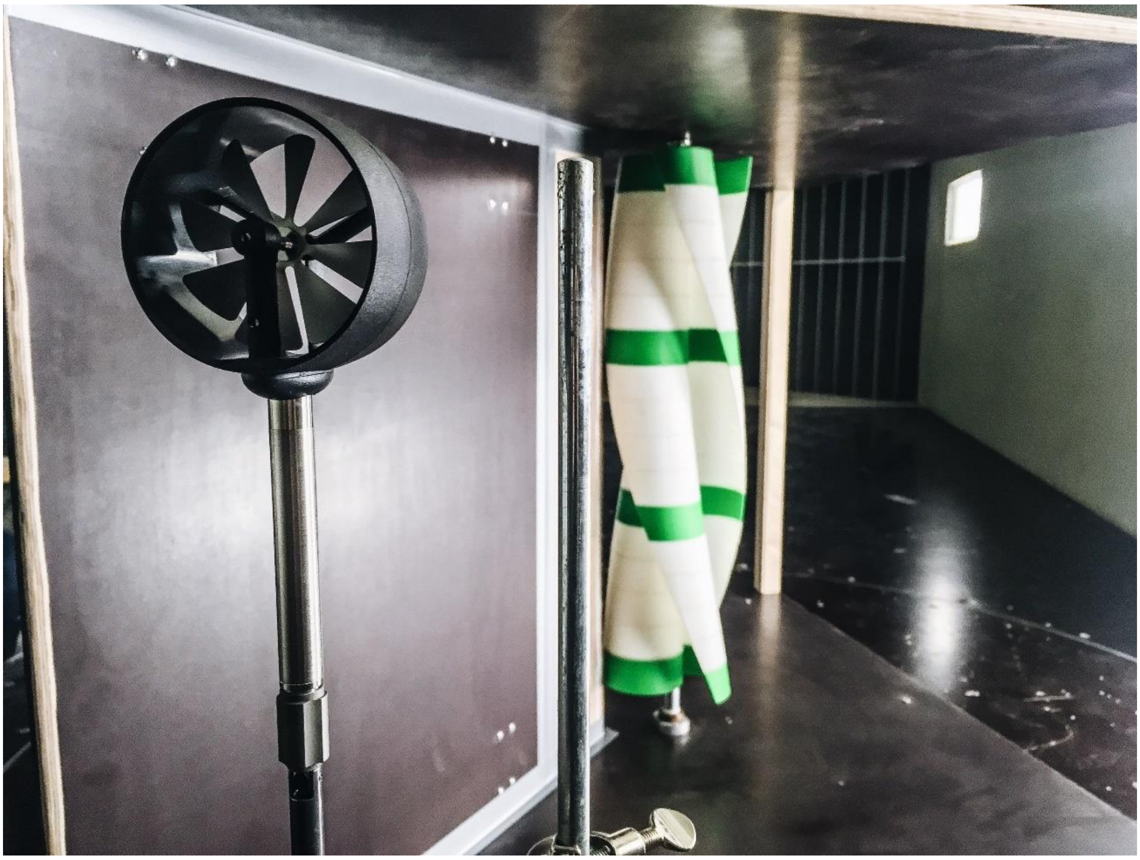


Figure 3.53. Wind tunnel test

In the picture above (Figure 3.X) there is shown the rotor, this is the first test, it is made just for knowing if the rotor is working with the wind conditions.

The sensor is placed in first place, and it used to measure the wind on the entrance of the GEMINI wind turbine, the difference with the wind tunnel theoretical value is noted to avoid undesirable results.

During the test, there is another characteristic measured that is not possible to have in consideration with the software simulations, the acoustic pollution of the wind going through the GEMINI wind turbine. Using a probe to measure it in every case studied it is easy to see if the noise level is too high to an urban environment (Figure 3.54).

Figure 3.54. Acoustic probe

After this test, there was another iteration and another wind tunnel test took place, this time testing some features that will be described in the conclusions chapter. Those are important to the correct continuation of this project in order to designed the most effective urban-placed vertical axe wind turbine and to help this planet staying cleaner more time.

4. CONCLUSIONS

This project was done to design the best option to use the GEMINI wind turbine to buildings in the most versatile and toughness way.

Using FEA software like SoidWorks, the different iterations necessary to arrive to the most optimized design are easier and faster to do. Even if this project has a couple of iterations, it is considered really important to the next people in charge to follow this process until the design is good in ergonomic, economic, and mechanical properties.

It is validated that the designed structure resists the load of an average wind from Belgium and the proper load of the whole assembly.

Seeing the results of the simulations, there are some interesting options for the following stages of this project:

- The selected external fairing is really heavy for the entire assembly. It is easy to see this effect in the frequency analysis, even if in the static one the difference of stress did not increase a lot between the two options, or at least it did not increase to a dangerous level; in the frequency analysis is easy to see the difference between the first modal shape when the principal structure is the only element analysed and when the other elements are added. The solution could pass through testing the open fairing commented in the options of the design, the one who was dismissed because of its complexity for designing and simulating.
- The vertical axe gives a particular torque efforts to the structure that are almost dismissed in these simulations, but there are still there, so it is necessary to think in another fixing system, like a ball joint or similar.
- In addition to the vertical axe, it is considered also important to think in another option to the rotor, maybe a change in the wind turbine is necessary and testing multiple horizontal axe rotors increases the efficiency of the whole assembly.

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ANNEX

In the Annex Document will be described some extra knowledge required to the complete understand of the Memory Document.

The different sections and references to the above document will be:

1. Attachment elements to the building
2. Simulation details
   - 2.1. General details
   - 2.2. Thickness Analysis
   - 2.3. Static Analysis
   - 2.4. Frequency Analysis

1. ATTACHMENT ELEMENTS TO THE BUILDING

The different types of attachments considered are:

- Wedge Anchors: they work by inserting them into a hole drilled into concrete. The concrete wedge anchor is then expanded, wedging itself securely in the concrete (Figure 1.1).

Figure 1.1. Wedge Fastener

- Sleeve Anchors: is the most versatile one. They work by inserting them into a hole drilled into concrete. Turning the nut pulls the working end of the sleeve anchor up through the sleeve, expanding and anchoring itself securely in the wall material (Figure 1.2).

