Structural Performance Requirements and Composite Materials

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***Abstract* - This paper seeks to show that the requirement of the performance requirements in aerospace, naval and automobile structures has provided the development of new materials and new manufacturing techniques. Typically, higher specific resistance values and stiffness combined with low specific weight are sought blade designs for wind generators and other components of such systems to obtain solutions using composite materials, particularly fixed term polymers endowed with fibrous reinforcements. The understanding of what is a composite material is necessary because it is the combination of at least two materials with heterogeneous phase, apart that have different properties and characteristics and their combination is required for making a single material, with compliance the properties of both materials, making their implementation attractive. To optimize production of the laminated on each project, it is essential to use the finite element model for obtaining the stress range experienced by the sample and thereby to obtain better mechanical properties for their use.**

***Keywords—* composites, finite element, mechanical properties.**

I. Introduction

Currently extensive research related to laminated carbon fiber fabric, aim to study and propose improvements in mechanical properties and all this related to the polymer matrix, which develops exponentially, where new features appear and add to generate a product that meets the design requirements.

The understanding of what is a composite material is necessary considered the combination of at least two materials with heterogeneous phase, different properties and characteristics and their combination is required for making a single material, with compliance the properties of both, making their implementation attractive. These conditions are achieve by combining the polymeric matrix and reinforcement, giving the structure significant mechanical properties.

Polymeric fibers are widely used for manufacturing composite materials. The properties of composites are strongly linked to the properties of the matrix and fibers, thus the study of the characteristics of the composite, the fibers and the matrix are fundamental in helping to fashion a quality product and make it interesting for the industry.

Within the range of mechanical tests, the tensile test is the most common, used for the mechanical characterization of materials and enables determination of properties such as strength, Young's modulus, longitudinal and transverse strain and Poisson's ratio. Because of the anisotropic characteristics of composites, it is interesting that the tensile test is carried out in longitudinal and transverse to the fiber direction.

The use of finite element method is of utmost importance for the design of structural components including wing blades, among others. Thus, the representation of laminated materials in FEM model must be accurate and correct, so that the results are consistent and high reliability.

II. Fundamentals

a. Fiber Materials

Warp is the manufacture of the fibers in the direction of length of thread and weft in the transverse direction, allowing the construction of these fabrics, which allow different resistances in both directions.

An understanding is associated with fabric mass per unit area, which defines the grammage expressed in g/m². It should be emphasized that all fabrics have equal mass distribution in the direction of the weft or warp. In this case, these fabrics will be unbalanced, as opposed to having a homogeneous distribution in both directions. This helps understanding the calculation of some physical and mechanical properties of these composites. Two fabrics groups was created: flat woven fabric pattern or satin, and setting twill.

In this paper was used the settings of woven twill 2 x 2, where a weft thread is interlaced under and over two warp yarns in successive movements.

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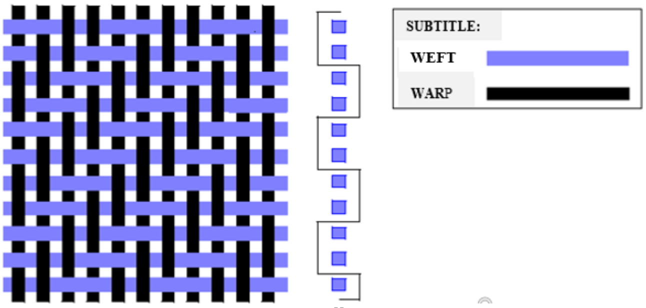

Figure 1. twill weave 2 x 2

b. Epoxy Resin

Epoxy resin is chemically defined as having at least two epoxy rings. The agents of epoxidation most common are per acetic acid, per formic acid and epoxidized vegetable oils. Epichlorohydrin (1-chloro-2, 3 - epoxy propane) is an universal agent, which carries an epoxy group that will react with chemical species that has active hydrogen. The bisphenol A [2, 2 - bis (4'-hydroxyphenyl) propane] is the most common chemical species containing these active hydrogen. Schlack synthesized the first epoxy resin with characteristics similar to those of today, it happened in Germany in 1933 from the reaction of epichlorohydrin with bisphenol A.

The large capacity of accession of epoxy resin brand indelibly characteristics, it may adhere to a large number of materials, coupled with their low shrinkage. When these cured epoxy systems have low fracture resistance usually results in around 1,0 MPa/m². Consequently, studies aimed to improve the thermal and mechanical properties. The viscosity of the epoxy resin is one of the fundamental parameters, with the temperature set processing conditions.

c. Density of the Composites Determination

The density of the composite material can be determined by liquid displacement technique as explicit in the technical standard ASTM D 792, taking as a basis three suitably prepared samples in rectangular shape and mass among 1 and 50g. In this case, use a balance equipped with a support device to measure the temperature of the liquid in the beaker located under the support. The bracket has two small plates for placing the sample, one on top of the device for weighing in air and another one at the bottom for weighing the fully submerged sample.

