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Internal Structure of Hybrid Airships
Airship Design and Structural Analyses

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Dissertação para obtenção do Grau de Mestre em

Engenharia Aeronáutica

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AVISO

A presente dissertação foi realizada no âmbito de um projeto de investigação desenvolvido em colaboração entre o Instituto Superior Técnico e a Universidade da Beira Interior e designado genericamente por URBLOG - Dirigível para Logística Urbana. Este projeto produziu novos conceitos aplicáveis a dirigíveis, os quais foram submetidos a processo de proteção de invenção através de um pedido de registo de patente. A equipa de inventores é constituída pelos seguintes elementos:

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As partes da presente dissertação relevantes para efeitos do processo de proteção de invenção estão devidamente assinaladas através de chamadas de pé de página. As demais partes são da autoria do candidato, as quais foram discutidas e trabalhadas com os orientadores e o grupo de investigadores e inventores supracitados. Assim, o candidato não poderá posteriormente reclamar individualmente a autoria de qualquer das partes.

Covilhã e UBI*, 1 de Outubro de 2015*

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(*Tiago Rodrigues dos Santos*)

Dedicatory

I dedicate this dissertation to my family and friends for supporting me all this time. Special thanks to my parents, Abel Santos and Zulmira Santos, for encouraging me and motivating me constantly. I also thank my brother to help me to achieve this work.

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Resumo

Os dirigíveis têm sido alvo de poucas pesquisas nos dias de hoje mas devido à evolução da tecnologia é possível voltar a pensar em novos conceitos como o dirigível hibrido. Este apresenta melhor eficiência em todos aspectos sendo possível pensar usar estruturas internas inovadores e eficazes com novos materiais que nos tempos antigos não existiam.

A estrutura interna varia consoante o tipo de dirigível e muitos deles têm problemas devido ao peso ou controlo e estabilidade. Os dirigíveis rígidos são pesados mas com a nova tecnologia é possível ter materiais muito mais leves e resistentes sendo a estrutura interna semelhante às estruturas internas das asas onde esta composta por cavernas e longarinas.

Para saber que tipo de estrutura a usar, foram estudados vários tipos de estrutura possíveis para um protótipo de um dirigível híbrido sendo a mais eficaz actualmente as treliças, apesar de haver possibilidades de começar a pensar no uso de estruturas *sandwich* num futuro possível. Todas as treliças têm os seus problemas. Foram analisados diferentes alturas e ângulos tendo em consideração ao estudo de treliças que eram usadas antigamente. Foram realizados testes práticos para comprovar o conceito da estrutura como também a rigidez da estrutura.

Para um estudo melhor de dirigíveis e todos os seus problemas estruturais foram realizados 4 protótipos e o início do estudo da estrutura interna de um dirigível híbrido. Os protótipos 1.0 e 1.5 são bastante semelhantes mudando alguns aspectos na estrutura donde se verificam os problemas estruturais como também as influências dos materiais na rigidez e dificuldades em fixar o material ao dirigível não-rígido. Nos protótipos 2.0 e 2.5 analisa-se alguns problemas na força criada pelos rotores à qual a estrutura interna do protótipo final vai estar sujeita a momentos elevados nas zonas onde se colocaram os rotores e asas. O estudo da estrutura interna é o início da construção de um protótipo final com estrutura interna rígida que irá englobar os sistemas de controlo e estabilidade do protótipo 1.5 e 2.5 sendo este chamado de protótipo 3. Este estudo irá permitir saber os pontos fracos e as dificuldades de montagem da estrutura interna do protótipo 3.

Conclui-se que é possível realizar uma estrutura interna com formato aerodinâmico pretendido tendo um peso baixo e elevada rigidez.

Palavras-chave

Dirigível Híbrido, Estrutura Interna, Cavernas, Longarinas, Encaixes, Propriedades Mecânicas, Madeira, Compósitos Não-naturais e Estruturas Sandwich.

Abstract

Nowadays, the research on airships has been declining over the years but the evolution of technology allows the possibility to think in new concepts such as hybrid airship. It provides better efficiency in all aspects, and it is possible to use innovative and effective internal structures with new materials that did not exist in older times.

The internal structure depends on the type of the airship, and many of them have problems due to weight or control and stability. The rigid airships are heavy but with the new technology can have material much lighter and durable. The internal structure is similar to the internal structures of wings, having frames and girders.

To know which kind of structure to use, it were studied various types of possible structure for a hybrid airship prototype and the most effective currently are trusses, despite there are possibilities to start to use sandwich structures in a possible future. The trusses have problems and because of that were analyzed different heights and angles taking into account the study from trusses used in other airships. Experimental tests were realized to prove the concept of the structure as well as the stiffness of the structure.

In order to make a better study about airships and all their structural problems, it was made 4 prototypes and the start of the study of the hybrid airship internal structure. The Prototypes 1 and 1.5 are quite similar in some structure aspects where it was identified the structural problems as well as the influences of material stiffness and difficulties to fix the material to non-rigid airship. The Prototype 2 and 2.5 was analyzed some problems because the force created by the rotor wherein the internal structure will be subject to high moments in areas where it is placed the rotors and wings. The study of the internal structure is the start of the construction of the final prototype with rigid internal structure which will include the control and stability system of the prototype 1.5 and 2.5, called Prototype 3. This study will allow knowing the weakest points and the difficulty to assemble the internal structure of the Prototype 3.

It concludes that it is possible to make an internal structure with the aerodynamic shape desired having a high rigidity and low weight.

Keywords

Hybrid Airship, Internal Structure, Frames, Girders, Fittings, Mechanical Propierties, Wood, Composites non-natural and Sandwich Structures.

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FEM	Finite Elements Method
PVC	Polyvinyl Chloride
PET	Polyethylene-Terephthalate
PES	Polyethersulfone
PMC´s	Matrix Polymer Composites
MMC´s	Metal Matrix Composites
CMC´s	Ceramic Matrix Composites
CCC´s	Composite carbon/carbon

1.Introduction

1.1 Motivation

According to the most recent technology advancements, the goal of this dissertation is an improvement in transport efficiency in order to reduce costs, time and air pollution. Airships had not usually got a great prominence in the air transport due to the unsustainable and lack of efficiency in the existent technology. Their dimensions and the number of air accident push them off of the market.

The total weight of the airship has been a serious problem, because it decreases substantially the efficiency of the lift generated by helium which causes the enlargement of the airship that makes it more capable of carrying heavy cargos.

The appearance of the composite enhanced the interest of airships wherein non-natural composites are material that is constantly improving. Plus, their production costs have been reduced making greater use of this type of material in airships. They are strong and have got low densities which make a substantial reduction in the structural weight.

Airships used the zinc-aluminum alloy which greatly increases in the weight compared with the carbon fiber. That is why the markets are increasingly exploring this type of material making it one of the best composites in terms of density and high strength. This material has been used in many transport areas to increase the efficiency of transport.

The truss structures used in airships are resistant to bending, torsion, compression and tension strengths. This type of structure provides a great efficiency in airships and they are common because of their low weight and good resistance. However, there is always something new on the market that can reduce their weight, for example, replacing truss girders by sandwich structures.

Using lighter and rigid structures will increase the airship efficiency, reducing the size and /or carrying heavy cargos.

1.2 Object and Objectives

The main goal of this dissertation is to idealize and to develop a structure that can support all loads which the prototype´s structure of the hybrid airship is subject as well as the type of material to use. Therefore, this dissertation is divided into two main chapters.

The first objective is to analyze the type of the structure to be used to the hybrid airship according to the design, where it has to support the envelope, gas cell, gondola (electrical equipment), wings, rotors and stabilizers according to the problems noticed from the prototypes. The supporters of the wings, stabilizers and electric motor should be simple to fit in and in order to make the assembly and maintenance more practical. The last phase is the study of the structures with numerical (ANSYS and Ftool) and experimental tests in order to validate the structures that will be used in the final prototype.

The second objective is the study of the structure of the wings, stabilizers and electric motor of the Prototype 1.5 and 2.5 to be implemented in a non-rigid airship. Looking at the analysis of the problems found in both prototypes, it is possible to take conclusions to avoid the same problems in the final prototype.

The last objective is to know the future problems that will appear in the construction, the fitting system and the structural stiffness of the prototype final. This prototype is a rigid hybrid airship with 9 meters.

1.3 Dissertation Structure

The dissertation development started from analysis of all types of the internal structures and materials used in airships. In this dissertation, the study will be divided into 4 chapters.

The first chapter is the study introduction, which is divided into three sub-chapters, the motivation, the object and objective, and the structure of the dissertation, respectively.

The second chapter is the state of art and contains the brief study of various types of airships structures, as well as new types of structure and material to use in final prototype.

In the third chapter are studied the trusses with different heights, angles and materials, and the practical tests to validate the structure and material.

In the fourth chapter is analyzed the tests of the prototypes as well as the internal structures.

The fifth (and last) chapter contemplates the dissertation synthesis, the final considerations and the prospects for future work in this matter.

2. State of Art

2.1 Introduction

The state of art is divided into two chapters in which the first address to a brief history of airships in order to understand how their internal structures level of development and to understand the weak points of each structure, observing the differences between semi-rigid, rigid and hybrids airships. The technology advances brought new materials that have never been used in airships and which are promising to be used in future.

It is necessary to know which material to use in the internal structure. They can be natural composites or polymers with high strength, low density, low cost and flexible. According to the future prospect, there is also a need for search for reusable materials.

2.2 Airship Structure

The first airships used heavy structures and the first recorded in history was the LZ1 Zepllin [1] which had an internal structure of tubular metal beams. This had 128.02 meters of length and 11.58 meters of diameter having 11298.42 cubic meters of hydrogen capacity. It had also two gondolas with 14 horse power of aggregates engines with one gondola in the front and other behind. The airship was not successful due to the overweight and the failures presented by the structure, caused by the weak tubular structure. Control and stability were other important factors of the airship failure.

With the identification of the problems, the improvements were made in the LZ2 which began using up triangular trusses (figure 1) increasing the stiffness and strength of the structure. The trusses are more rigid than the beam, so they transfer the forces to the supports by axial compression and tension instead of creating displacement and break up in small individual members in order to reduce the deformation members which are subjected to compression loads. The triangular trusses can sometimes use less material than conventional beams. They have started to be used in the majority of the airships due to torsion and buckling efficient [2].

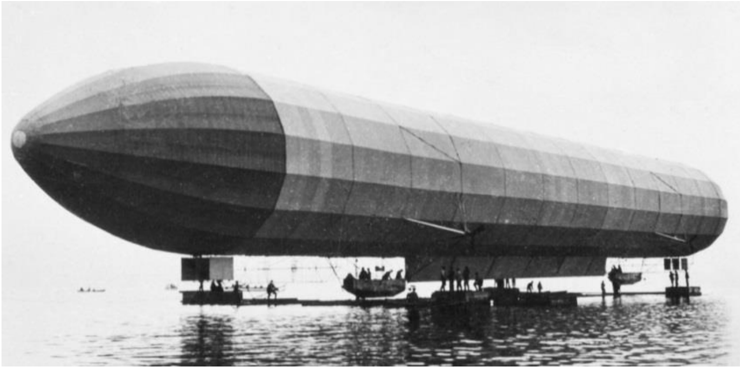


Figure 1: Zeppelin Graf LZ2 airship [1].

PAX is a semi-rigid using keel and trusses, covered with a tissue envelope with some stiffness due to the bamboo structure. The gondola was fixed with bamboo instead of wires and ropes in order to have a good fixation without balancing [3].

Astra-Torres is a semi-rigid airship that revolutionized the internal structure of the airships. It counts with the presence of longitudinal strings in your envelope in order to create three lobes (figure 2). Each frame was made by permeable curtains, metal wires and struts to create rigidity to the airship through the excess of pressure level of the gas. This effect “it would act as an internal rigid structure” [4:2]. The support was inside of the envelope where the gondola and the keel are supported by wires which are attached to the top of the envelope. This type of airship allows collisions without suffering damage.

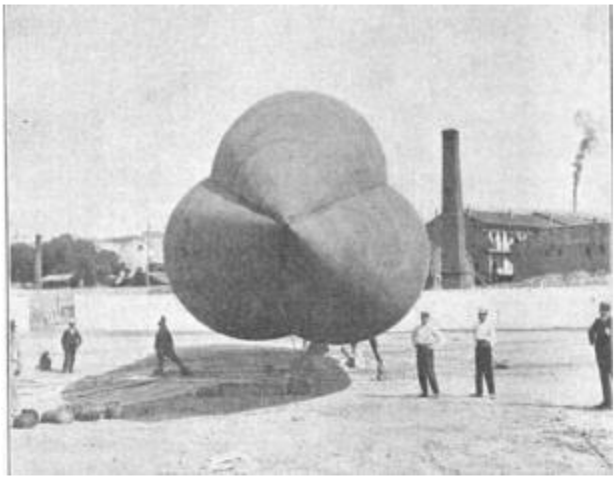


Figure 2: Astra Torres airship [4].

The demands increased in transport, so the large airships were made to carry a large number of people and also to serve as air support in combat. The RZ 101 and the Akron were large rigid airships. They had the ability to take light aircraft and throw them in the air. The internal structure of triangular trusses presented with three keels in order to give greater rigidity to the structure. The upper keel gave support to the valve for the gasbags as the low keels served as support for the engines and space for the crew walk inside of the airship. The stabilizers were affixed on the main frames [1, 5].

The airships in development are hybrid airships in which the information about their structure is scarce. These may have a rigid or semi-rigid structure in order to assure aerodynamic shape to generate lift during the flight [6, 7]. Hybrid airships produce lift by buoyancy, aerodynamic and rotors, having three concepts together that makes the airship has the best of each one to achieve less consumption, and more autonomy and range. [8]

To improve the efficiency is possible to install photovoltaic panels Cadmium-Indium- Cadium-germanium (GIG) making it cover at the top in order to create a hybrid-powered by diesel/gasoline engine and electric engine. [9]

- **Structure**

In the twentieth century were built several airships with different types of structure and they are considered non-rigid, semi-rigid and rigid. In airships hybrids, i.e., the most modern airships are rigid or semi-rigid structures wherein the hybrid airship must have an aerodynamic profile in order to generate lift. The aerodynamic profile cannot be deformed as in the non-rigid airship [8].

The non-rigid airship, as called blimps, it has a gondola attached to balloon with wires where the gondola have an engine to generate traction. It is limited in cargo transportation, stability and control having fixed stabilizers with tension wires to fix. These are good for publicity and surveillance but they are very limited to weather conditions.[10]

The rigid and semi-rigid airships are subjected from longitudinal forces and bending moments due to the gas pressure, shear forces and bending due to aerodynamic forces, buoyancy and weight of the entire structure and equipment. The static shear and bending forces are caused by structural weight and buoyancy while the aerodynamic forces comes from air pressure caused in the envelope of the airship generating lift (bending and shear forces).

In the first drawings of the airship design cannot be sure of the total weight (equipment, structure, engine, wings, stabilizers and supports) of the airship. The total weight and the position of each material are estimated in the first draws. Knowing the total weight estimated, it is possible to estimate the airship dimensions and the position of the gasbags wherein will know the position of the forces generated by the buoyancy. The total buoyancy (positive force) and the total weight force (negative force) must match to the center of gravity making the airship statically balanced.

To calculate the shear forces and bending moments, it is necessary that the buoyancy and weight forces are concentrated in the main frames instead of being distributed throughout the structure.

Table 1: The calculation of the total forces and moments which the frames are subjected to [10].

Station (meters)	Gross Lift (lbs)	Fixed Weight (lbs)	Disposable Weight (lbs)	Total Weight (lbs)	Load (lbs)	Shear (lbs)	Bending Moment (mlbs)
0	307	2.618	0	2.618	-2.311		0
						-2.311	
10	1.453	1.877	0	1.877	-424		-23.110
						2.735	
20	2.812	1.902	0	1.902	910		-50.460
						-1.825	
30	4.496	1.991	2.276	4.267	229		-68.710
						-1.596	
40	5.789	2.328	2.200	4.528	1.261		-84.670
						-335	
50	7.128	2.389	5.182	7.571	-443		-88.020
						-778	
60	8.218	5.858	1.512	7.370	848		-95.800
						70	
70	8.985	2.708	2.378	5.086	3.899		-95.100
						3.969	
80	9.402	2.091	5.656	8.747	655		-55.410
						4.624	
90	9.510	9.483	6.100	15.583	-6.073		-9.170
						-1.449	
100	9.540	3.224	6.055	9.279	261		-24.660
						-1.188	
110	9.584	3.069	5.704	8.773	811		-36.540
						-377	
120	9.560	8.183	5.016	13.199	-3.639		-40.310
						-4.016	
130	9.536	3.096	1.790	4.886	4.650		-80.470
						634	
140	9.417	3.064	5.562	8.626	791		-74.130
						1.425	
150	9.003	2.712	5.406	8.118	885		-59.880
						2.310	
160	8.169	8.057	2.259	10.316	-2.147		-36.780
						163	
170	6.778	3.076	2.653	5.729	1.049		-35.150
						1.212	
180	4.467	3.212	1.227	4.439	28		-23.030
						1.240	
188	2.222	1.520	0	1.520	702		-13.110
						1.942	
194,75	258	1.100	1.100	2.200	-1.492		0
Total	136.634	74.558	62.076	136.634			

The shear forces are the sum of the total loads in the frames and the bending moment is the integration of each distance between the frames wherein the result of the bending moment in the last frame must be zero as in the first frame (Table 1).