Figure 1.2. Sleeve Anchor

- Drop-In Anchors: works by dropping them into the predrilled hole in the concrete and using a setting tool that expands the anchor within the hole in the concrete (Figure 1.3).

Figure 1.3. Drop-In Anchor

- Machine Screw Anchor: they are female type concrete anchors and they have internal machine screw threads (Figure 1.4).

Figure 1.4. Machine Screw Anchor

- Leadwood Screw Anchors: the sheet metal screw expands them in the concrete (Figure 1.5).

Figure 1.5. Leadwood Screw Anchor

- Single Expansion Anchors: work by inserting a machine-threaded bolt into the anchor they expand against the concrete at a single point. It is set flush with the base material and is considered a light to medium-duty fastener (Figure 1.6).

Figure 1.6. Single Expansion Anchor

- Double Expansion Anchors: work in the same way than single expansion anchors, but they expand against the concrete in two points. The double expansion allows for better holding values (Figure 1.7).

Figure 1.7. Double Expansion Anchor

2. SIMULATION DETAILS

Here there are presented some details of the simulations, like screen-shots or equations used by the program to run the analysis.

2.1. General Details

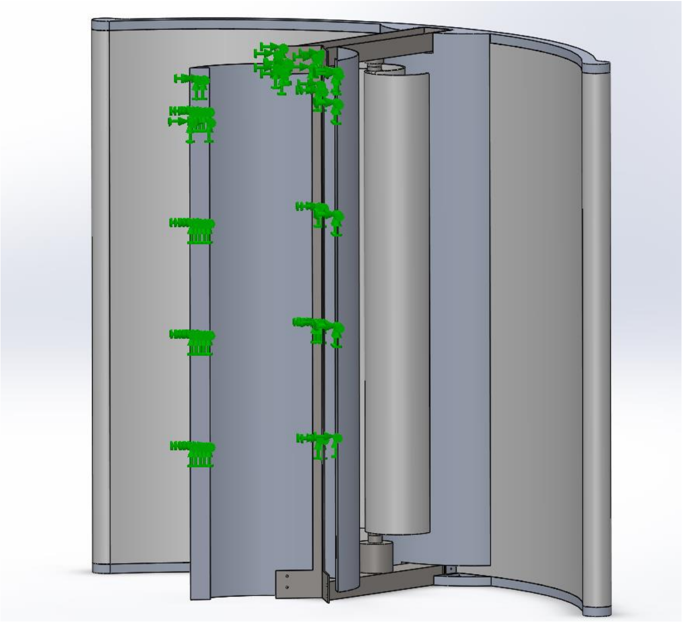

Figure 2.1. Fixed part during the analysis

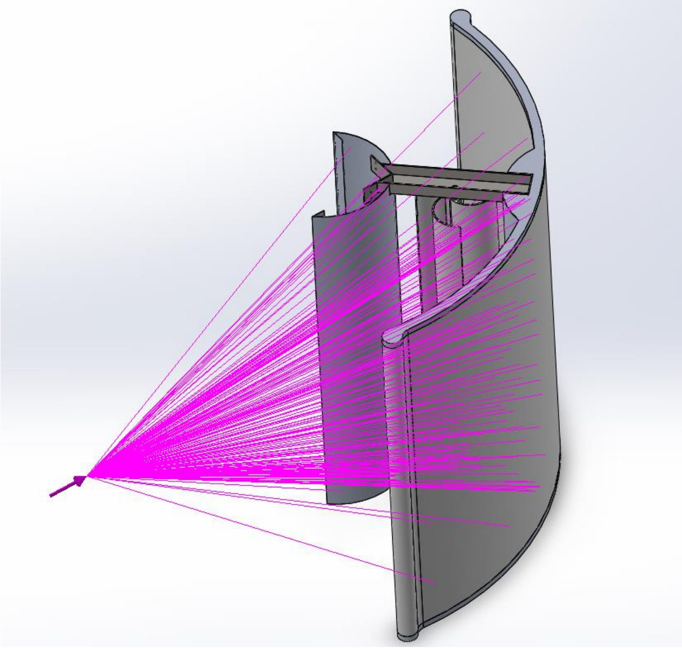

Figure 2.2. Wind equivalent load for the analysis

2.2. Thickness Analysis

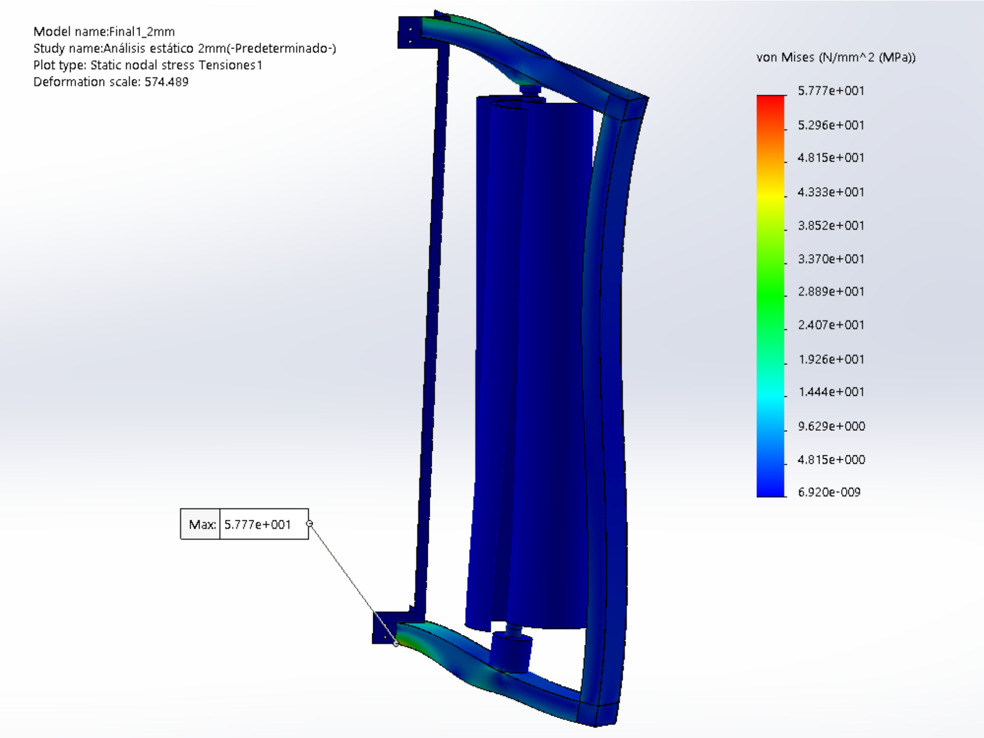

Figure 2.3. 2 mm thickness stress results: 57,77 MPa with a deformation scale of 574,49