The main wire-cross frame has high flexural strength and stiffness in relation to the intermediate frame has not crossed-wire, where they have greater flexibility because of the presence of the gasbags. The main frames support greater loads from the gasbags and the resultant forces on the keel which they are distributed along the longitudinal and shear wires. “The stresses resulting from weight and buoyancy forces on the main frames are rarely more than 30% as large as those resulting from deflation of a gas cell”. [10:203]

Zeppelin Graf used Deep Rings (frames) and this type of structure is commonly used by airships flying at 4000 feet or above. This structure does not have transverse wires considering that all are main frames. The gasbags are separated by netting in order to endure the pressure difference between two cells or deflation one of them. The disadvantage of this structure in relation to main frames cross-wired is the strength to distortion due to opposing forces caused by the lift and weight of the structure. The frames is having this disadvantage, it requires more girders to hold on small loads, making an easier calculation structure due to not having many uncertainties in the distribution of stresses. Another benefit, it is having access to the interior of the structure during the flight.

The intermediate frames have main function to keep the longitudinal stiffness of the airship. These frames are more flexible because they cannot cross wires and they are subject to gas pressures due to the netting of gasbags. The longitudinal girders, the nettings of gasbags, transverse girders above and below to the joints, they improve the distortion strength caused by the gas bag and shear forces. Knowing the tension of the girders from the main frames and the lift caused by shear forces, it is possible to calculate the movement of the joints of the intermediate frames. The main frames as the intermediate frames, the girders are over the frames which the longitudinal girders are fixed in the main frames and continued in the intermediate frames.

One of the fundamental rules in the girders is the members must be centered and aligned, i.e., "the center line of lattice members shouldn’t intersect on the center line of the longitudinal members" [10:222]. In Zepelin, it does not occur where the structure support better the compressive loads due to the members have space between them in order to improve the fixation to the channels. These channels are longitudinal and there are different types of transverse section (figure 3) where the channel makes the union of members in triangular trusses. The triangular trusses with equilateral triangles are more resistant to compression loads while with isosceles triangles are better to support bending and column loads when it has greater height than the width of the base.

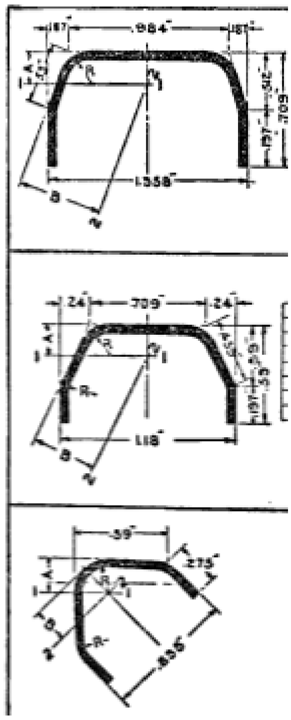


Figure 3: Different types of channel [10].

The triangular trusses have higher resistance to various types of loads (torsion, compression, tension and others) but there are some structure's critical failures which are more common. The critical failures are at bending, channel's torsion and bending, crushing and buckling of the structure, and diffusion.

An improvement of the girders in triangular structures was the appearance of tubular structures having more advantages than the channels used in traditional girders. These had lower weight and it has more resistance that the channels used before. It is possible to increase the length of the girders reducing the number of frames. However, it has some disadvantages like the inspection of corrosion inside of this material and creation of joints in order to build a tubular triangular truss.

Zeppelin Company built a new type of girders consisting in four plates using two sides and two covering the top and bottom. These plates had circular and triangular drilling in the structure to reduce the weight. This type of structure helps to reduce construction costs, to minimize the difficulties in creating joints, and to reduce the structural failures between the channels and the joints. As all structures present disadvantages and one is using more quantity of material due to the drilling of four plates, despite the duralumin is reusable reducing the cost of construction of the girders.

The joints of the girders are the most complex part of the truss due to the material has to transmit loads, wherein the girder is subjected to the individual members. These joints can be thin plates in order to be easy to work creating the shape required to make the connection. They are rigid to endure the loads that tend to break the connection. A disadvantage of this plate is in breach rivets or tears the drill of the plates. The joints are having many connections together tend to have higher reinforcement to increase the stiffness, and many of them are in the main and intermediate frames. The girder should have a heavier channel along the joint in the intermediate frames since it has to endure greater bending forces. [10]

With the advances in technology begins to be possible to create joints in composites which it was not very practical because of the difficulty in the production of composites [11]. The joints in composite may be by adhesive bonding, co-curing process, stitching and mechanical joint with or without adhesive, and the best one is the mechanical joint in order to be faster and more practical in the assembly [12]. This type of technology is under development but it is very promising for the construction of joints in trusses.

2.2.1 Trusses

After a review of various types of airships we observe that all semi-rigid and rigid present triangular trusses because these have a higher resistance to deflection and deformation where the loads can be distributed to compression loads and tensile in order to prevent displacement of the structure. This type of structure has been made of steel, aluminum, aluminum alloys, bamboo and more currently in carbon fiber as the Zeppelin Nt.

As mentioned in LZ 2 Zeppelin, the trusses are special structure to distribute the loads to individual members where they are subjected to compression and tension axial loads. The joints do not allow the rotation which does not imply that individual members act as support members. This simplifies the analysis of the stress in the structure which has been made many calculations of trusses in the twentieth century. A rigid structure, the truss, it considers the moments in the joints are zero making easier to calculate the axial loads with computational methods.

Through equilibrium equations, it can be determine all axial forces of the members which there are several methods to solve the calculations according to the following:

-The simplest method is to consider the joints like a single body (node) that you can determine the tension or compression of each member, i.e., method of joint. Since there are not joint moments, it will be two equilibrium equations for the joint and three equilibrium equations for the whole structure.

-The forces may also be calculated by equilibrium forces which the structure is divided into two parts where the equations are applied to calculate the axial forces, i.e., method of sections.

These conventional methods have their limitations to determine statically trusses primarily to space and larger trusses. Sometimes it has to resort to the (FEM) Finite Element Method for elastic truss structure.

The joints are crucial part of the structure and they have to endure with the compression and tension loads of the truss members suffering a pressure wherein it will cause the distribution of loads throughout the truss.

The quadratic truss built without a diagonal member (figure 4 (a)) present deformation in the shape without changing the length of the structure member as explained in figure 4. To avoid these situations, a member diagonally in a quadrilateral (figure 4 (b)) provides more rigid structure wherein there is not deformation of the shape of the structure transmitting to all loads in axial [11].

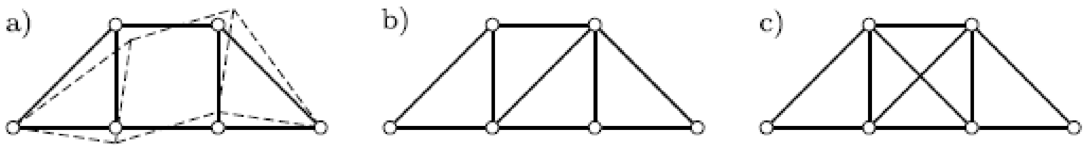


Figure 4: Truss (a) without diagonal member, (b) with one diagonal member and (c) with 2 diagonal members [13].

To know if the truss is statically determinate we use the following formula:

$$b = 3 * j - r \quad (1)$$

Where b is the numbers of members, j is the number of nodes and r is the number of reaction forces. If the expressions are equal, it means that the structure is statically determinate and if the equation is different, it is indeterminate (figure 4 (c)). To solve an indeterminate equation it is necessary to know the stiffness of each member being easier to use software.

- **Method of Joints**

Since the lattice is statically determinate by the method of joints, it will calculate the axial forces to which the member is subjected. Initially, through the equilibrium equations, the reaction forces are calculated for each support truss from the following equations:

$$F_x = R_{Tx} \quad (2)$$

$$F_y = R_{Ty} \quad (3)$$

$$M = F_{ty} * x \quad (4)$$

Where F_x is the total forces applied in the x-axis direction, R_{Tx} is the total reaction forces in the x-axis direction, F_y is the total forces applied in the y-axis direction, R_{Ty} is the total reaction forces in the y-axis direction, M is the moment in one node, F_{ty} is the forces and reaction forces in the y- and x-axis direction and x is the distance in the x-axis direction of the forces and reaction forces in the y-axis direction.

When discovered the results of reaction forces at each support, it is possible the determination of axial forces which the member is subject having the example in figure 6.

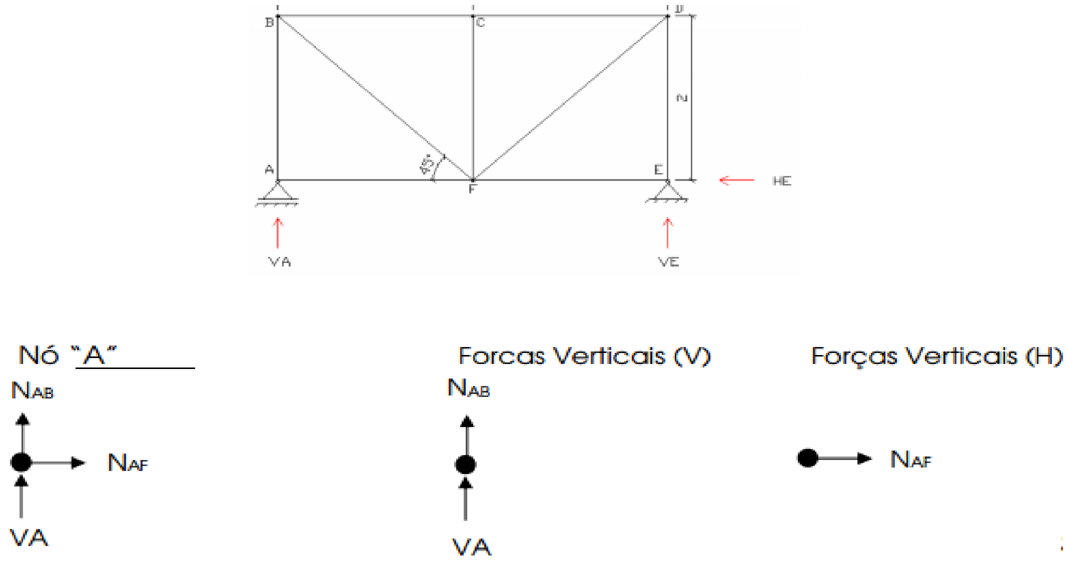


Figure 5: Example of calculation of the member's axial forces [13].

As shown in the figure 5, in each node the axial forces have to be calculated using the equilibrium equations.

In triangular trusses is also possible to use the method of nodes but it is better to use FEM due to the complexity of making calculations in a triangular lattice.

- **Method of sections**

This method consists in dividing the truss in two parts and the division of these two parts is possible to determine the forces of the members by the three equilibrium equations. As in the method of nodes, initially it will have to find out the reactions forces. This method only allows discovering the forces of each member in the area where is split and it is necessary to make the same method in other parts of the truss. [13]

- **FEM**

FEM is very used because it is easier to work and effective to calculate structures showing reliable results, and the software *Ftool 3.0* is a program which determines the axial loads, the moments and the displacement of the truss [14].

2.2.2 Sandwich Structures

The sandwich structure is a concept that it has been around for a long time which join two or more materials with different mechanical properties in order to get the best of both materials. This type of structure has like aim, to increase stiffness and strength with lower costs and weight. Other advantages are non-corrosive material, low water absorption, sound insulation and heat, and the possibility to be created aerodynamic shapes of this material with lower cost.

Comparing the composite sandwich panel with the metal panel, it has the result in figure 6.

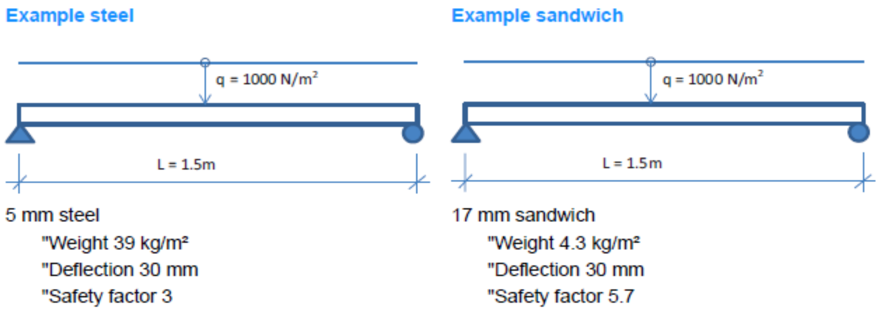
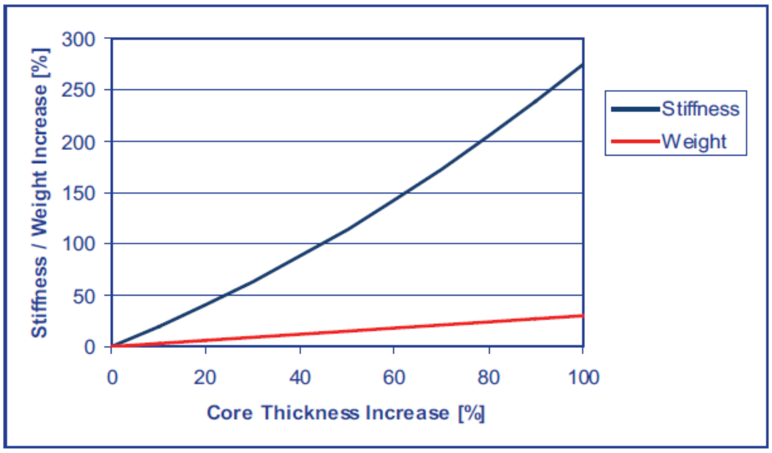


Figure 6: Comparing a metal panel with composite sandwich panel [15].

What differs from the sandwich panel to metal panel is the thickness which is 3.2 times larger but it is lighter, and it has a higher safety factor than the metal panel. It can be observed that increasing the thickness can have more stiffness in the structure and in the graph 1 can conclude the difference with the variation of weight.

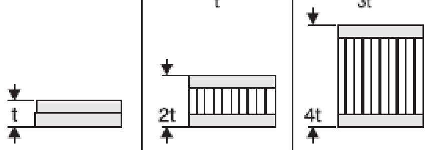


Graphic 1: Difference between the stiffness and weight [15].

The surfaces must have a high strength to compression and tension loads while the core must have a higher shear strength making the joining of two mechanical properties in different materials in order to have a high strength to different loads with a light structure. The core has to be resistant to shear to create greater rigidity to the structure. The faces are normally of steel, aluminum and composite materials resistant to traction and compression. Between the face and the core must be an adhesive that can transfer shear, tension and compression stresses and joining the materials [15].

The various materials used in the core are foams of polyvinyl chloride (PVC), polyethylene - terephthalate(PET), polyethersulfone (PES), balsa, syntatic phenolic, polyisocyanurate and graphitic. These have good mechanical properties, and the balsa and syntatic phenolic have the best flexural strength.

The core does not need to have foam or wood. Honeycomb core is also a feasible solution which it is possible to have even better results than the foam, depending on the material. As in the sandwich structure, the greater thickness has the honeycomb sandwich, higher is the flexural strength as shown in figure 7.

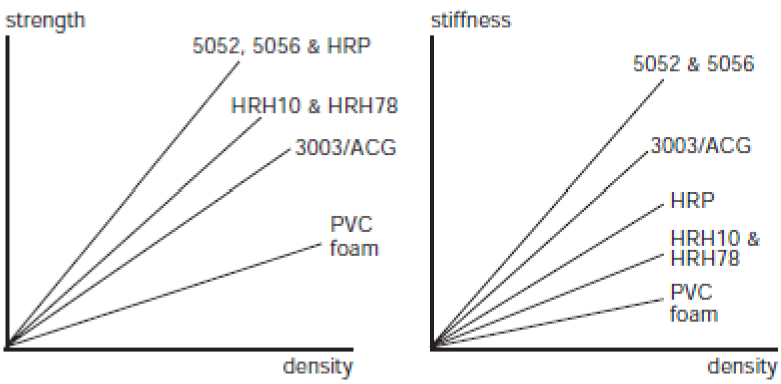


	Solid Material	Core Thickness t	Core Thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Figure 7: The difference of the thickness increase of honeycomb sandwich [16].

The cells may have various shapes and the most common are hexagonal and OX cells where the hexagonal cells have a lower density with the same thickness than OX cells.

The follow graphs make a comparison of different materials where stresses and stiffness are proportional to the density.



Graphic 2: Difference of different materials in honeycomb sandwich [16].

It can analyze for the same density, the aluminum and fiberglass have far better results than PVC foam in sandwich structures [16].

2.3 Material

The man is constantly discovering new materials and many of them are created by man because of the advancement of technology, making a possibility to use the new materials to improve the efficiency of the airships.

The most important aspects to find out the mechanical properties of materials is high young modulus, shear modulus, Poisson coefficient and low density. These properties will help to know the results about the stiffness and bending strength of different materials.

Many airships were built over the twentieth century and many of them have different materials since wood, aluminum and high-tensile steel. The first material and more consistent to use, it was the wood because it presents good mechanical properties. Schutte-Lanz and PAX used in their airships plywood and bamboo respectively. With the evolution of technology appeared duralumin, an aluminum alloy that has replaced the wood and start to be used in most airships due to having good mechanical properties, and lighter than high tensile steel. The disadvantage of this aluminum alloy is the corrosion and sometimes it is not visible, and can cause a failure in the material wherein the risk of failure can be reduced increasing thickness of the material. One advantage is to be easy to handle after the heat treatment, taking two to three days to recover the maximum strength [10].