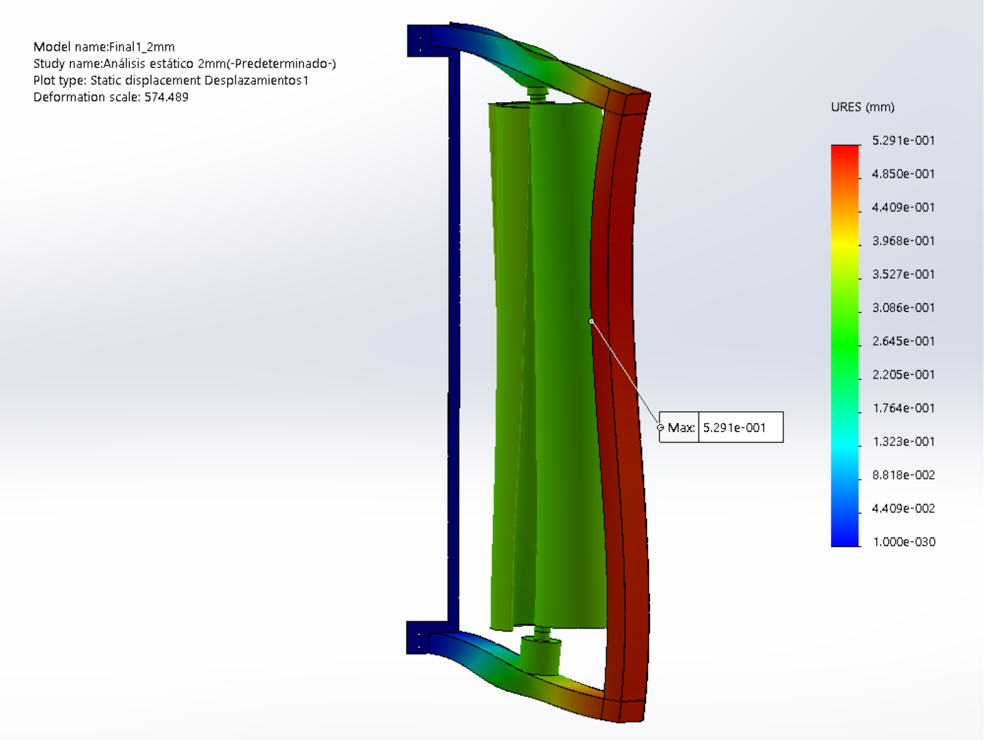

Figure 2.4. 2 mm thickness displacements results: 0,53 mm with a deformation scale of 574,49