Steel is a heavy material compared to other material despite having high strength to tension and compression, this material is not common to be used in airships, in the exception of semi-rigid may require a very strength material in the keel having to support many loads concentrated in one place.

2.3.1 Wood

Wood is a natural orthotropic material where the fibers are oriented longitudinally which makes greater strength in tension and compression. The tree growth causes circular fibers which it is visible frontally on longitudinal axis a radial and tangential property in the wood. The mechanical properties depend of such factors as the species that growth in natural environment, type of adhesives for joining many layers of wood, timber geometry and density. The wood is divided into two classes which they are hardwood and softwood where the hardwood has internal cells usually thicker and have a higher density than softwood [17].

The most common mechanical properties of wood are modulus of rupture, work to maximum load in bending, compression strength parallel to grain, compression stress perpendicular to grain, shear strength parallel to grain, impact bending, tensile strength perpendicular to grain, hardness and tension strength parallel to grain, and the less common are the torsion strength, toughness, creep and duration of load, fatigue, rolling shear strength and fracture toughness. There are defects that may impair the mechanical properties of wood and the density, knots, slope of grain, annual ring orientation, reaction wood, juvenile wood, pitch pockets, bird peck, compression failures, extractive and properties of timber from dead trees.

The wood to be considered composite must be attached by adhesive where the composite wood is divided into various categories such as panel products, structural composite lumber and wood-nonwood composites. The differences in mechanical properties between natural composite and natural wood are in table 2.

Table 2: The mechanical properties of wood.

Material	Specific gravity	Static bending properties			
		Modulus of elasticity		Modulus of rupture	
		GPa	($\times 10^6$ lb in^{-2})	MPa	(lb in^{-2})
Clear wood					
White oak	0.68	12.27	(1.78)	104.80	(15,200)
Red maple	0.54	11.31	(1.64)	92.39	(13,400)
Douglas-fir (Coastal)	0.48	13.44	(1.95)	85.49	(12,400)
Western white pine	0.38	10.07	(1.46)	66.88	(9,700)
Longleaf pine	0.59	13.65	(1.98)	99.97	(14,500)
Panel products					
Hardboard	0.9–1.0	3.10–5.52	(0.45–0.80)	31.02–56.54	(4,500–8,200)
Medium-density fiberboard	0.7–0.9	3.59	(0.52)	35.85	(5,200)
Particleboard	0.6–0.8	2.76–4.14	(0.40–0.60)	15.17–24.13	(2,200–3,500)
Oriented strandboard	0.5–0.8	4.41–6.28	(0.64–0.91)	21.80–34.70	(3,161–5,027)
Plywood	0.4–0.6	6.96–8.55	(1.01–1.24)	33.72–42.61	(4,890–6,180)
Structural timber products					
Glued-laminated timber	0.4–0.6	9.00–14.50	(1.30–2.10)	28.61–62.62	(4,150–9,080)
Laminated veneer lumber	0.4–0.7	8.96–19.24	(1.30–2.79)	33.78–86.18	(4,900–12,500)
Wood–nonwood composites					
Wood plastic		1.53–4.23	(0.22–0.61)	25.41–52.32	(3,684–7,585)

According to the table 2, the only natural composite which shows better results than natural wood is structured timber products and it is divided into two subcategories. The product glued-laminated timber are several layers glued together in the same direction as the grain giving better physical and mechanical properties of each material. "Structural composite lumber (SCL) products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber" [18:12-5] and sawdust with less strength are dispersed within the structure having much less effect on strength property than natural wood.

With the advancement of technology the wood is no longer used in airships due to the appearance of new materials with better resistance ratio / weight than wood. The materials most used in airships were plywood, bamboo and ash wood where the mechanical properties are in the following table 3 [18, 19, 20, 21].

Table 3: The mechanical properties of wood to use in Ansys [18, 19, 20, 21].

	Balsa	Ash	Plywood	Longleaf Pine	Bambu
ρ (kg/m^3)	155	580	410	590	700
E X direction (MPa)	3347	11400	8556	13700	15110
E Y direction (MPa)	55.22	1003.2	3444	828,85	n.d
E Z direction (MPa)	169.36	1567.5	3444	1537	n.d
μ XY	0.488	0.44	0,22	0.365	0.26
μ YZ	0.231	0.36	0,22	0.342	n.d
μ XZ	0.229	0.371	0,22	0.332	n.d
G XY (MPa)	198.81	1366.86	71	1180.1	890
G YZ (MPa)	136.22	965.58	25	997.26	n.d
G XZ (MPa)	18.4085	965.58	25	199.452	n.d

The woods used in previous airships have some differences wherein the bamboo has better resistance but it has high density in relation to other materials. Bamboo is a tubular and hollow wood having good torsion strength, and favoring the remaining woods. It should be noted that these dates are an average because the dates are not from the same author as the results may be obtained from different wood [18, 19, 20, 21].

2.3.2 Non-natural Composite

The composite is joining two or more materials in order to create a superior and unique material [22]. The origin dates back many centuries ago but the first non-natural composite was in 1935 where it was created the first fiberglass combined with plastic polymer creating a rigid and light structure. This make the appearance of fiber reinforced polymers having appeared later the Kevlar (aramid fiber), carbon fiber, boron fiber and basalt fibers [23].

The composites are divided by category which depend on the matrix polymer matrix composites (PMC's), metal matrix composites (MMC's), ceramic matrix composites (CMCs) and composite carbon / carbon (CCC's). The polymer matrix composites are the best results in the stiffness with low density which may be thermoplastic or thermosetting. The composites exhibit better results than many other materials on various parameters (figure 8) [24].

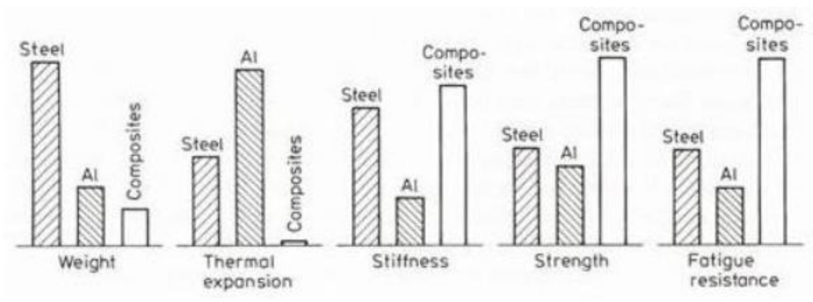


Figure 8: The difference of mechanical properties between composites, aluminum and steel [24].

Between composites there is also a significant difference where they depend on the orientation of the fibers and the characteristics of each material.

Table 4: The differences of mechanical properties between the different composites [24].

Fiber	Density (g/cm^3)	Axial Modulus (Gpa)	Traction Strength (Mpa)	CTE (ppm/K)	Axial Thermal Conductivity (W/m.K)
E-Glass	2,6	70	2000	5	0,9
HS-Glass	2,5	83	4200	4,1	0,9
Aramide	1,4	124	3200	-5,2	0,04
Carbon UHM (PAN)	1,9	590	3800	-1	18
Carbon UHS (PAN)	1,8	290	7000	-1,5	160
Carbon UHMK (pitch)	2,2	895	2200	-1,6	640
Carbon UHK (pitch)	2,2	830	2200	-1,6	1100
Steel	7,8	210	<2000	11	43

According to the table 4, it can observe that the carbon has many better results than any other composite and it has a very low density with high tensile strength. Due to the good mechanical properties of the carbon fiber, the current airships use this material for the internal structure.

Despite the advantages of the carbon fiber, it also has some disadvantages wherein the production costs of this composite are much more expensive than aluminum. The tendency is decrease the costs with the evolution of the technology and optimization. The epoxy resin is used in the composite which is non-recyclable. If the material is damaged, it is impossible to recover without replace with a new piece [25].

There are several types of adhesives that can be applied to structures but not all have good mechanical properties regarding to tension, compression and shear strength. One of the strongest glues is currently the epoxy and it is waterproof, flexible and resistant to heat, cold and chemical exposures. However presents some disadvantages such as the long curing time, surface preparation and a low strength shell. Adhesive polyurethane has also good mechanical properties but it expands and it has the disadvantage compared to epoxy does not have a high resistance to bonding [26].

2.4 Conclusion

Many airships had some fails in their internal structure causing many air disasters a long time ago. However never gave up using the airships to civilian or military and it is currently one of the researches to find out an efficient and environmental transport. Although the knowledge still very theoretical, there are increasingly more hypotheses to become real the existence of hybrid airships with a strong lightweight structure.

The materials show the technology advances, as well as the cost of production decreases. Some natural materials are good for some applications and optimization of the structure and the new types of structures can have good results with high resistance to various types of loads. The potential of each material depends largely on the manufacture and rigorous for aeronautics structures. The construction of structure is also another important factor in the structure and material stiffness.

3. Structural Development of the Airship

3.1 Introduction

The hybrid airship has an aerodynamic shape similar to the airfoil analyzed [27]. This must show an internal structure that respects the limits of the shape and make it possible to build according to the resources available. The material as well as structural analysis, it will be essential to know if the structure is reliable to be used in the Prototype 3.

In this chapter, it will be presented proposals for the internal structure of the Prototype 3 as well as the theoretical and practical results of possible structures for the airship.

3.2 Airship Structure

3.2.1 Structure Design[1]

The hybrid airship (Prototype 3) has some minimum requirements that must be fulfilled like the lower limit of helium volume, about 17.865 m^3, and the maximum mass limit of the internal structure, about 9 kg. The Prototype 3 is composed of four wings with rotors (two of them in the front and others in the back), two stabilizers, and one electric motor (figure (9)).

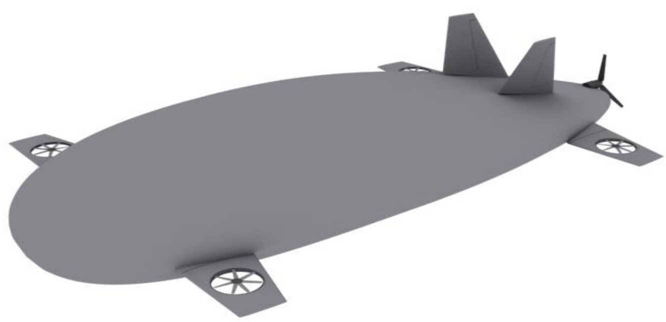


Figure 9: Prototype 3 [27].

The airship's internal structure has to be very light and resistant, because it represents a fairly high volume which makes to increase the risks of high twists and moments. The airship's internal structure has to respect the outer envelope shape [27] for good aerodynamic

[1] *Parte da dissertação relevante para efeitos do processo de proteção de invenção referido no Aviso no início deste documento.*

efficiency. To create the profile will be needed a structure similar to the wings where they have frames with girders to support and to give shape to the airship. The internal structure is composed of nine frames, one hundred sixty girders and also a nose, tail, wings and stabilizers supports (figure 11). The supports will be responsible to support, and transmit, all loads and moments along the frames and girders, without breaking any material. The wings and rotors will create moments on the support because of the generated lift. The stabilizers supports have the same function as the wings support, but the moments are lower. The nose support will be responsible to connect the girders with the frame 1, while the tail support will be responsible to connect the girders to the frame 9 and support the electric motor. These supports must be strong and light, to not increase the weight of the entire structure. After finding out the center of gravity of the airship, the batteries, servos and other electrical equipment must be placed in this center, that is statically in equilibrium.

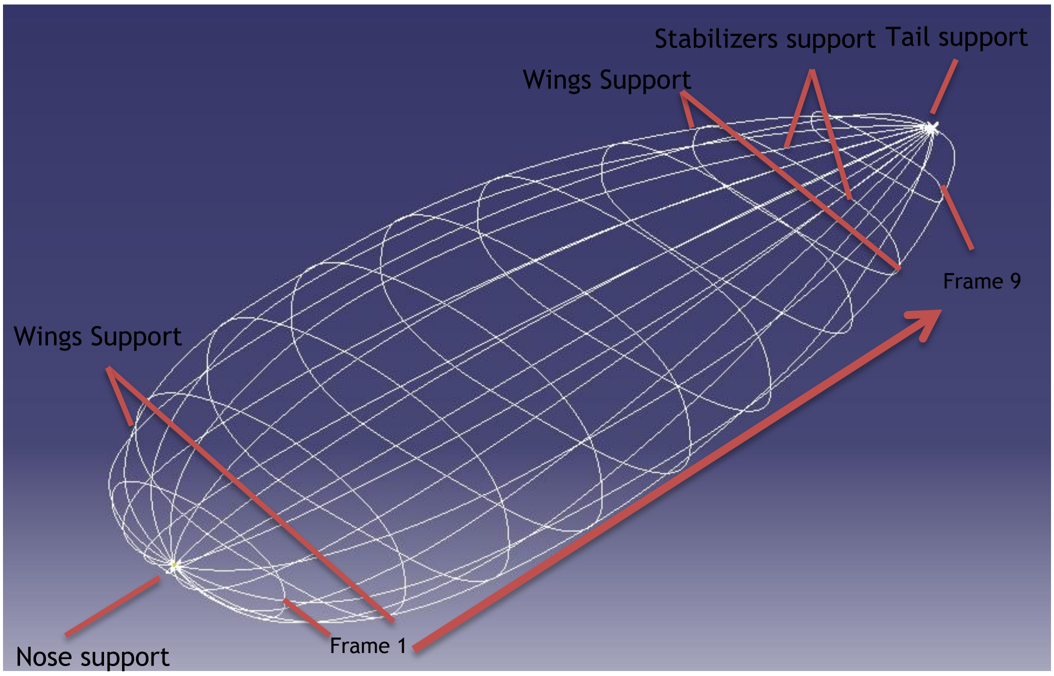


Figure 10: Airship Internal Structure (Prototype 3).

The spacing between frames and girders is very important, but even more important is the fitting that allows the union of all the girders and frames wherein will be responsible to transmit all loads to the truss. The fittings must be simple and effective to maintain or disassemble structure and the hybrid airship has to be easy to assemble and transport due to their dimensions and the work conditions. The material proposed to the fitting is carbon fiber as well as the piece that it is responsible for fixing the junction of the frames and girders as illustrated in figure 11.

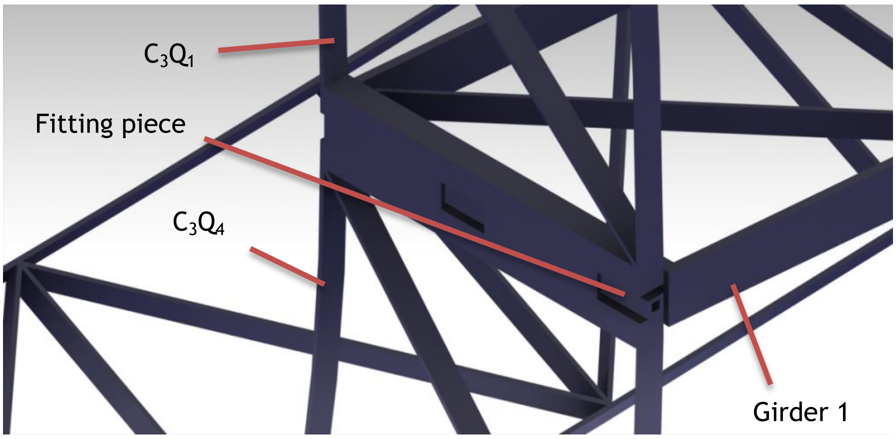


Figure 11: The fitting system of the main girders and frames.

To respect the aerodynamic shape, the girders should not be much spaced between them for the envelope can not bend as well as the space between the frames should be short. According to the initial design of the airship was estimated to be only 12 girders but to improve the stiffness of the frames, it was introduced more four girders in each quadrant of each frame. The frames are divided into four quadrants and the center is the chord line of the airship airfoil. The airship has four main girders and these girders have to support the weights of the wings and torsion of the entire structure where the main girders are 1, 5, 9 and 13 as described in the nomenclature of figure 12. Regarding the number of frames, it is chosen in order the main girders do not have more than one meter length between frames, which makes a total of 9 frames along the airship.

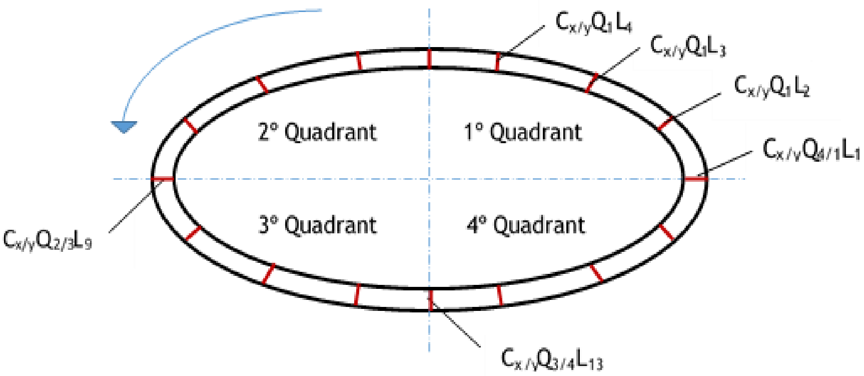


Figure 12: Frame nomenclature.

In the draw of the frames, it was necessary to pay special attention to the height and width of the Prototype 3, designed to respect the limits, where the maximum width is 3.5 meters and the maximum height is 1.8 meters at the maximum thickness of the airfoil. The largest frame will have major problems of stiffness, but to build it will be easier than the smallest frames because they present more pronounced curvature at the extremities (width). The largest frames have lower stiffness and it is necessary to balance the spacing between the girders to increase the stiffness of the frames, thus, in each frame it was designed equidistant points along the perimeter of the girders, getting the same spacing between them. It was found that this process was time consuming and the condition to create such a structure would be complicated, proceeding to a simple design which the girders have an angle in relation to the center of chord line. The angles take into account the equidistant points (figure 13).

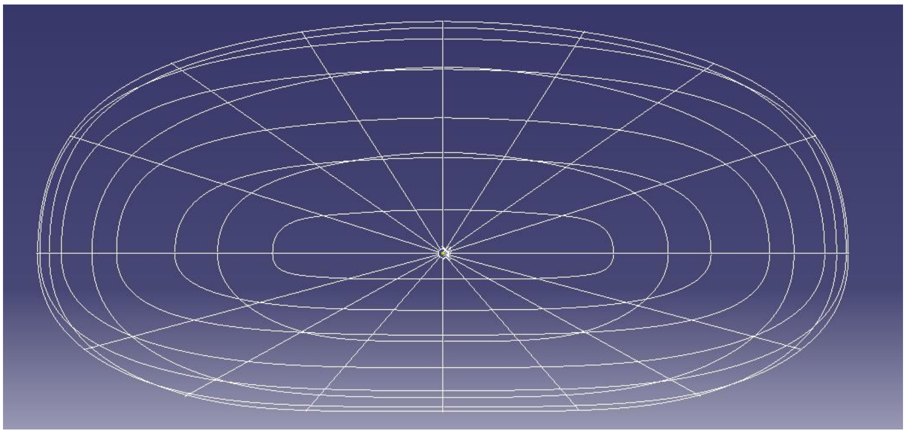


Figure 13: Angles of the girders.

The nose and tail support must be very rigid structures because it will support the connection of all girders. The tail support will also have to support the propulsive motor with push propeller. The material has to be wood because it is easy to do shape and provide higher stiffness. The nose support is a tubular piece which the girders can be fixed with the respective angles (figure 14 a)) while the tail support is a more complex structure where the girders connect to a wood circular board (figure 14 b)). For the girders to join to the wood board, it is necessary to reduce the girder height along the length.

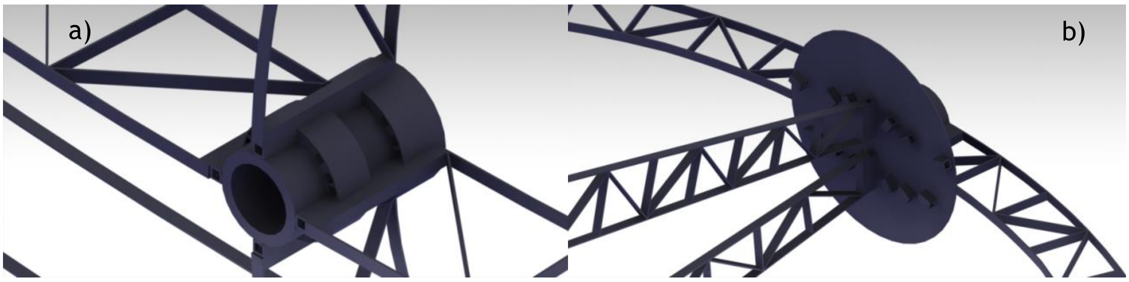


Figure 14: a) Nose support b) Tail support.

With the results of the Prototype 2, the position of the wings and stabilizers supports in the Prototype 3 will be established in the frame 2 and 8. The wings supports (figure 15) will be placed in the frames and between the girders in order to transmit all loads from the wing and stabilizers to the airship's internal structure. The support has to hold all moments generated by the lift from the rotors and the rotation of the wings. With the high loads and moments, the fittings of the girders, frames and supports need to be more rigid than the carbon fiber. One alternative is to use wood or metal fittings to connect the frames and girders to the wings supports.

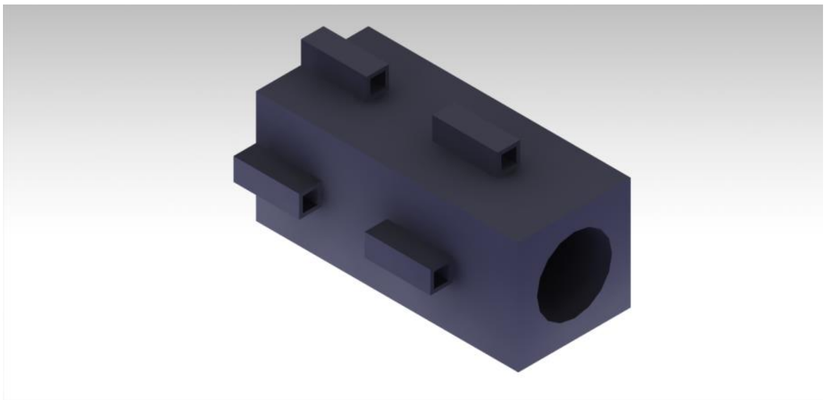


Figure 15: Wings support.

The stabilizers are in the same situation as the wings, for the exception of the support that will be different since the stabilizers are not in the main girders, but they should always be in the frame position for the loads to be distributed to the frame and the girders. The support will be fixed by pieces responsible for attaching the girders and frames, which the example is in figure 16.

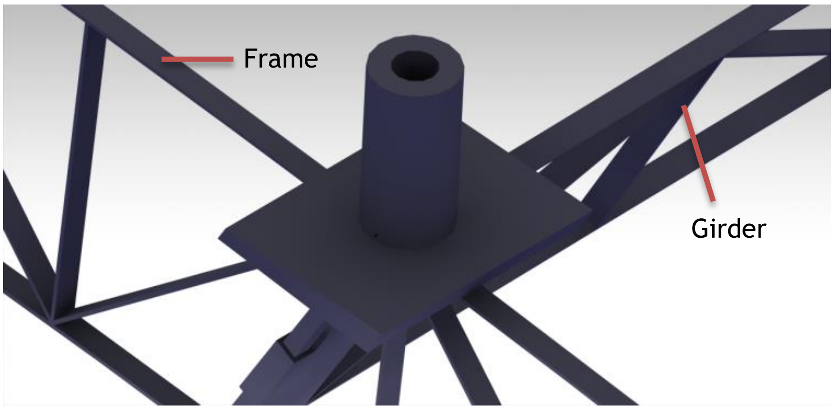


Figure 16: Stabilizers support.

The remaining material will be fixed in the structure wherein the gasbags have to be fixed by strings in several points of the frame and lower girders. The gasbags are advised, in the girder and frame, to be fixed close to the fitting points, because in the space between girders and frames, the structure is weak to deformation and torsion. The strings have to be well tensioned to reduce the balancing of gasbags. The batteries, ESC and other materials may be fixed like in the other prototypes through Velcro, which is effective and safe. If necessary a larger contact area, it is possible to glue a board or gondola outside the girder to provide more space to all materials. The board and gondola should not disturb the fitting of the frames and girders.

3.2.2 FEM Analysis

The sandwich structure with two laminated carbon fiber faces and the core with depron, it was found out, that the total weight was high to the stiffness and resistance to bend desired.

The sandwich structure with Airex in core showed better results and higher stiffness, but higher weight. Thus, using this type structure does not become feasible for the airship where it is necessary high stiffness of the structure and low weight. The sandwich method cannot be excluded when there are other solutions besides Airex and Depron with better mechanical properties, such as there is honeycomb sandwich or phenolic foam for the core.

Not all materials are accessible and some properties are far from reaching the strength/ weight of carbon fiber. It was thought to make carbon fiber trusses wherein the joints are made by epoxy glue. The mechanical properties of the carbon fiber used to perform structural calculations are in table 5.

Table 5: Mechanical properties of carbon fiber

Property	Units	Direction	Values
Density	kg/m^3		1500
Tensile Modulus	GPa	Longitudinal	280
		Transverse	8
In-plane shear modulus	MPa		5
Major Poissons ratio			0.3
Tensile Strenght	MPa	Longitudinal	350
Compressive Strength	MPa	Transverse	250
Tensile Strain		Longitudinal	1.05
		Transverse	0.5
Compressive Strain		Longitudinal	0.85
		Transverse	2.5
In-plane shear strain			1.2
Thermal coefficient	10^{-6} K^{-1}	Longitudinal	-0.3
		Transverse	25

To know the axial compression and tension forces of the trusses elements, it is applied the method of joints. Because the structure has many nodes, it was used the software Ftool 3.00 to calculate the axial forces of each web element and the displacement of the truss. The truss used to perform the calculations was 8 cm of height and 1 m of length. The height of 8 cm was chosen according to the fitting system that allowed a greater area to connect girders and frames. The angle of the diagonal web element is about 45 degrees which makes the behavior better to bending loads.

To be able to have the results from Ftool 3.00, it is necessary to enter the Young Modulus, Poisson ratio and Thermal Coefficient of Expansion, the sectional area and length of the truss, nodes, supports and loads imposed on the truss. After enter the dates, in the first test was applied 24N in center of the truss and the second test was applied 4 N in 6 nodes at the lower nodes of the truss.

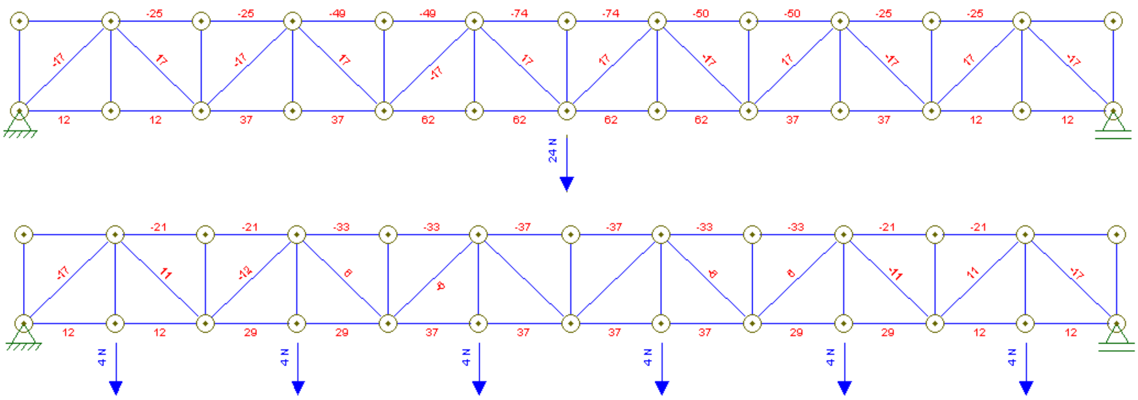


Figure 17: Numerical test on *Ftool* to find out the axial forces.

Comparing the results (figure 17), it is verified in the first test, the diagonal web elements have the same axial load module in every web elements while in the second test the axial loads are different. In relation to the displacement the results obtained in the first test was 1 mm and in the second test was 0.638 mm. The displacements results are only approximation because of the software that recognizes isotropic materials.

To more detail analysis, it resorts to ANSYS Software (static structural) to apply the FEM, wherein it is analyzed where there is greater deformation and the most problematic points. This analysis can help to reinforce these weak points in the structure in order to provide more stiffness and better performance. According to the previous truss, we search an optimization of the structure at different heights from 5 to 10 cm with the diagonal web elements having an approximate angle of about 45 ° and 60 °. This optimization may also takes into account the total weight of the structure. The most important results of this analysis is the normal stress, equivalent stress (Von-Mises stress), total deformation, d / w and stress intensity, where d is the total deformation and w the weight. Table 6 shows the maximum stress values where the maximum normal stress is the maximum principal stress in the x-axis direction; the maximum equivalent stress is the Von-Mises failure criterion for a ductile material; and the stress intensity is the difference between the maximum principal stress and minimum principal stress which is equal to twice the maximum shear stress.

Table 6: Numerical test results on Ansys with different angles and height of the web elements.

Without lateral supports						
Distributed load - 20 N (lower flange)						
Height	Weight (kg)	Total deformation (m)	Von-Mises Stress (Pa)	Normal Stress (Pa)	Stress Intensity (Pa)	d/w
Aproximately angles of 45º						
5 cm (45.346º)	4.19E-02	0.00012289	2.45E+07	1.93E+07	2.46E+07	2.93E-03
6 cm (44.177º)	4.19E-02	0.00011863	2.20E+07	1.93E+07	2.21E+07	2.83E-03
7 cm (44.767º)	4.27E-02	0.00011746	2.11E+07	2.04E+07	2.14E+07	2.75E-03
8 cm (44.177º)	4.30E-02	0.00012409	1.86E+07	1.59E+07	1.90E+07	2.89E-03
9 cm (42.331º)	4.26E-02	0.0001366	1.94E+07	1.94E+07	1.94E+07	3.21E-03
9 cm (47.547º)	4.26E-02	0.00012444	1.76E+07	1.46E+07	1.76E+07	2.92E-03
10 cm (45.346º)	4.46E-02	0.0001372	1.96E+07	1.96E+07	1.96E+07	3.07E-03
Aproximately angles of 60º						
5 cm (59.836)	5.29E-02	0.00013808	2.30E+07	1.95E+07	2.35E+07	2.61E-03
6 cm (59.54º)	5.32E-02	0.00013119	2.04E+07	1.64E+07	2.08E+07	2.46E-03
7 cm (59.54º)	5.38E-02	0.00012787	1.84E+07	1.41E+07	1.88E+07	2.38E-03
8 cm (60.692º)	5.57E-02	0.00012855	1.69E+07	1.24E+07	1.73E+07	2.31E-03
9 cm (58.622º)	5.39E-02	0.00012424	1.60E+07	1.10E+07	1.64E+07	2.30E-03
10 cm (61.238º)	5.75E-02	0.00012924	1.49E+07	9.96E+06	1.52E+07	2.25E-03
Distributed load - 20 N (upper flange)						
Height	Weight (kg)	Total deformation (m)	Von-Mises Stress (Pa)	Normal Stress (Pa)	Stress Intensity (Pa)	d/w
Aproximately angles of 45º						
5 cm (45.346º)	4.19E-02	0.0001225	2.37E+07	1.98E+07	2.38E+07	2.92E-03
6 cm (44.177º)	4.19E-02	0.00011772	2.08E+07	1.68E+07	2.09E+07	2.81E-03
7 cm (44.767º)	4.27E-02	0.0001187	1.87E+07	1.48E+07	1.88E+07	2.78E-03
8 cm (44.177º)	4.30E-02	0.00012181	2.26E+07	1.66E+07	2.31E+07	2.83E-03
9 cm (42.331º)	4.26E-02	0.00014059	2.08E+07	2.08E+07	2.08E+07	3.30E-03
9 cm (47.547º)	4.26E-02	0.00012238	1.61E+07	1.61E+07	1.62E+07	2.87E-03
10 cm (45.346º)	4.46E-02	0.00014083	2.04E+07	2.04E+07	2.04E+07	3.6E-03
Aproximately angles of 60º						
5 cm (59.836)	5.29E-02	0.000138	2.31E+07	1.97E+07	2.32E+07	2.61E-03
6 cm (59.54º)	5.32E-02	0.00013121	2.03E+07	1.66E+07	2.03E+07	2.46E-03
7 cm (59.54º)	5.38E-02	0.00012785	1.82E+07	1.44E+07	1.83E+07	2.38E-03
8 cm (60.692º)	5.57E-02	0.00012857	1.66E+07	1.28E+07	1.66E+07	2.31E-03
9 cm (58.622º)	5.39E-02	0.00012446	1.55E+07	1.16E+07	1.55E+07	2.31E-03
10 cm (61.238º)	5.75E-02	0.00012941	1.43E+07	1.08E+07	1.44E+07	2.25E-03

After the analysis, it is verified that the truss with 7 cm of height provides the best results in deformation and all stresses compared to the other truss. In the structural analyzed, there is a rotating joint due to compression and tension caused by imposed loadings on the structure. However, this truss is relatively small compared to the size of the frame wherein the frame is less resistance to torsion, bending and shear forces. To avoid these deformations as well as rotation in the joints, it was placed a lateral support semicircle of carbon fiber laminated improving the stiffness of the structure.

The truss will suffer torsion because of the tension of the strings of the gasbags, wings and stabilizers. It is necessary to make a study to prevent the truss break up by torsion and it is applied a moment of 1 Nm in the center of the truss to study the stresses and deformation. The results obtained are in the table 7.

Table 7: Numerical tests results with moment around x-axis.

Without lateral support				
Moment around x-axis				
Truss height	Weight (kg)	Total deformation (m)	Stress Intensity (Pa)	d/w
5 cm (45.346°)	4.19E-02	0.0090984	2.64E+08	2.17E-01
6 cm (44.177°)	4.19E-02	0.009131	2.54E+08	2.18E-01
7 cm (44.767°)	4.27E-02	0.0089584	2.42E+08	2.10E-01
8 cm (44.177°)	4.30E-02	0.0086502	2.29E+08	2.01E-01
9 cm (42.331°)	4.26E-02	0.0082635	2.16E+08	1.94E-01
9 cm (47.547°)	4.26E-02	0.008325	2.17E+08	1.95E-01
10 cm (45.346°)	4.46E-02	0.0078999	2.04E+08	1.77E-01

To understand the behavior of the frame and girders assembled, it was made a numerical test which shows the critical deformations and stresses when applied a load in bottom frames and girder. The total load applied in the frames and girders, is the forces generated (lift) by the gasbags which is 79.27 N. In figure 18, shows a frame 3 and 4 connected by girders and it is applied a load in 20 points of each frame and in 4 points on girder 11, 12, 13, 14 e 15 (figure 12).