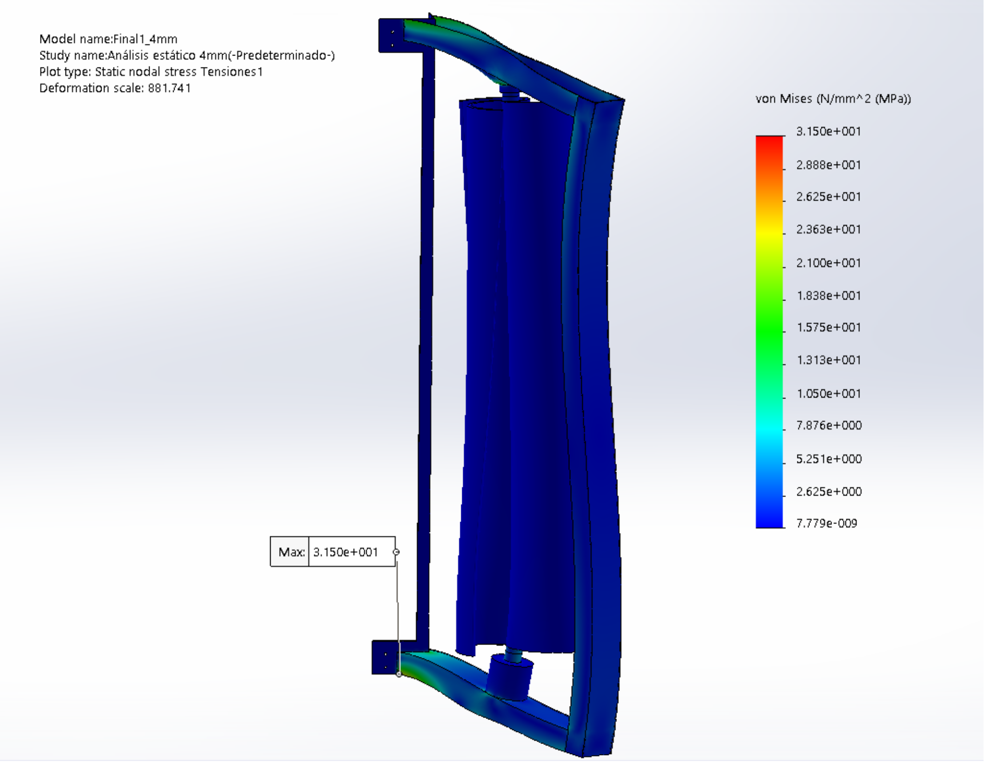

Figure 2.5. 4 mm thickness results: 31,50 MPa with a deformation scale of 881,74

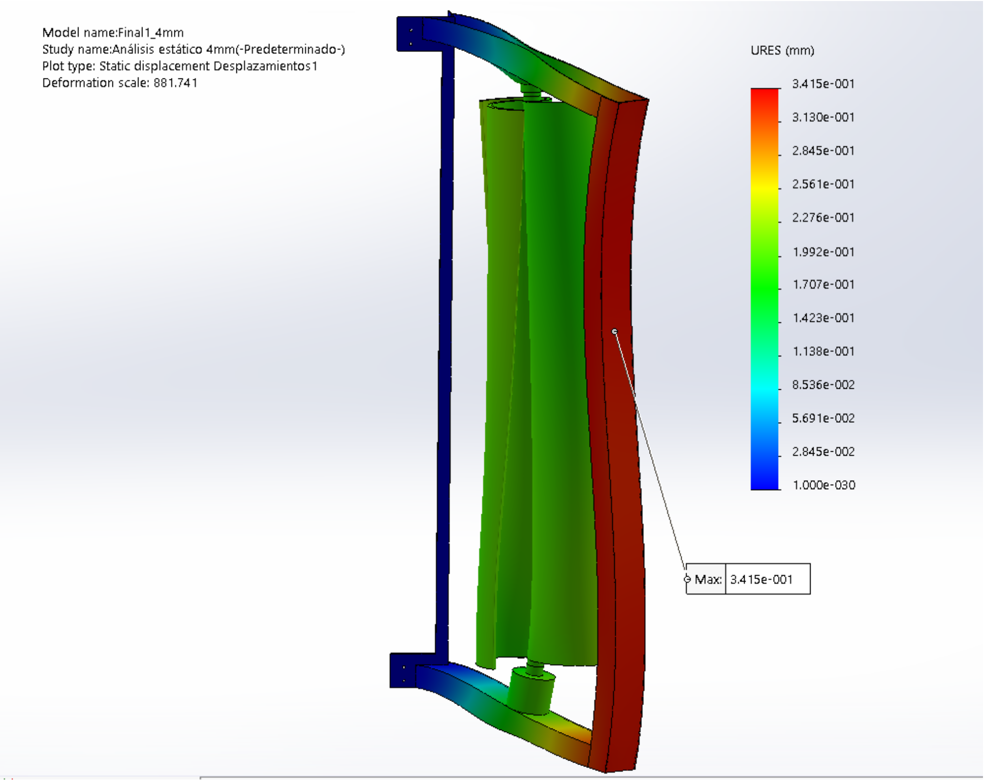

Figure 2.6. 4 mm thickness results: 0,34 mm with a deformation scale of 881,74

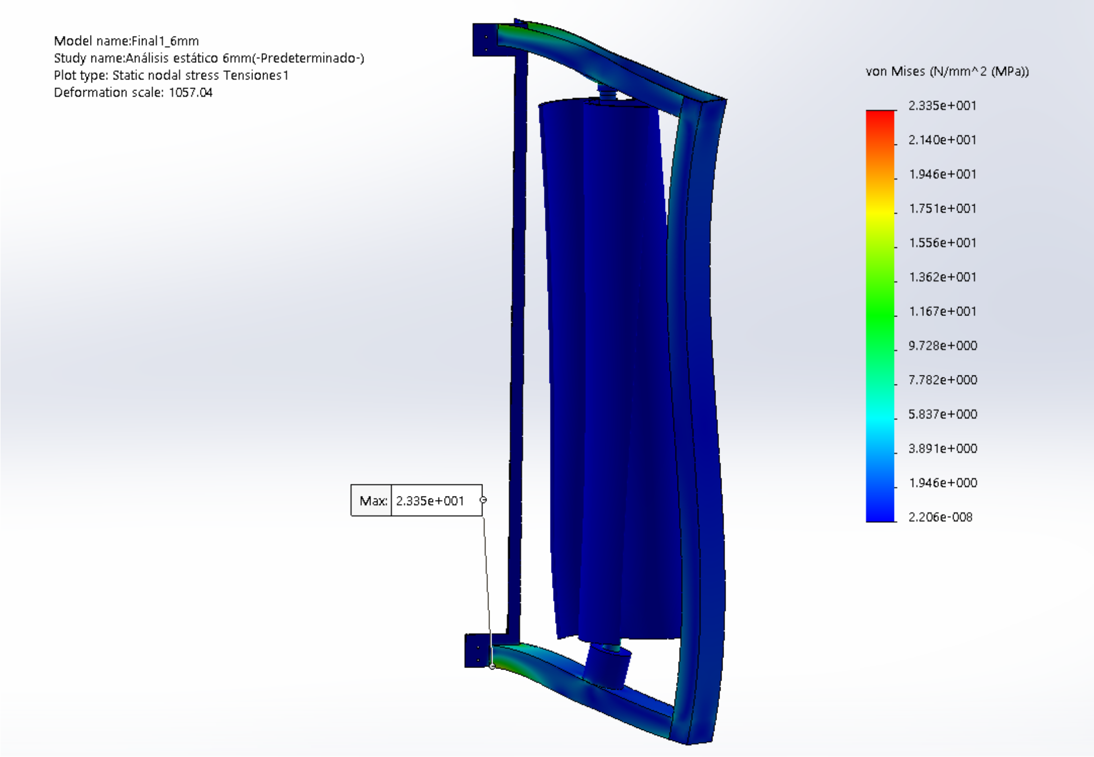

Figure 2.7. 6 mm thickness results: 23,35 MPa with a deformation scale of 1057,04