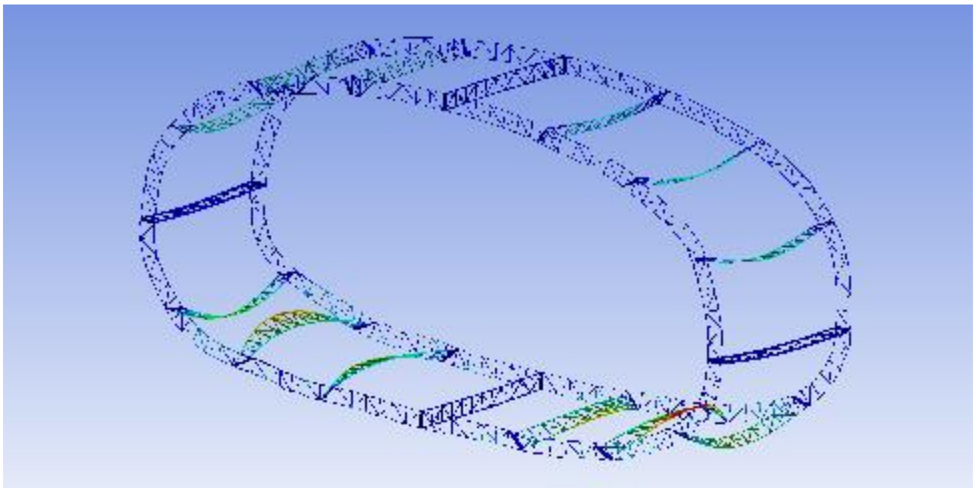


Figure 18: Frame 3 and 4 assembled with girders.

The diagonal girders on the top are showing bending, even if there is not any load applied on the girders, because in this test was active the inertia relief wherein means the structure has acceleration gravitational (weight structural). It is observed that the girder is not strong enough in the center. The main girders doesn´t show that problem because they have more thickness and they are stronger.

Table 8: Numerical test of the frame 3 and 4 assembled with girders.

Material	Weight (kg)	Total deformation (m)	Von-Mises stress (Pa)	Normal Stress (Pa)	Stress Intensity (Pa)
Carbon	1.8362	0.0001019	8.45E+05	8.26E+05	8.46E+05

According to the results (table 8), we can observe the deformation and the stress are really small because the forces are distributed along the frame and girders. The problem is the torsion caused by the string when it is fixed on lower flange of the girder.

3.2.3 Experimental tests

Depending on the fittings of the main girders and frames, they have to be connected in one point. The trusses analysis was chosen to be 8 cm in height which has good results despite it do not have the best result from the table 6. The truss has 8 cm of height and cutting the fittings pieces will be simpler, due to each piece is 1 cm of height to connect the frames and main girders.

It was built four small trusses (figure 19) with different materials, wherein it was made trusses elements with carbon fiber, balsa or plywood and balsa. It was observed that the construction of the truss elements made by balsa, it was more complicated because it has lower shear strength. Increasing the thickness of the truss elements, the trusses have more stiffness and higher shear strength but it takes more time to make the joints. Using plywood in upper and lower flanges, it is improved the shear strength but depends on the material used in the web elements. The carbon fiber truss shows the best result making the structure more reliable. The problem of the carbon fiber, it is hard to cut the material.

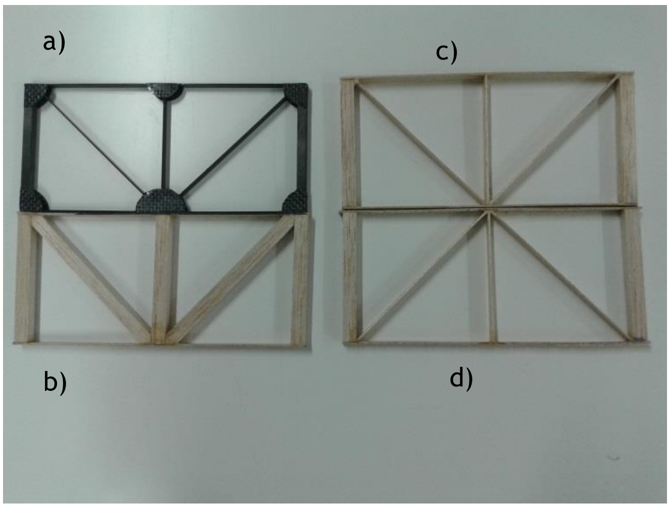


Figure 19: Truss elements made by a) carbon fiber; b) balsa c) balsa d) balsa and plywood.

To know the stiffness of the structure, it resorts a practical test with a carbon fiber truss of 1 m of length, 8 cm in height, and 48 grams of total weight. The first test was just to test the structural stiffness and the ability to hold two kg as projected before. In this test have been used two polystyrene to stabilize vertically, and applying a load with the bucket in the center of the truss to test the flexural strength. The bucket has been attached in lower flange to the structure with Dyneema, and it was applied, increasingly, 200 grams of metal weights (figure 20).

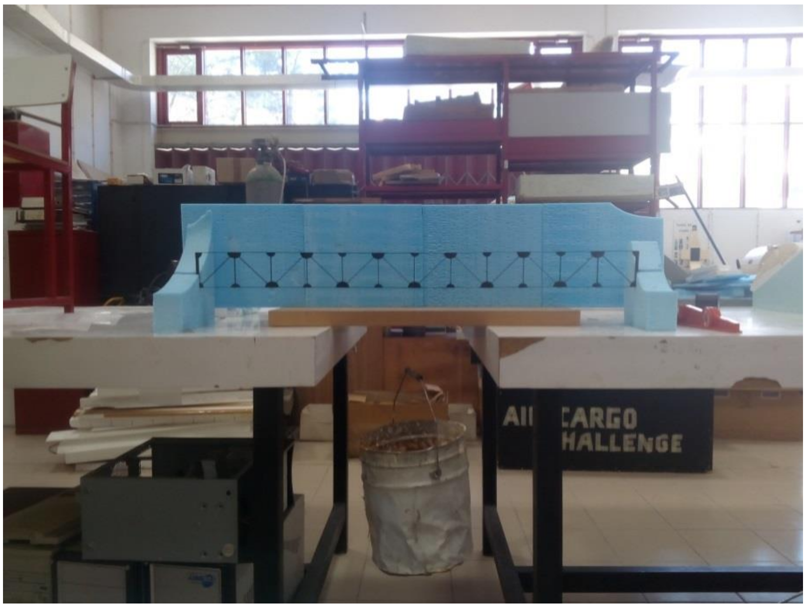


Figure 20: Experimental test applying one load in the center of the truss.

Reaching 2.5 kg, it was checked that the truss has sufficient stiffness to be used as main structure of the frame. This experimental test also gives an idea some defects such as torsion of the entire structure due to not having rigid supports in the extremities, the balancing of the wire and the bucket to be fixed on the lower flange.

Table 9: Numerical test applying one load in the center of the truss.

With lateral supports					
Load applied of 24,525 N in the center					
Truss Heigh	Weight (kg)	Total Deformation (m)	Von-Mises stress(Pa)	Normal stress (Pa)	Stress Intensity (Pa)
8 cm (44.177°)	4.90E-02	0.00028804	4.2444E7	5.5272E7	4.5825E7

According to the numerical test (table 9), it is checked the structure has a very small deformation in relation to the practical test, but differing in the fact that there is no torsion in the calculation of the numerical test.

In the second and destructive test were placed 6 empty water bottles, attached with Dyneema in the upper flange of the truss, having a small bars of balsa to support (figure 21). The balsa had a little effect due to the force exerted by the weight of the bottle, which was higher for the shear strength of balsa. The joints are epoxy glue, having been glued at the same time of the lateral supports. Each empty bottle weighed about 82.5 grams, and it was applied to each 200 grams of water, starting to alternate from one extremity to the other extremity until all bottles were 200 grams. Once every bottle had the same weight, it was returned the same process until the structure broke up. The structure was attached with two wood supports, in order to the structure does not to suffer torsion at the extremities as in the previous test. To reduce the torsion in the central part of the structure, it takes into account to reduce the distance of the strings between the bottles and the truss.

Figure 21: Experimental test applying 6 loads in the truss.

The structure broke when the total weight of all the bottles was about 7.2 kg, and the problems which caused the rupture was the unglued of epoxy glue on web elements, which were in the center of the structure. This happened because the contact area, between the diagonal and vertical web elements and the upper and lower flanges, is small despite the lateral support helps to create a larger area. Another factor that influences their unglued is the torsion that the structure was having because of the bottles are not completely perpendicular to the longitudinal web elements and causing balance. It was not possible to know the total deformation result of the experimental test, because we had not access to any tool that could measure this result.

Table 10: Numerical test applying 6 loads in the truss.

With lateral supports						
Distributed load of 11,772 N in 6 structural points						
Truss height	Weight (kg)	Total deformation (m)	Von-Mises (Pa)	Normal stress (Pa)	d/w	Intensity stress (Pa)
Bottles attached in upper flange						
8 cm (44.177°)	4.90E-02	7.43E-05	1.90E+07	6.75E+06	0.001516327	2.0523e7
Bottles attached in lower flange						
8 cm (44.177°)	4.90E-02	7.54E-05	1.91E+07	7.73E+06	0.001538776	2.1307e7

According to the numerical results (table 10), we checked a very similar behavior to what happened in the experimental test wherein the structure presented a very small deformation and the problem in the test, was the unglued along with the torsion caused in the center of the structure. In relation to the previous efforts, we observe a significant improvement due to the load being distributed in 6 points rather than 1 point in the center of the structure.

To optimize the cost and weight, it was built another structure wherein the flange and vertical supports are carbon fibers while the diagonal and vertical web elements in balsa (figure 22). This structure was registered with 43 grams, but it has some structural problems where one diagonal web element has some fractures and one web element vertical was misplaced. These defects were caused in the construction due to the pressure from the lateral supports in the gluing and the low shear strength of the balsa.

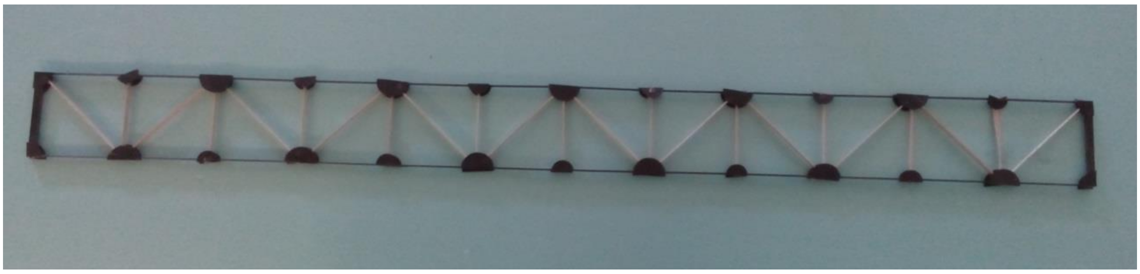


Figure 22: Truss with balsa in web elements.

The test was realized with the same method that the test above, except the bottles were attached on the lower flange. In this test, the structure broke up at 2.4 kg and this time the balsa broke up instead the gluing of the structure. During the test, it was observed that the diagonal web elements began to bend until to fracture and cause total rupture of the structure, making impossible to recover the balsa parts while the structure with carbon fiber only needs a new gluing.

Table 11: Numerical test applying 6 loads in the truss.

With lateral supports						
Distributed load of 3,924 N in 6 structure points						
Truss height	Weight (kg)	Total Deformation (m)	Von-Mises (Pa)	Normal Dtress (Pa)	Intensity Stress (Pa)	d/w
Bottles attached in upper flange						
8 cm (44,177°)	3,09E-02	0,0022321	6,01E+07	5,65E+07	6,2048e7	0,072236
Bottles attached in lower flange						
8 cm (44,177°)	3,09E-02	0,0022267	6,04E+07	6,05E+07	6,2311e7	0,072061

According to the numerical test (table 11), it is observed a very similar behavior with the experimental test. The total deformation of the balsa structure was far superior to the carbon causing the rupture. This test has to take into account that when applied on the lower flange, that affected the torsion of the structure but without differences for final result.

The balsa, despite to be fragile, it can be used in vertical web element if necessary to reduce costs or even some extra weight. The balsa is not recommended because if it fractures it will be harder to repair wherein needs more careful and time-consuming to replace another new piece.

To optimize is always necessary to look for new possible solutions to be used in the truss elements. To reduce the weight, there was a study with different materials in the web elements comparing the results from the truss with carbon and balsa, and it is observed the differences in results as follow.

Table 12: Numerical test applying 6 loads in the truss with different materials.

Without lateral support						
Distributed load of 3.924 N in 6 structural points						
Load applied in the upper flange						
Material	Weigth (kg)	Total deformation (m)	Von-Mises (Pa)	Normal stress (Pa)	Stress Intensity (Pa)	d/w
Carbono	4.90E-02	2.72E-05	2.45E+06	2.54E+06	2.46E+06	5.54E-04
Balsa	3.09E-02	0.0021818	3.63E+07	3.58E+07	3.70E+07	7.05E-02
Plywood	3.44E-02	0.0015292	2.92E+07	2.87E+07	2.98E+07	4.45E-02
Bambu	3.83E-02	9.52E-05	4.05E+06	3.99E+06	4.11E+06	2.49E-03
Ash	3.66E-02	8.95E-05	3.87E+06	3.82E+06	3.93E+06	2.44E-03
Longleaf Pine	3.68E-02	0.00025697	8.32E+06	8.21E+06	8.47E+06	6,99E-03

According to the theoretical results (table 12), it is analyzed that the Ash is the best result in weight and the deformation despite it has more 5 grams than balsa. If it is possible to obtain this material with these mechanical properties, it is a case to consider using in the future in the truss for the Prototype 3, having always to validate the results with a practical test.

In the destructive testing of carbon fiber truss, it is observed that the web elements are unglued which make a serious problem. It was done destructive tests to find out the resistance of the glue and the fittings. It was made three types of tests where has been tested the shear strength inside the fitting (figure 23 a)), the lateral of the piece (figure 23 b)) and the longitudinal stress of the fitting (figure 23 c)). The aim of these tests is to simulate the fittings and know the strength limits to build in the Prototype 3.

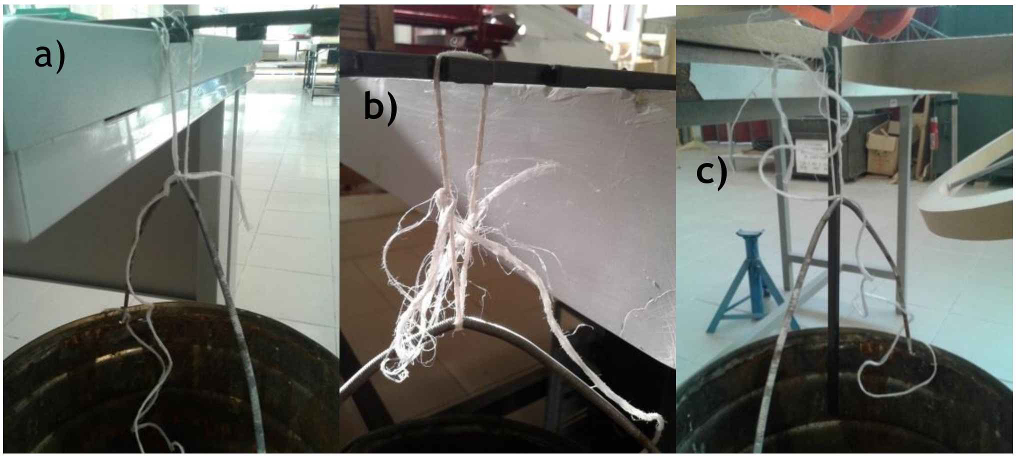


Figure 23: a) Shear strength test b) lateral test and c) longitudinal test

Analyzing the three tests, the only one wherein the glue was given in, it was in figure 23 b) at 6.195 kg. This type of fitting is used to fit the main girders to the frames, and to avoid their unglued is advisable to reinforce the gluing with a larger contact area and lateral supports. For the other tests, the structure gives in due to rupture of the material. In figure 23 a), the fitting broke up at 5.445 kg wherein is responsible for fitting the diagonal girders and frames. As this have low shear strength, it should consider changing the fittings on the supports of the wings, stabilizers, nose and tail by strong material. Regarding the figure 23 c), the fitting give in at 9.465 kg having good longitudinal shear strength. We can conclude that the glue is not the problem but the material with lower shear strength.

3.3 Conclusion

The drawings on CATIA are essential to build the prototype 3 to know the dimensions of the structures as well as to solve problems in the difficulty of the assembly structure. These allowed knowing the future difficulties in the construction of some parts such as the nose, tail and stabilizers supports. The entire design process had to take into account the requirements for the prototype 3.

The most reliable material is carbon fiber that is the essential material for the construction of prototype 3, but this does not prevent the new materials to be used in some parts of the internal structure. Despite the trusses have the best results, it does not mean it is not possible to use other structures or different construction methods to improve the whole structure.

The experimental tests allowed the validation of the materials as well as the construction method wherein the big problem is contact area for gluing of the web elements. These have to be particularly cautious in the construction and it is necessary to search for improvements.

Finally, it was conclude that the best truss tested was the carbon fiber truss with 7 cm of height. This truss is sufficiently rigid and lightweight to be used in the prototype 3, but it can be made an optimization of the results obtained with different material in truss elements.

4. Prototypes Development

4.1 Introduction

Analyzing the airship´s operation is sometimes complicated due to the results are very empirical. It is necessary to make practical tests to get a better idea of the buoyancy, control and stability, structure and construction methods.

The tests were divided into 3 prototypes and the Prototype 3 is a combination of the Prototype 1 and 2 but with a rigid internal structure. The main goal of Prototype 1 is to study the control and stability of the hybrid airship with four wings, two stabilizers and one electric motor and Prototype 2 is to study the control and stability of the quadcopter with pitch variable. The aim of Prototype 3 is to study an airship with the same configuration from Prototype 1 and 2 but it was internal structure rigid. The experimental tests from Prototype 1 and 2 will allow detecting some uncertainties, about the airship, to make sure there will be no problem in the final prototype (Prototype 3). The Prototype 3 is a more complex internal structure wherein is necessary to demonstrate the assembly system and the stiffness.

4.2 Prototype 1[2]

The first prototype is a blimp that shows no internal structure and it is a balloon made of PVC with aerodynamic shape. The aim of this prototype is to test the stability to take-off and if it is able to keep stable during the flight with the help of buoyancy caused by helium. It is introduced four wings (two front and two rear wings), two vertical stabilizers and one push motor in order to get balance and stabilize, with wings generating lift.

Having no internal structure represented a problem to fix the material on the balloon. To solve this problem, it was necessary to build some supports to fix the wings, stabilizers and motor, wherein the supports were bonded using adhesive double-sided tape where it is the stronger than all other tape-adhesives available. This support allows greater bonding area and more rigid fixation.

The wings supports have to follow the lateral profile of the balloon for the entire contact area which is bonded with adhesive double-side tape. It is necessary to draw and cut in the polystyrene, the shape of the balloon in two polystyrene plates, wherein they are glued to a third board with contact glue having the same shape. This third is bigger and must be flat on

[2] *Parte da dissertação relevante para efeitos do processo de proteção de invenção referido no Aviso no início deste documento.*

the opposite face bonding, for the wings are aligned to the wind direction. This plate has three aluminum tubes with different positions to fix the wings. In the supports, the servos were placed in the interior of the foam where it was necessary to drill and do not cause aerodynamic disturbances. To improve the support fixation, the adhesive tape was bonded on the top of the support connecting to PVC in order to help in aligning the wing.

The wings are made of polystyrene and reinforced with a white adhesive tape on the upper and lower surface, having in the interior one aluminum tubular spar. To attach the spar to the wings support is necessary that the aluminum tube has bigger radius in the support, and permit the rotation of the wing. To rotate the wings, it is necessary to create a support of carbon glued to the root of the wing in order the servo can move the wing without causing damage to the foam. The connection between the servo and the wing was made by a steel rod with a high stiffness to be able to move the wing without buckling (figure 24).

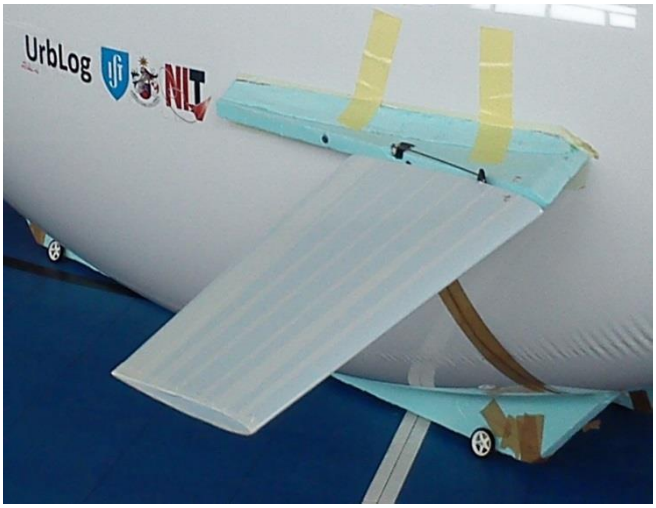


Figure 24: Wings and wings support.

For the vertical stabilizers (figure 25), it was not necessary a support to fix to the balloon and the span was smaller than the wings. The airfoil symmetrical stabilizers made by foam were bonded with Velcro to PVC, and it was used Dyneema string to balance and align the stabilizers. The string passes by both stabilizers being glued with epoxy on wing tip, which it is tensioned between two stabilizers to align. To improve the alignment, the string is tensioned and attached to PVC with Velcro in order to align the position of the stabilizers. The servo was placed inside the polystyrene, and it was connected to the plastic in the rudder with a steel rod.

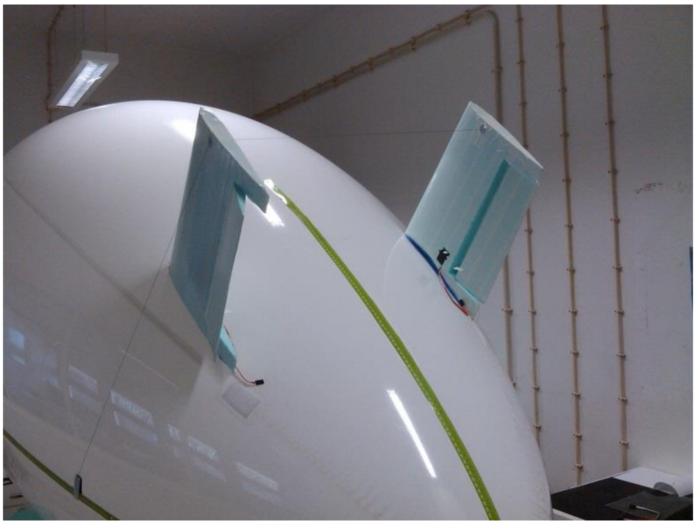


Figure 25: Stabilizers.

The engine must have a fixed support that withstands the vibration and tension. It had to be constructed a rigid structure that withstands the loads caused by the electric motor (figure 26). The structure was made by laminated carbon fiber with shape cone. To attach this structure to PVC on the back, it was glued laminated carbon fiber with rectangular shape in the base of the cone to the outside, in order to use Velcro at the ends. The electric motor is added at the top of the cone where there is a carbon plate to enhance the strength and wear caused by the engine.

Figure 26: Electric motor support.

It was necessary to keep the airship leveled for taking off, but due to the shape of the airship, it was impossible. For that reason, a landing gear that allows taking off and landing in a safe manner was built. The structure of the landing gear is compound with two foam plates and two wheels on both plates. The upper surface with the shape of the balloon was initially attached with Velcro to PVC which turned out unstable and did not attach correctly, and it was decided to use double-sided tape. The wheels, from landing gear, had a balsa plate to support the fixation in the foam, in order that the wheel axel does not corrode the polystyrene foam when the airship is taxiing or rolling on the ground. The support plate and the steel axel of the wheel were glued to polystyrene with epoxy glue.

The electric wires of the servos to the controller, the batteries and the ESC were all glued by Velcro and adhesive brown tape. The double-sided tape is strong enough to attach the string and the Velcro to all electronic equipment.

With the structure assembled on the balloon (figure 27), there was trouble on the inclination of the wings support. The support created was not good enough to keep the wings aligned and the balloon caused instability in fixing due to gas pressure on PVC. Another problem was the landing gear twist during the taxiing and rolling on the ground of the airship and required Dyneema to align the polystyrene boards.

During the flight tests it was verified that the runaway was not enough length for the airship to fly at reasonable altitude. Due to the lack of space, it was necessary to create more traction to get to minimum speed that could generate enough lift on the wings. These problems are due to the high total weight of the vehicle which can not be easily lifted by the buoyant force produced by the available volume of helium. To reduce the weight of the structure, it was replaced new lighter aft wings which changes the position of the center of gravity of the airship wherein moved to the nose to have more equilibrium in the flight. Even with this new arrangement, the structure continued to be heavy and it was necessary to create a prototype 1.5 with lighter structure to study the leveled flight with more buoyancy.

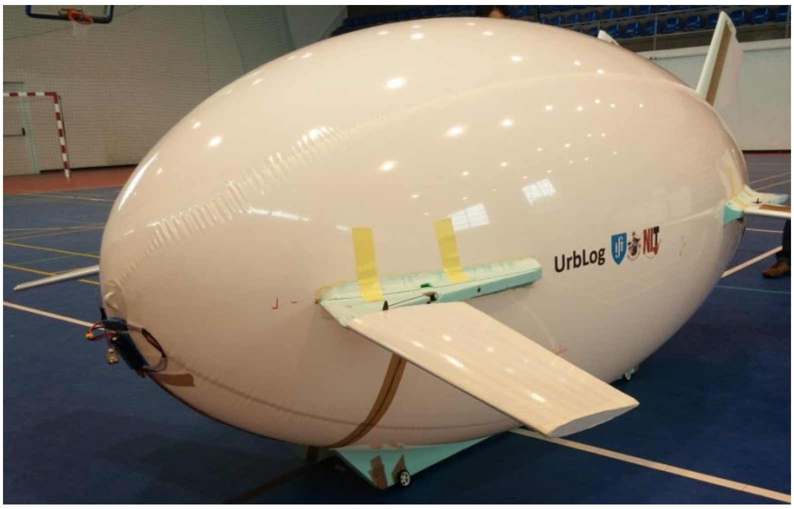


Figure 27: The Prototype 1 assembled.

- **Prototype 1.5**

This airship has the same configuration as Prototype 1, where the structure is much lighter, enabling the airship to have a cruise flight. It was removed landing gear because it was not necessary to test the taking off of the airship. The electric motor was replaced by a lighter one, it was made new wings and it was created another type of lighter supports than the Prototype 1.

The wings have the same airfoil but a smaller span. The internal structure of the wings (figure 28) is balsa instead of foam which presents ribs and a spar at one third of the leading edge. At the leading edge, where the wing is subject to higher pressure coefficients, there is balsa which is covered with thermal shrink film in order to cover the wing without possible deformation during the flight. In the wing root, a polymeric material was glued to the axis of the spar which connects to the servo, allowing the rotation of wing angles. The stabilizers have the same internal structure as the wings but the span of the wings is the same as Prototype 1.

Figure 28: Wings of the Prototype 1.5.

The supports (figure 29) were completely changed and it was created a new support made in various pieces of balsa, plywood and laminated carbon fiber. In the figure 29, we observe the assembled structure have two rectangular plates laminated carbon fiber which will make the contact area with the PVC for a more rigid fixation. These two boards were bonded to PVC with double-sided tape to support all stresses caused by the weight of the support and rotation of the wings. To assemble the structure of the supports, it was necessary to glue several pieces of balsa and plywood with contact glue to have sufficient thickness in order the servo to fit inside the support. The internal parts of this support are balsa and the external are plywood due to its higher stiffness compared to balsa. This support has two separate structures wherein the frontal will endure the weight of the wing and the rear structure will prevent the frontal support move along the horizontal axis. Structures are connected with two plywood boards where they are fixed with plastic screws in the connection. The screw on the front structure allows the change of the pieces from the servo’s support with the beam’s support of the rotors making the assembly and the alignment of the wings and the rotors easier for Prototype 2.5. For the support not to be under stress, the Dyneema was placed within the bore which fits the screw, where it can withstand the weight of the wing and of the support, and also the lift generated by the wings. The supports were also built on a 3D printer, but due to be heavy and taking too much time to print, wood was chosen to make the structure, despite this being less rigid.

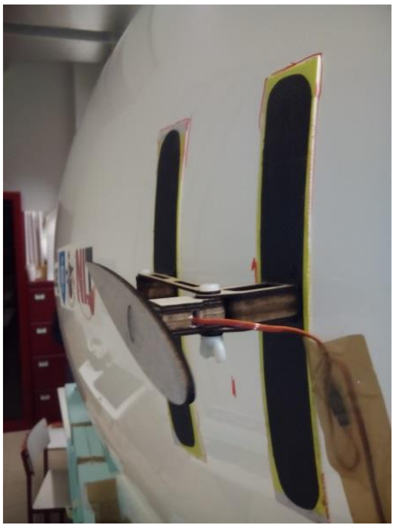


Figure 29: Wings support of the Prototype 1.5.

During the flight test several problems were identified where the weight of the total structure was still too high to allow the equilibrium of the airship in the air. The wings could not keep aligned due to the weight and the changes of the angle of attack during the flight. The Dyneema was bonded on the tip of the wings and on the axis of the spar. This allow the rotation and at the same time aligning the wing with the tensioned string. The servos were in constant struggle because they had to support the weight and the rotation of the wing, but even the help of Dyneema, it is need to pay attention to the type of servo to use in the Prototype 3, because the servo has to rotate the wing without so much effort (figure 30). Due to strong compression of the screw on the balsa, the balsa started to wear out. The servos were under stress due to the weight and rotation of the wings. To reduce the weight of the total structure, the material of the stabilizers was changed to depron, losing the yaw control of the airship because do not have servo and support to move the rudder. Using depron was possible to advance the center gravity in longitudinal axis in order to be more stable and having more buoyancy force produced by helium.

Figure 30: Prototype 1.5 assembled.

4.3 Prototype 2[3]

This prototype is similar to a Quadcopter but the difference is within the variable pitch propellers. This is a simple structure in which four bars to support the rotors and propellers. The bars are connected to a central piece of fiber carbon with the controller, battery and ESC's centered. However, this prototype was not enough to study the control with the airship buoyancy and it was necessary to build a Prototype 2.5 to test this control in the airship.

- **Prototype 2.5**

The airship structure is exactly the same as Prototype 1.5. It does not have wings and stabilizers, traction motor and the support of the motor, instead of wings, is placed rotors (figure 31). The support structure undergoes a modification where the fixation of the servo is replaced by the rectangular aluminum fitting which supports the propeller and the rotor. To fix the rotors and propellers to the aluminum spar, it is used one carbon board drilled in order to be aligned. Another modification, when compared to the Prototype 1.5, it was the placement of the gondola to the airship to attach to the PVC, the controller, battery and servos to make these leveled. To avoid the situation of the upward trend of the rotors, due to the lift generated, it was placed Dyneema in order to prevent unalignment of the rotors.

The rotors exert great force and create a lot of vibration in the structure due to the fact that the airship is non-rigid which led to the failure of the support of the rotors even using braces. Due to excessive force, the support moves too much causing danger of perforation in the PVC. To prevent this situation, more strings were used in order to try to endure all efforts and vibrations caused by the rotor. Another problem it was that bolt of the wood could not

[3] *Parte da dissertação relevante para efeitos do processo de proteção de invenção referido no Aviso no início deste documento.*

endure the vibrations, which allowed the aluminum spar to move longitudinally, causing the contact of the propellers with the PVC. The test was only conducted with fixed pitch and it was found out that it was impossible to keep stable the airship, due to buoyancy caused by helium.

Figure 31: The Prototype 2.5 assembled.

4.4 Prototype 3

After proved to be possible to control the airship in accordance with the requirements, the Prototype 3 will be a scaled down model, of a real airship. This will present an internal rigid structure which will have to be strong enough to support the entire weight of the rotor wings, stabilizers, batteries, motor and propeller as well as the aerodynamic forces and the lift generated by gasbags, rotors and wings. This will have to respect the airfoil in which the airship has aerodynamic characteristics to enable lift generation, for the cruise flight.

The structure will consist of nine frames, two tubular pieces, one in the nose and one in the tail, and 160 girders. The tubular parts will be responsible for fixing the girders, which gives shape to the nose and tail. Between the frames the connection is made with 16 girders. To reinforce the resistance to torsion between frames, it is used tensioned string-crossed of Dyneema, i.e., it is tensioned to improve the structural stiffness.

The composition of the frames will be trusses because they have better results in tensile strength, compression, bending and torsion. These will require lateral supports to increase the stiffness and avoid the displacement of the web elements of each truss.

Due to space and existing material conditions, it was necessary to divide the frame into 4 parts, which originated weaker points. Ideally the frame should be built in a unique and complete piece, which prevents detachment in some web elements of the truss. It was necessary to plan a simple fixation to allow an easy assembly. The fitting of the main girders allows the connection between the frames of different quarters, and the main girders between the frame 2 and 3 with the girders from the frames 3 and 4 as exemplified in the figure 11. Regarding the other girders, they are connected within the fitting of a frame quadrant, as can be seen in figure 32 making it simpler and easier to fit.

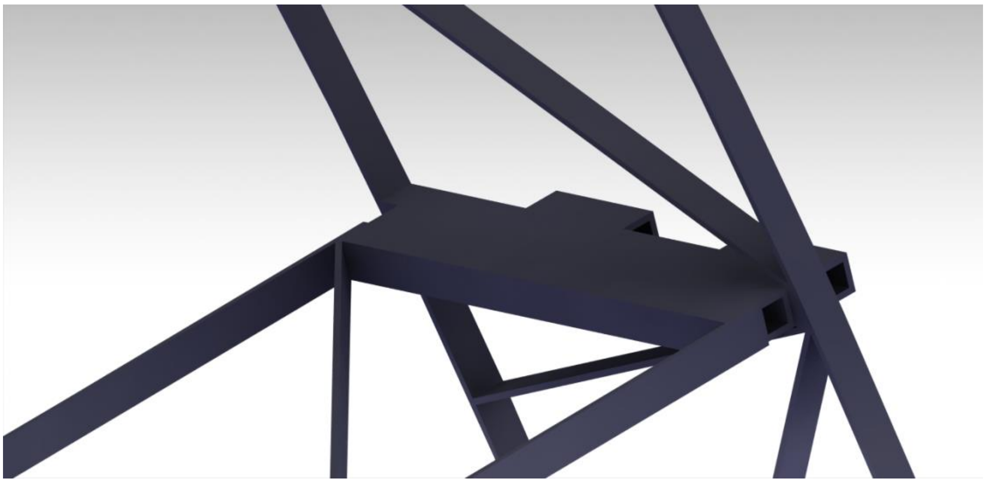


Figure 32: The fitting system of the diagonal girders.