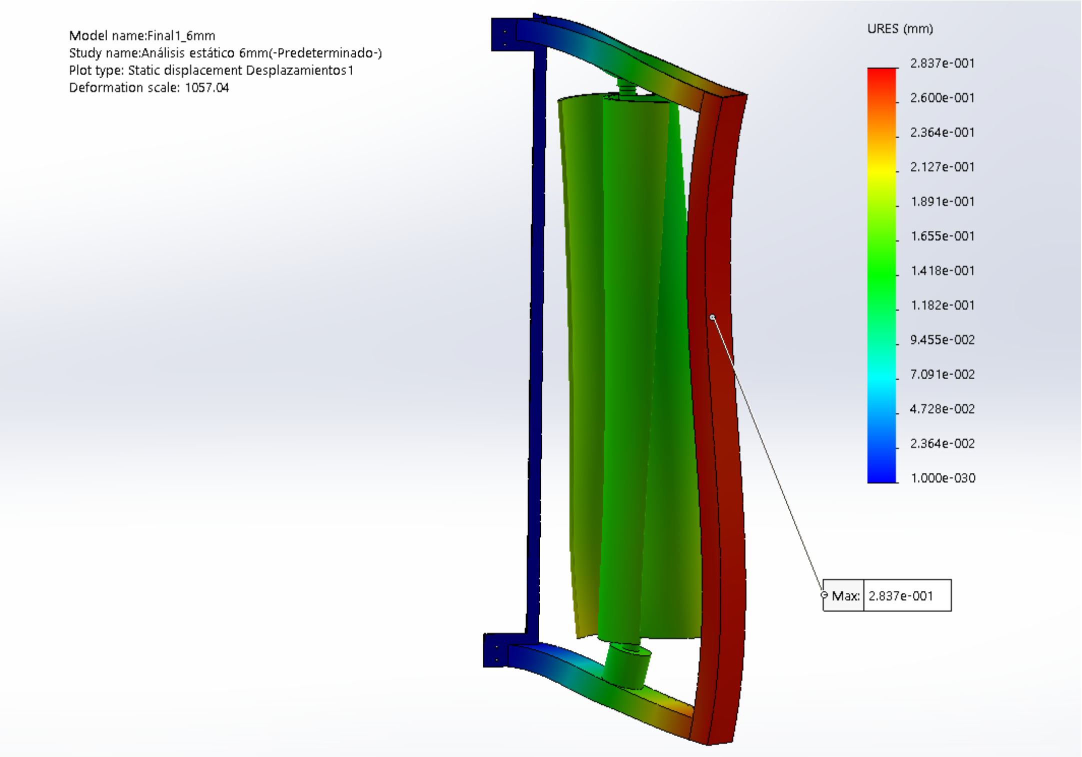

Figure 2.8. 6 mm thickness results: 0,28 mm with a deformation scale of 1057,04

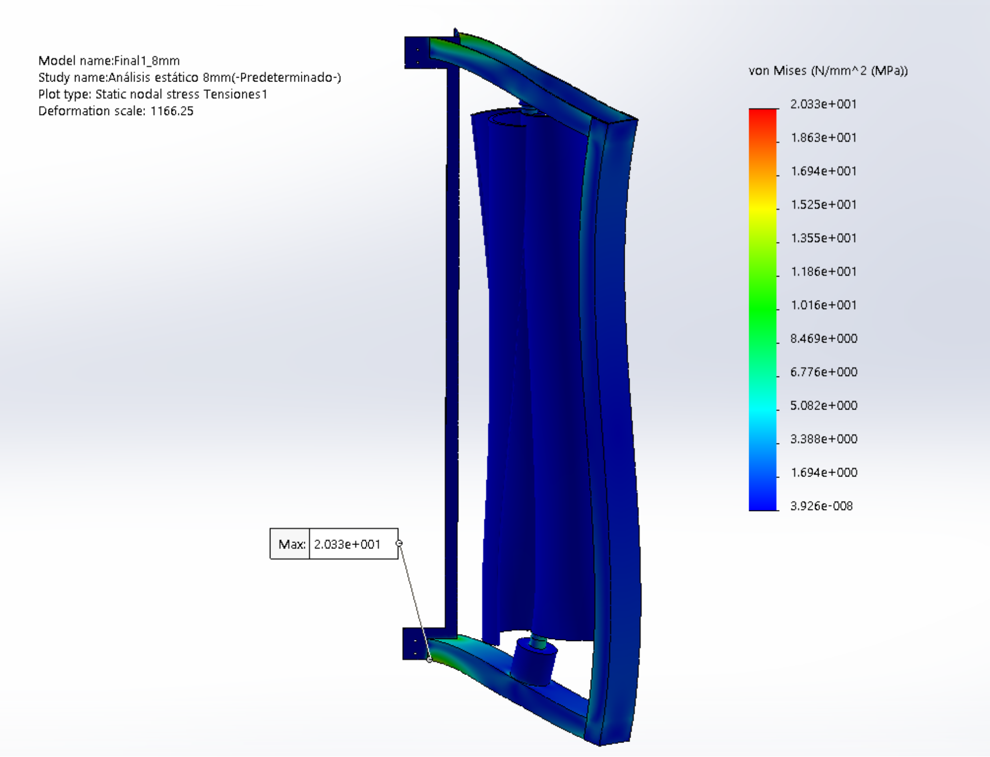

Figure 2.9. 8 mm thickness results: 20,33 MPa with a deformation scale of 1166,25

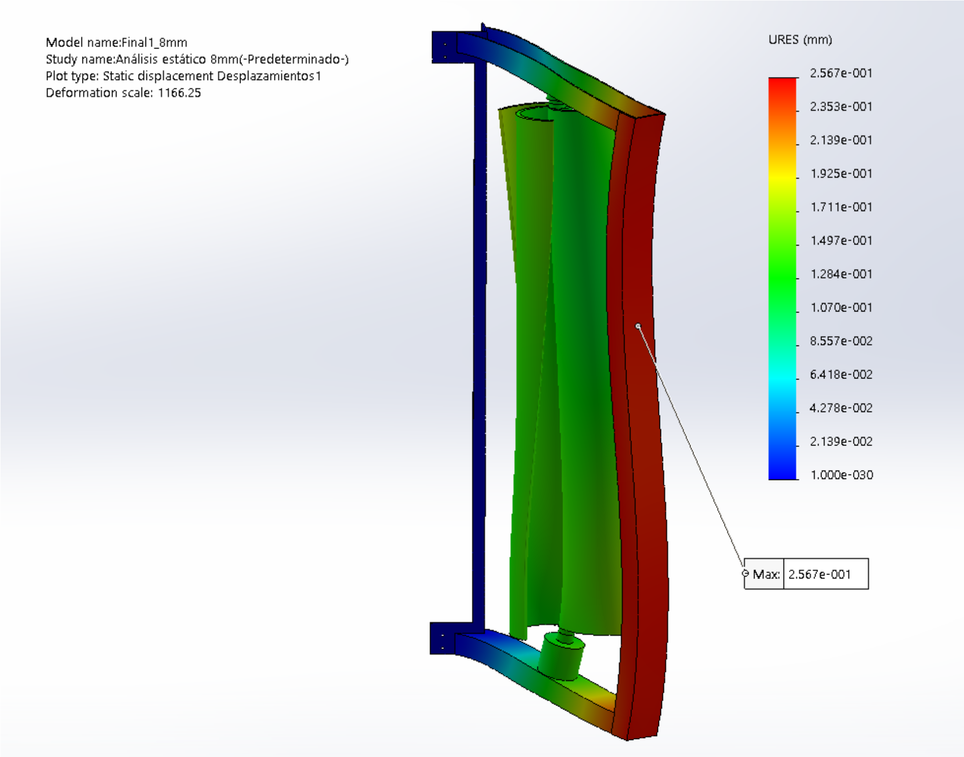

Figure 2.10. 8 mm thickness results: 0,26 mm with a deformation scale of 1166,25

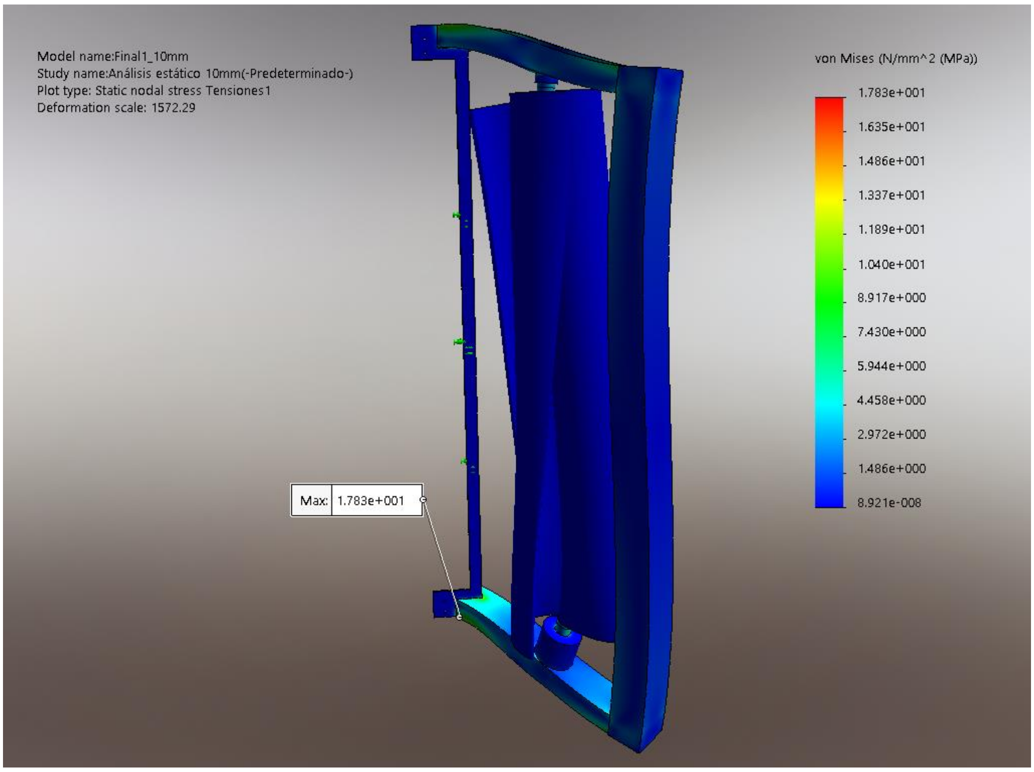

Figure 2.11. 10 mm thickness results: 17,83 MPa with a deformation scale of 1572,29

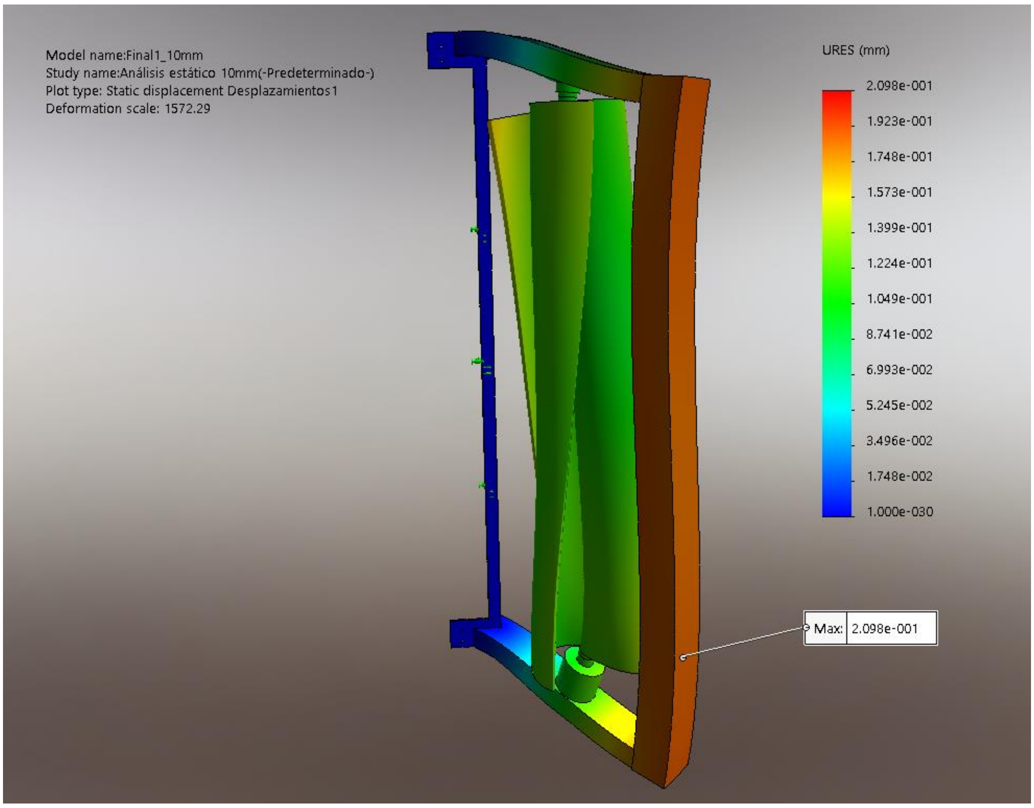

Figure 2.12. 10 mm thickness results: 0,21 mm with a deformation scale of 1572,29