The main girders have web elements with greater thickness to reduce the torsion of the entire structure, which in turn increases the stiffness and weight. These showed a higher stiffness but they take more time to build due to the stiffness and thickness of the material.

Figure 33: The frame 3 and 4 assembled.

In figure 33 only 8 girders are displayed because there was not much time to build the other girders due to the fact that the construction is a lengthy process. The total weight of the structure is 1.905kg.

During the assembling there were some problems especially in the main girders, in which their assembly was complicated in the fitting. The height difference caused by the lateral supports of the trusses, construction defects due to excess glue and the slightly misalignment of the fittings, did not allow an easy assemble which sometimes breaks some parts in the fitting causing the rupture. Therefore, to solve the problem a more simple solution had to be found to offer an easy assemble, having the same principle as the assemble of diagonal girders between frames where they only make connection between two parts, i.e., one girder with one frame as shown in figure 32. Due to lack of time, it was necessary to use braces to simulate the assembly wherein it shows a high stiffness despite the fact that assembly should be practical and reusable.

Transporting entire frames may cause the risk of breaking them due to torsion which it happened due to the lack of support by the girders. During the assembling, it was proved to be fragile without any fixation, as such, for greater protection of the structure, must be mounted by an appropriate jig that can carry it and keep it fixed until the girders assembly.

The frame is divided into 4 parts creating weakness points in the extremities where the fit are present. The upper and lower flanges of the carbon fiber frame cannot resist to the stresses caused by torsion and bending, provoking the detachment of these web elements at the extremities where it has the connection of the frames and girders.

Figure 34 shows a solution encountered to overcome the problem above. The addition of the carbon fiber board with an L shape created a larger contact area, which in turn reinforced the joint.

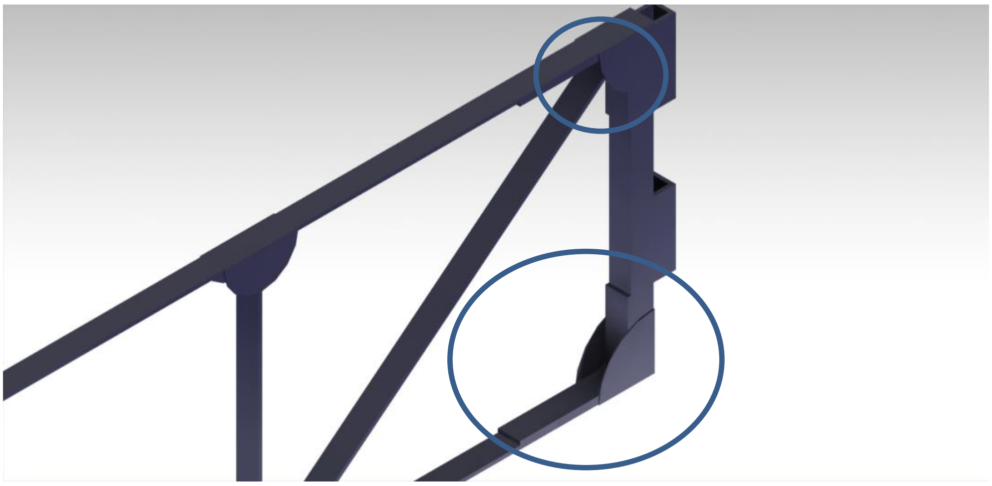


Figure 34: The reinforce of the truss.

The structure only showed a high stiffness when adding cross-string of Dyneema between the girders. To tension, it has to take into account the stress caused by the wire which may be creating excessive torsion throughout the frame getting the structure twisted. The string had better tension when it was glued with cyanoacrylate in the fittings. The area of contact for the web elements is larger and this almost does not need the lateral supports.

Figure 35: The frame 3 and 4 assembled with gas bag.

After the assembly the entire structure and the tensioned string (figure 35) were moved vertically to observe the design and shape of this upright with the balloon as well as the actual appearance of the dimensions. However, there were problems (previously mentioned), that the frames have more weak points due to the absence of L carbon pieces, to reinforce. Overall, the entire structure behaved very well, only having to improve some aspects regarding the construction of the frame, mainly in the gluing which is the essential point of the truss where the glue and supporters make the joint. This transmits the stresses to all web elements of the carbon fiber truss.

4.5 Conclusion

The results are promising wherein is possible to acquire greater knowledge about the airships and their problems. The analysis of each prototype allows searching for new solutions and improvements for efficiency and viability of structures to use in Prototype 3.

The Prototype 1 shows various structures problems related to the weight and rotation stresses wherein prevents the wings are aligned. Using Dyneema in the prototype 1.5, it was the solution which enabled the reduction stress of the main structures. In the prototype 2.5, the Dyneema was essential to prevent the moves of the rotors and be able to move the airship.

The assembly of two frames and girders of the Prototype 3 allows knowing how the internal structure is reliable as shown in the initial drawings. It was concluded that the fittings system is simple and easy to assemble allowing a transport easy and faster, and more efficient to maintain. In this prototype, the Dyneema improved stiffness of the structure making more resistant to bending loads and endure the stresses in the most vulnerable points.

With this information, it is possible to improve the structure in the weaknesses points in order to be approved for construction of the Prototype 3.

5. Conclusion

5.1 Dissertation Synthesis

The airships are generating a growing interest but the airship's internal structure is a limitation to freight transport because of the weight and stiffness. The internal structure needs to be light and strong enough to be able to endure all loads which it is subjected. Sometimes the heavy structure does not allow carrying heavy cargos, reducing the efficiency. This dissertation includes a study of the type of material and structure to use in a hybrid airship as well as the study of structural problems from each component of the internal structure.

The airships have 3 types of structure; they are non-rigid, semi-rigid and rigid. The non-rigid has great difficulties in control and stability while semi-rigid and rigid has problems in terms of weight and stiffness structural decreasing the helium efficiency for the same volume as a non-rigid airship. All material has to be light wherein the new technologies and new materials allow the improvement in the airships efficiency. The new materials did not exist in the twentieth century, allowing the topic of airships to come to discussion as a future possibility to be used as an air transport.

The structure of Prototype 3 as well as the airship design is studied to make the internal structure and all the pieces required to support any kind of material (wings, stabilizers, engine, batteries and others). It takes into account the type of material, structure and simple assembly with the resources available. It is studied the trusses and materials to use where the theoretical and practical tests allows the validation of the concept and the material of the structure. With the test results, it is possible to know the major problems of the structure which one of them it is the unglued of the web elements due to small contact area. This can be improved by placing larger side supports wherein increases a little more weight in all structure.

Prototype 1 and 2 was built to study a new concept of control and stability of the airships. The two prototypes were not enough to approve the tests, and then it was made Prototype 1.5 and 2.5. In the Prototype 1 is studied the structural problems wherein the wings are heavy causing the difficulty to align and leveled the wings. In version 1.5, it is resorted to the use Dyneema in order to prevent these problems and reduce the servo efforts. The material of the supports, wings and stabilizers have been replaced by balsa, plywood and thermal shrink film, allowing the airship had more buoyancy with lower weight. Prototype 2 is a study of a quadcotper with variable pitch wherein version 2.5 is implemented in the airship in order to study the control with buoyancy. The structures have a lot of problems because the moments created by the rotor due to their effort to generate lift, causing the rupture of some materials. Regarding to the prototype 3, it was started the study of the structural and assembly problems. These problems are detected in order have not the same problems in the final structure, and improve other important aspects. The assembly also allows knowing the actual dimensions of which frames and other problems like the stiffness and strength structures that are not detectable in the structural design or testing.

5.2 Final Considerations

The airship design reaches the initial objectives where all the requirements are respected. However, the design might be changed depending on the construction of gasbags and the position of the center of gravity. Maybe it is necessary to reduce the length of the initial girders for the heavier frames are near the position of the center of gravity, improving the stability. The design of supports (wings, stabilizers, nose and tail), it was not studied, the structure and assembly have to take into account the structural problems of each prototype to know the stresses and moments that the frame will suffer. The supports have to be strong enough to endure all loads and transmit them to the frames and girders.

The carbon fiber trusses respect the limits of the weight and the minimum flexural strength under a 19,62 N point load. With the optimization of the construction, the angles of the web elements, the material and the height of the lattice, it is possible to know the best results of each lattice. Although the most of the truss elements of the material is carbon fiber but it does not mean that other materials cannot be used in the web elements as Ash which has good mechanical properties and low density. The major problem is the resistance of the carbon fiber in the fittings and the gluing in the weakest point. To solve these problems have been created a larger area to glue and reinforce the fittings to prevent the stresses.

Prototype 1 has a heavier structure, reducing the buoyancy of the airship. Due to this problem has been created version 1.5 where the wings, stabilizers and supports were much lighter, generating more buoyancy. Their structures have problems to align the wings wherein was used Dyneema to help the supports. Prototype 2.5 has problems with the moments created by the rotors because they are not fixed on a rigid structure causing vibrations in the balloon and consequently the movement of these without lifting the airship. Even using Dyneema, it was quite complicated to keep it stable. The assembly of Prototype 3 had the same problems as in the truss tests having to be reinforced in glue areas. Regarding the assembly, this presents a big problem in the connection of the main girders and frames where the difficulty was hard and it was necessary to change the fitting system to the fitting system of the diagonal girders.

In conclusion, the structure assembled for Prototype 3 shows good results and promising to the construction of the whole structure, but it is necessary to make a computational study to know the points that will have more problems. In this structure also should perform some experimental tests to find out how the structure reacts to the torsion.

5.3 Prospects for the Future Work

Due to the current work and acquired knowledge and experience it is believed that the next steps in this work should cross the following topics:

- Search for new materials for optimization of the internal structure;
- Optimize of the wings, tail, nose and tail supports;
- Calculate of the entire assembled internal structure;
- Search for new structural solutions;
- Optimize the structure strength;
- Improve the system of fittings;
- Develop a method to fit the wires of the gas bag to the structure.

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ANNEX 1

Scientific Paper Accepted for Publication at the 18th ATRS Conference

18TH ATRS WORLD CONFERENCE

AIRSHIPS AND AEROSTATS TECHNOLOGY. A STATE OF ART REVIEW

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ABSTRACT

Nowadays new airships or Light than Air (LTA) aircrafts and aerostats are being tested and used for military and civilian purposes all over the world. This revived interest about airships and aerostats brings a multitude of new technical concepts resulting from a deep interdisciplinary research so that the actual state of art about them paves the way for renewed horizons regarding its use and operation in the next future.

With those technological improvements it is expected that airships will become soon a competitive mean of transport for linkage mainly with areas only served by weak or degraded transport infrastructures. Regarding the principles of sustainable development of air transport, airships are also the most environmentally friendly vehicles with lower fuel consumption and higher endurance. Therefore they are conquering new still unexplored markets.

This work aims to present a state of art review about history and use of airships and aerostats, and to evidence how technological improvements in the recent past may impact positively its performance and thus its use in different scenarios in future.

KEYWORDS: Airships and aerostats, Technological improvements, Air transport sustainability

CLASSIFICATION: Aviation and Economics Development, Aviation Case Study, Inter-Modal and Air Travel Alternatives

1. INTRODUCTION

The rebirth of this mean of transportation capable of overcoming some disadvantages of the conventional ones brings interesting economic benefits in the medium and long term scenarios as they may offer the same services at lower costs while stimulating new commercial and industrial activities.

The background of airship technology comes from the XVIII century. Since then all these years were of scientific and empirical improvements. Nowadays these constitute the basis of a sustainable future in several related emerging technologies making possible the use of airships in even more safety contexts.

Also those improvements brought a multitude of technical new concepts as a result of an interdisciplinary research and effort. Consequently the state of art about airships paves the way for the reappearance of its use within renewed scenarios which require the most environment-friendly air vehicles with lower fuel consumption and higher endurance.

All over the world there are several countries where airships are being used for military and civilian purposes as Canada, Brazil, and Australia among others. India, for example, prepares the use of airships for the connection to remote areas with poor surface infrastructure which only can be reached by air or walking due to seasonally bad weather conditions.

This paper is organized as follows: 1) a brief introduction on the theme; 2) a state of art review about technological characteristics and operational constraints; 3) a description of some technological problems and related solutions; 4) a brief overview about airships potential; 5) a brief description of the related legislation; and 6) some conclusions.

2. STATE OF ART REVIEW

2.1 Technological Characteristics

As the envelope constitutes the main structural element of airships it requires particular care since the design phase until the end of its operational lifetime. The envelope should be designed to fulfill some key requirements such as to resist to loading forces in flight and on the ground conditions, i.e., those which may limit the resistance of the envelope. This procedure is crucial to minimize any leakage of the lifting gas (0.3 liters/m^2 per day) and also to withstand adverse climatic agents such as ice, wind, snow, UV radiation and extreme temperatures.

Also the choice of materials is crucial for the exit of the airships construction and use and thus should follow the highest standards as stated by Miller and Mandel (2002).

Since a few years ago several research works sustain the importance of the use of renewable energy systems as electrical propulsion and energy storage, photovoltaic systems, and residual heat removing systems.

In 2001 NASA's Glenn Research Center conducted a research work about propulsive systems in airships involved in long-term missions (Miller and Mandel, 2002). This project tried to optimize the design of the vehicle thus maximizing its efficiency, as it was necessary to consider the energy and propulsive systems and the aerodynamic performance as a whole simultaneously to guaranteed the minimum weight of all the systems aboard and to ensure the proper balance between the generation/storage of solar energy and the energy consumption in the propulsion, taking into account seasonal variations of wind and sunlight, mission objectives, maximum weight of the vehicle, and latitude and altitude of flight too.

Different operating altitudes provide airships with different technical characteristics. Based on the operational altitude airships can be divided into three main categories (Figure 1).

Modern airships are equipped with advanced avionics and electronics systems which ensure safe operation and good maneuverability in all flight phases as Fly-By-Wire (FBW) and Fly-By-Light (FBL) controls.

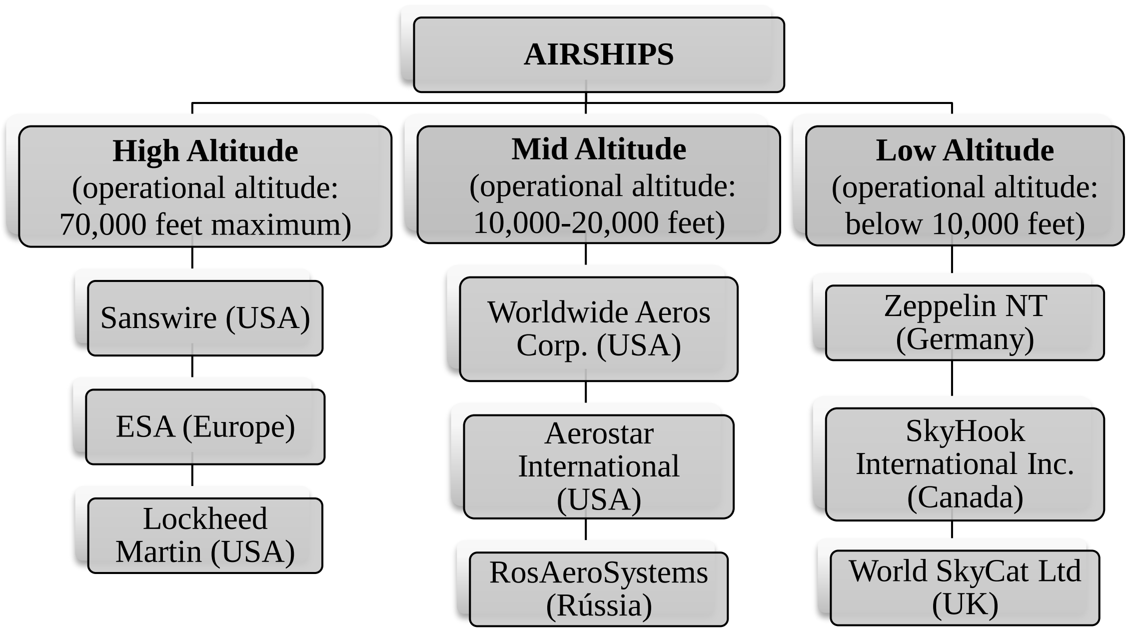

Figure 1. Airships Operational Altitude and Related Investment Companies

Flight data processors and flight control systems constitute management systems for data exchange as the Onboard Managing Data Exchange System (ODEMS). If necessary airships use modern navigation systems to enable night operations too such as Ground Position System (GPS) - based, infrared vision systems and meteorological sensors.

Airships design and construction as well as its flight operations follow all safety standards imposed by international authorities (as International Civil Aviation Organization, ICAO) as any other aircraft.

Figure 2 resumes a state of art review about some related technological characteristics: structures, materials and new construction techniques; and propulsion systems, control and stability.