2.3. Static Analysis

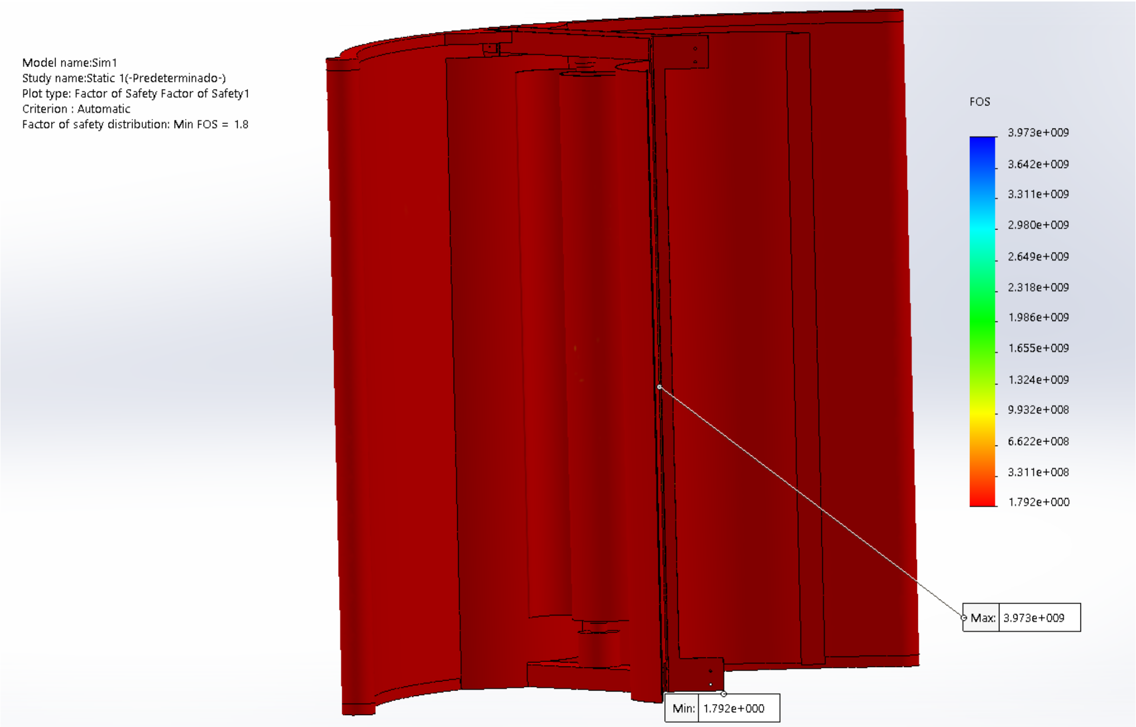

Figure 2.13. Safety Factor for the final design

It is easy to see that the lowest safety factor is of 1,8, so the structure is safe from failure. The highest safety factor is placed in the principal structure where the beams touch the buildings, reducing the effect of loads. It is calculated using the equation:

$$Facture\ of\ Safety = \frac{\sigma_{limit}}{\sigma_{VonMises}}$$

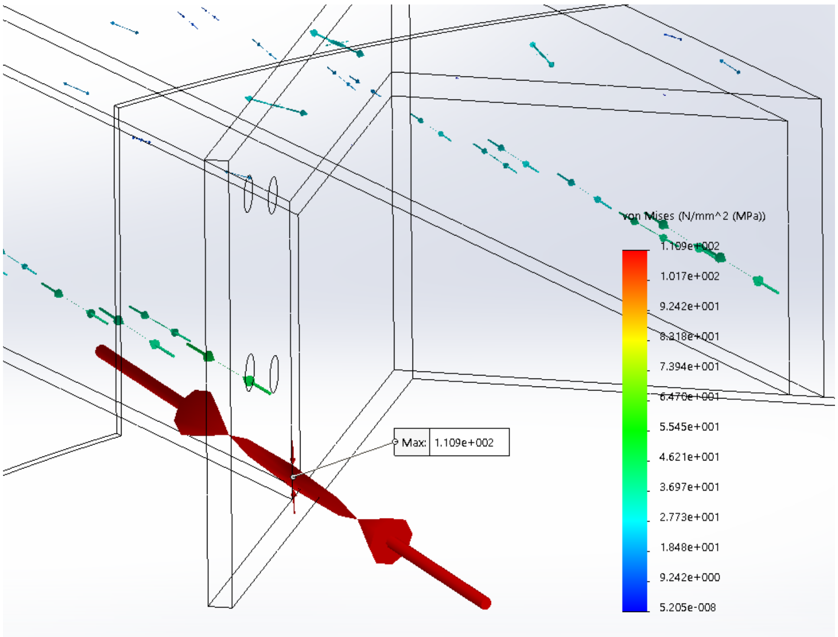

Figure 2.14. Detail of the max. Von Mises stress in tensor plot mode

2.4. Frequency Analysis

The other modal shapes for the whole assembly are presented here.

The mode shape amplitude plots illustrate the profile of the mode only (i.e., the displacement of nodes relative to each other). The displacement values are calculated based on various normalization procedures.