2.2 Operational Constraints

There are two main constraints related to the operation of airships: the bouncy control and the climatic factors.

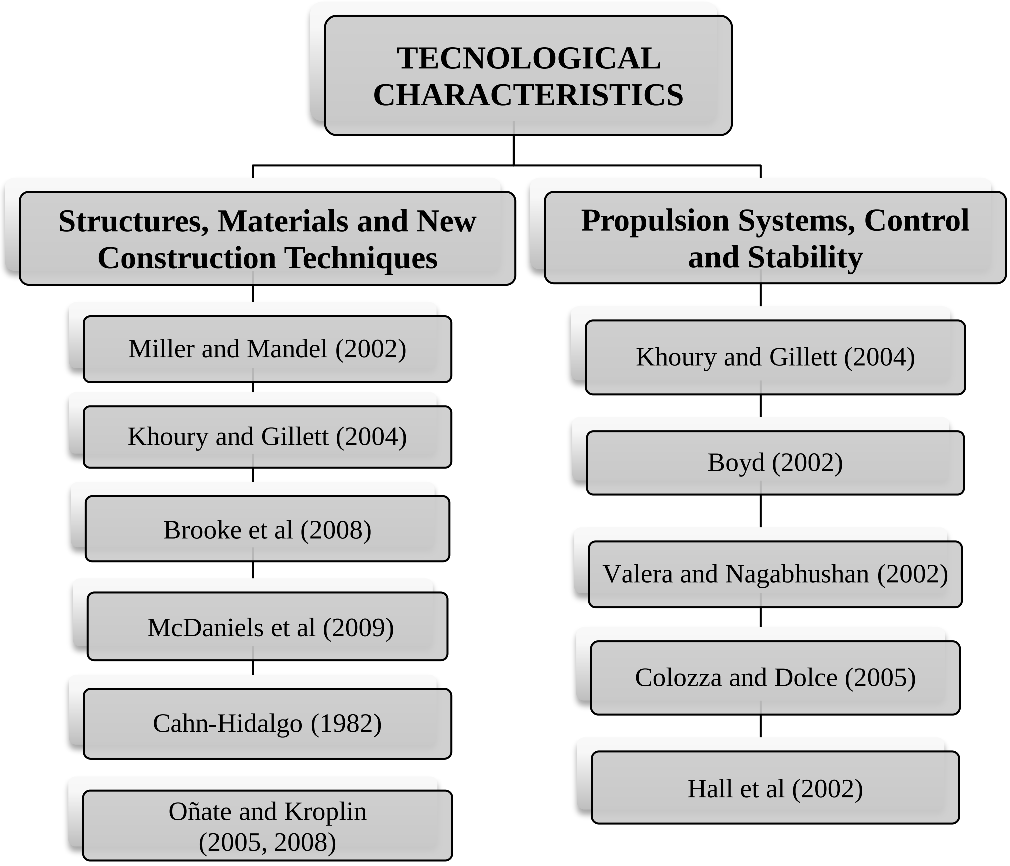

Figure 2. State of Art Review Related to Some Technological Characteristics

The buoyancy control always has been a primary problem but advances in the airship's technology are finding workable solutions to ensure safety flight conditions. Airship balance is affected by several factors such as: fuel consumption, differences in the barometric pressure, temperature changes in the surrounding air and/or in the lift gas, precipitation, humidity, etc. Nowadays the buoyancy control can be achieved through mechanisms of weight compensation.

Another operational constrain is related with climatic factors. Statistically more than 20% of aircraft incidents/accidents are due precisely to climatic factors (Table 1). All means of transportation are more or less affected by them but its influence over airships operations is more evident: the ratio volume/weight is high making it very sensitive to wind effects; and the higher drag factor relatively to its low thrust force hinders the maneuverability and the control against adverse air currents. However modern airships are equipped with specific equipments which enable safety flights under the requirements of ICAO.

Table 1. Key Climatic Factors Affecting Transportation Modes

	Transportations Modes				
Climatic Factors	Maritime	Road	Rail	Air	Airship
Thunderstorm	**Little affected**	**Little affected**	**Affected**	**Affected**	**Affected**
Heavy rain	**Little affected**	**Affected**	**Little affected**	**Affected**	**Affected**
Strong wind	**Affected**	**Little affected**	**Little affected**	**Affected**	**Much affected**
Storm	**Much affected**	**Much affected**	**Affected**	**Much affected**	**Much affected**
Ice	**Affected**	**Much affected**	**Little affected**	**Much affected**	**Much affected**
Hail	**Little affected**	**Affected**	**Little affected**	**Much affected**	**Affected**

3. TECHNOLOGICAL PROBLEMS AND SOLUTIONS

There are some major technical problems which may affect the lifecycle of airships among which we selected the following: should it be rigid, semi-rigid or non-rigid; how to maintain it on the ground; which gas should be used to fill in for lift; and which sources of energy must be used. Below we propose some solutions for each of them.

3.1. Should it be rigid, semi-rigid or non-rigid?

The advantage of using the RIGID structure is that it has low Drag (that means less fuel consumption), high stability and easy to manufacture/low production cost; and the advantage of using the NON-RIGID structure is that it has more lifting power than the rigid one (Figure 3).

In our opinion the best option is to choose a SEMI-RIGID structure which has the quality of both (Figure 4). It will be cost effective as well as with high lifting power.

	RIGID	NON-RIGID
LOCATION OF PAYLOAD	Internal to envelope	External to envelope
PAYLOAD SIZE (weight & volume)	less than non-rigid	more than rigid
DURABILITY	Punctures (holes) do not jeopardize structure integrity	Punctures in envelope cause immediate pressure and integrity loss. Must be patched quickly.
GROUND HANDLING	Envelope shape and internal payload minimize cross-wind input	Gusty winds necessitate more ballast, tethering
TIME TO PRODUCE	Components are fabricated in parallel, and quickly integrated at once	Component fabrication & integration must be done in series
COST	Production cost is low due to fast production time	Production cost is high to sequential production

Figure 3. Rigid and Non-Rigid Airships (Pevzner, 2009)

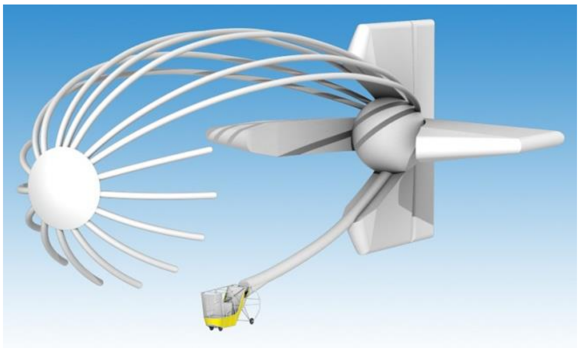

Figure 4. Semi-Rigid Airships (Apexballoons, 2013)

3.2. How to maintain it on the ground?

To solve this problem we propose at least three solutions: a water tank; a vector thrust model; or a mobile ground weight.

3.2.1. **A Water Tank:** it is possible to use a water tank inside of the airship. During flight the ballast tank will be empty and whenever landing or suspending the ballast tank will be refilled. The disadvantage of this method is that it is necessary to install an extra weight inside the airship and this will require a more complex ground infrastructure for water refilling as well as this will decrease the safety factor (Figure 5).

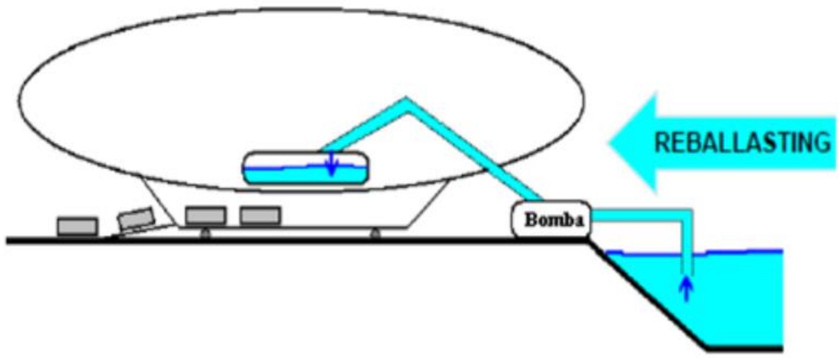

Figure 5. Refilling System of the Ballast Water (Pevzner, 2009)

3.2.2. **A Vector Thrust Model:** it is possible to use a propulsion system (vector thrust model) to compensate the buoyancy force responsible for the lift itself. But since it will be necessary to produce thrust in negative direction of buoyancy it will be required more fuel consumption too. Thus this is not a cost effective method. But even so the system may be used for some in flight or landing/suspending maneuvers (Figure 6).

Figure 6. Vector Thrust Model (Prentice and Hochstetler, 2012)

3.2.3. **A Mobile Ground Weight:** it is possible to use a mobile ground weight for maintaining the airships as in a horizontal position as possible whenever it is on the ground. Also it is possible to use an hydraulic system for the same purpose. Since it will be a mobile system it will not require any complementary and complex infrastructures. Hence it will be not only a cost effective but also a safe solution (Figure 7).

Figure 7. Mobile Ground Weight (Modern Airships, 2013)

In our opinion the best solution to maintain the airship on the ground is the use of a Mobile Ground Weight.

3.3. Which gas should be used to fill in for lift?

Hydrogen has the highest lift force per unit of volume but it is an highly inflammable gas too (Table 2). So it isn’t possible to use hydrogen.

Table 2. Gas properties (Boon, 2004)

Gas	Density (kg/m^3)	Lifting Force (N/m^3)	Comment
Hydrogen	0.085	11.2	Inflammable, relatively cheap
Helium	0.169	10.2	Inert, relatively expensive
Hot Air	0.906	3.14	Inert, very cheap, relatively poor lift
Methane	0.756	4.5	Inflammable, relatively cheap

Helium is the next candidate as it has an important lifting force per unit of volume and it is an inert gas too. Thus Helium seems to be the best option as a lifting gas for the airship.

3.4. Which sources of energy must be used?

There are several studies about the application of renewable energy systems (electric propulsion and energy storage, photovoltaic systems, and residual heat removing systems) within airships design. The general concept is to optimize the design of the aircraft thus maximizing its efficiency, considering the energy and propulsive systems and the aerodynamic performance as a whole simultaneously to guaranteed the minimum weight of all the systems aboard and to ensure the proper balance between the generation/storage of solar energy and the energy consumption in the propulsion, taking into account seasonal variations of wind and sunlight, mission objectives, maximum weight of the vehicle, and latitude and altitude of flight too.

The idea is that solar energy is attached directly to the electric motors driving the airship propellers. Electric motors which substitute superconducting magnets in place of traditional copper wire are used to reduce the weight of the motors. The surplus of electricity generated during daylight operations is used for the electrolysis of water and thus the production of oxygen and hydrogen which in turn are stored to be used in night operations or under bad weather conditions. Exhaust water produced by fuel cells as well as condensed water from the ambience are kept onboard as ballast: to be pulled off or used aboard as needed to adjust or maintain the airships' buoyancy. Bio-Diesel powered electric generators may be used as a back-up system of solar and fuel cells.

There are several airships using solar energy as Nanuq (Figure 8) a so called Solar Ship designed to carry payloads up to 30 tons of cargo for distances up to 6,000 km and at speeds up to 120 km/h. When Nanuq is empty it requires take-off and landing runways of 60 m and 100 m long, respectively, and even when it is fully loaded a runway of 200 m long is enough for the take-off (Solarship, 2012).

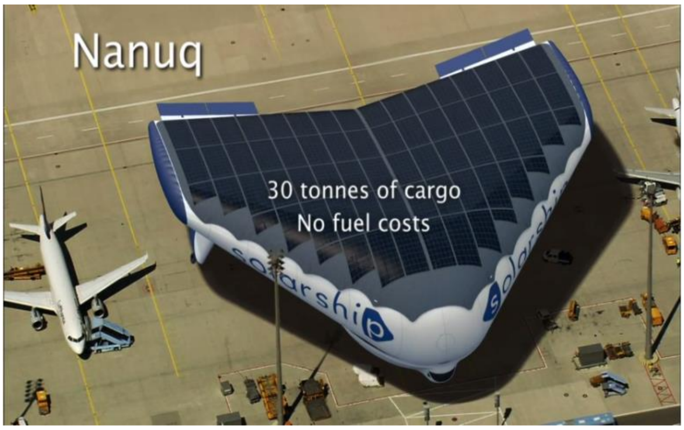

Figure 8. Nanuq Airship (Technewsdaily, 2013)

The main advantages of a solar powered airship are:

- It may fly to any location without need traditional airports to operate from;
- It doesn't need long runways and landing and take-off as these operations may be done quite vertically and from everywhere: unprepared fields, ice-fields, desert sands, heavy shrub-lands, lakes, rivers, or even the ocean;
- It can fly over oceans, mountains, i.e., all around the world;
- It is slower than commercial jets but faster than trucks, trains, or ships; and
- It can carry hundreds of passengers or several tons of cargo.

4. AIRSHIPS POTENTIAL

Airships require neither complex nor expensive infrastructure for landing and take-off. So they have a wide range of applications from civil to military purposes:

- **Surveillance and Monitoring**: airships may realize long-range missions and perform long endurance flights without refueling; when equipped with adequate radio naviogation aids they may act as platforms for surveillance/monitoring missions too (Bilko, 2007);
- **Transportation of General, Heavy, Indivisible and/or Perishable Cargos**: airships provide more economic operational costs than those of commercial

aircrafts and with less maintenance costs too; Storm and Peeters (2011) underline how airships may compete with the railway for long distances - because its ability to link point-to-point nodes, with road in the tourism sector for distances over than 200 km, and with the cruises in the maritime for distances between 200 km and 1,000 km;

- **Transportation of Passengers**: using airships tourits may overflight landscapes and/or protected environments;
- **Defense**: in this particular airships have been used not only for surveillance and monitoring but also for the transportation of troops and general cargo; during the World War II airships were used to carry tanks – for example the Turtle Millennium class Airships carried up to 8 Abrams M-1 tanks (60 tons each) at a time and put them down quite anywhere ready to fight, while Lockheed C-5 Galaxy Aircrafts only carried 2 tanks at a time and required specific airfields for landing and take-off (Knoss, 1998).

Since ever environmental concerns may influence the choice of/among transportations systems. Storm and Peeters (2011) stated that the environmental impact of the airships operating at moderate speeds (between 100 km/h and 150 km/h) is similar than that of the railway, thus classifying them as a green transport system.

5. LEGISLATION

The rebirth of airships evidences either the lack of legislation about its operation in several countries - i.e., the incapacity of some national regulators to establish operational standards, or the amount of different rules which may impact negatively over some international flights:

- ICAO recommends its member states to follow the Annex 2 about Rules of the Air;
- FAA recommends its members to follow the FAR Part 91 about General Operating and Flight Rules;
- European Aviation Safety Agency (EASA) follows the so called Acceptable Means of Compliance and Guidance Material to the rules of the air, and has

Specific Airworthiness Specifications (SAS) for airships as well as requirements to emit Airships Type Certificates (ATC); also in Europe there are some Airship Transport Requirement (ATR) which mean that some performance tests are needed to prove structural strength of the envelope of the aircraft when operating under bad weather conditions (Szirmai *et al.*, 2012);

- In Portugal the national Civil Aviation Authority (INAC) emitted a Technical Information related to airships (INAC, 2011) although for non commercial use - which is a transcription of PART M of EC Regulation No. 2042/2003 of EASA (2011); later INAC inform the aeronautical community about the EC Regulation No. 923/2012 an up-to-date document of EASA too.

6. CONCLUSIONS

The background of airship technology comes from the XVIII century. Since then all these years were of scientific and empirical improvements so nowadays these constitute the basis for a sustainable future in several related emerging technologies making possible the use of airships in even more safety contexts.

Also those improvements brought a multitude of technical new concepts as a result of an interdisciplinary research and effort. Consequently the state of art about airships paves the way for the reappearance of its use within renewed scenarios which require the most environment-friendly air vehicles with lower fuel consumption and higher endurance.

The buoyancy control always has been a primary problem but advances in the airship's technology are finding workable solutions to ensure safety flight conditions. Another operational constrain is related with climatic factors. However modern airships are equipped with specific equipments which enable safety flights under the requirements of ICAO.

There are some technical problems which may affect the lifecycle of airships among which we selected the following: the choice among rigid, semi-rigid or non-rigid structures; how to maintain it on the ground; which gas should be used to fill in for lift; and which sources of energy must be used. We sustain that the best options for each of them are, respectively: to choose a Semi-Rigid structure; to use a Mobile Ground Weight system; to use Helium as lift gas; and to chose Solar Powered solutions.

Airships require neither complex nor expensive infrastructure for landing and take-off. So they have a wide range of applications from civil to military purposes: surveillance and monitoring; transportation of general, heavy, indivisible and/or perishable cargos; transportation of passengers; defense, etc.. See as since ever environmental concerns influence the choice of/among transportations systems. Storm and Peeters (2011) precisely stated that the environmental impact of the airships operating at moderate speeds is similar than that of the railway, thus classifying them as a green transport system.

The rebirth of airships evidences either the lack of legislation about its operation in several countries - i.e., the incapacity of some national regulators to establish operational standards, or the amount of different rules which may impact negatively over some international flights. Consequently, and in parallel with the improvement of the technical specifications of airships is necessary to ensure interoperability of its flight operations in international flights across the planet.

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