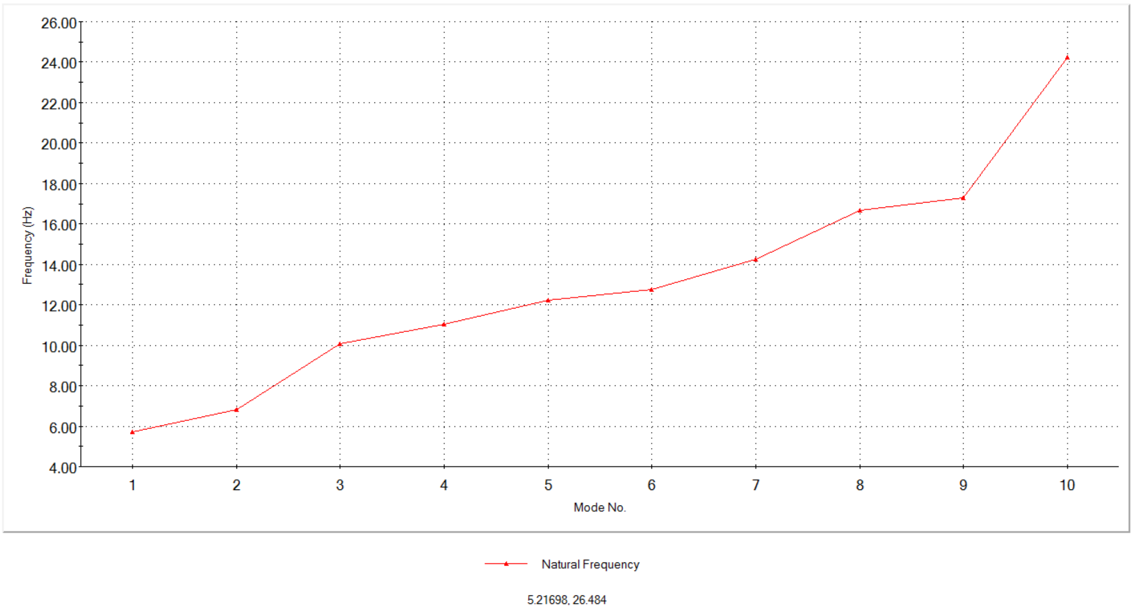

Figure 2.15. Evolution of frequency of the different modal shapes

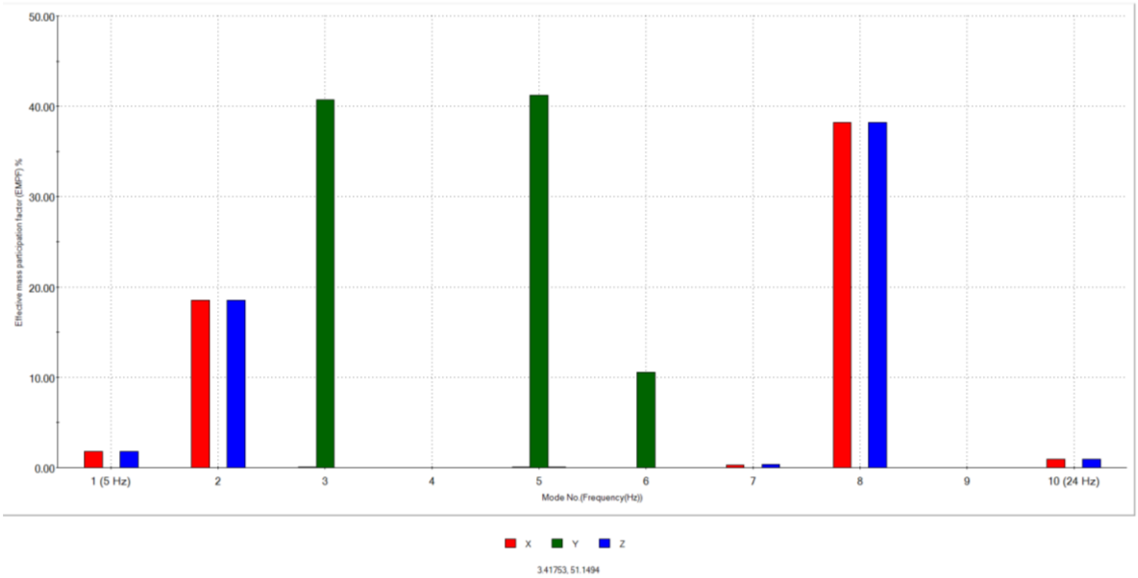

Figure 2.16. Different mass participations for each modal shape

The Effective Mass Participation Factor (EMPF) provides a measure of the energy contained within each resonant mode since it represents the amount of system mass participating in a particular mode. If a mode has a large effective mass it will be a significant contributor to the response of the system.

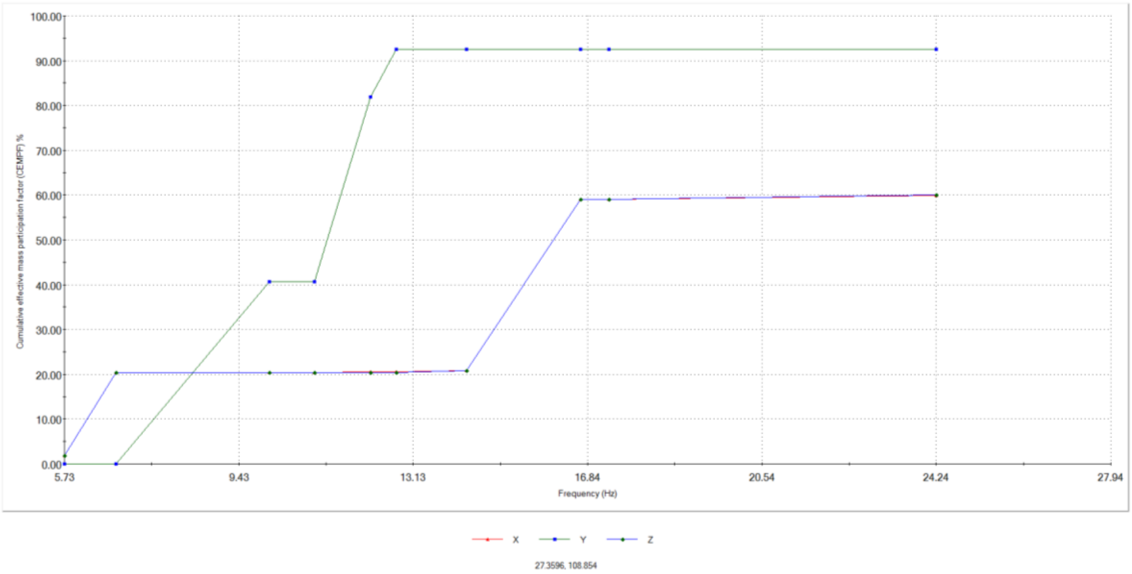

Figure 2.17. Representation of the cumulative effective mass participation factor

Between 12 Hz and 13 Hz is the value of the resonant frequency where the Cumulative Effective Mass Participation (CEMPF) for the direction Y reaches 80%. It is an important load for the whole structure from this 80% of cumulative mass participation.