For the calculation of the density (d_c) the composite used the following equation:

$$d_c = \frac{m_a}{(m_a - m_s)} \xi \delta_1 \qquad (1)$$

Where:
m_a = air mass
m_s = submerged mass
d_1 = density of the liquid

d. Tensile Test

Consists in applying an increased uniaxial tensile load on a specimen until break. Obtaining the length variation as a load function (P). This type of test is widely used in engineering due to the quantitative data of the material's mechanical characteristics. In addition, it is possible to obtain in this test the ultimate strength (σ_u), yield strength (σ_e), Young's modulus (E), resilience modulus (U_r), ductility e coefficient of strain hardening (n). Composite materials shows an interesting behavior of the fiber, the polymeric matrix and the composite material (fiber + matrix).

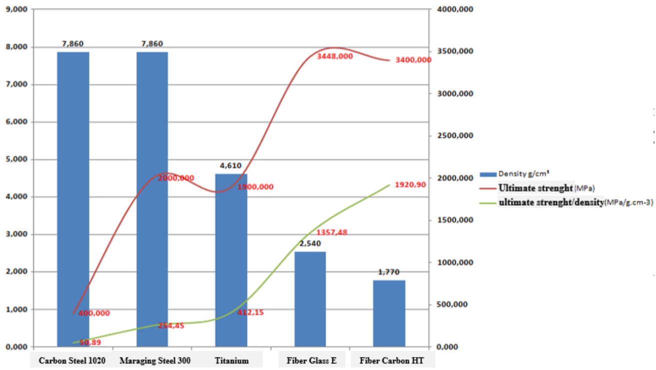

Figure 2. Fiber Mechanical Properties

e. Unfilled Volumes Determination

The existence of unfilled volumes in a composite material is considered as structural failure and as consequence, the mechanical properties of the material are changed. Improving the material process has a great importance, because on composite material it is important that unfilled volumes fall below 2%, according to the need can reach fall below 1%. Within this point, can be determined the quantity of unfilled volume by the following equation:

$$V_v = 1 - (V_f + V_m) \qquad (2)$$

Furthermore, considering the function of the mass fraction and the fiber density, of the mass fraction and the matrix density, and the composite real density (d_c), can obtain the following equation:

$$V_v = 1 - \left(\frac{m_f}{d_f} d_c + \frac{m_m}{d_m} d_c\right) \qquad (3)$$

Where:
V_v = Unfilled Volume
m_f = Fiber´s Mass
d_f = Fiber´s Density
m_m = Mass Matrix
d_m = Matrix´s Density
d_c = Composite´s Density

f. Finite Element Method

Companies in the metallurgical and automotive sectors as well as automotive and mechanical engineering industry, often face structural failure problems in testing their products. These problems are often solved by improvisation or trial and error method. This approach to the problem results in higher production costs and difficulties in meeting deadlines.

In order to overcome the difficulties, many companies have been carrying out new development programs and optimizing existing configurations, using the most powerful tools of analysis, such as CAE (Computer Aided Engineering) and applying the Finite Element Method (FEM) in solving structural problems and other mechanical applications. The research activities and development of new products using the CAE technology have achieved high quality products and higher performance.

The limitations of the human mind is such that it cannot understand, or predict the behavior of the whole system and the phenomena in one operation. Thus arises the idea that, from the understanding of the behavior of each element, it is possible to understand the system behavior. This is the easier way for an engineer to solve the problem. This reasoning has implications also in the mathematical methods used in systems behavior description.

In many situations, the identification of components of a system, or more particularly a structure, seems an obvious task. For example, for a spatial structure comprising metal beams only, it is natural to identify the individual components of beams or elements connected to each other only in the joints or structural, form the structural assembly.

Another common idea, which becomes fundamental in structural analysis, is the idea of stiffness. There is an idea of stiffness from the first applications with elastic elements (or springs) of basic physics. The concept of equivalent spring (or equivalent stiffness) to a set of springs, is also part of the day-to-day technician. Therefore, it is also the address to structural analysis. The stiffness of the structure depends on the stiffness of each element. One can assemble the structural stiffness from the stiffness of each element. This is the first idea of the finite element method: the structure, mechanical component or, in general, the solid body is subdivided into a finite number of parts (elements) that are interconnected by discrete points, which are called nodes. The structure can be represented an assembly of elements that constitute a mathematical model, also called structural model.

There are in day-to-day mechanical applications, different components with quite different characteristics structures formed only by beams, such as a complete structural box of a vehicle, the components of a chassis, bumpers, axes, machine components, etc. differential housing in such cases, the solid body is artificially divided into certain finite number of elements also connected the nodes. That is, if it makes an approximate representation of the continuous piece.

The following figure represent finite element models of various mechanical components; the elements subdividing the structure can be observed.

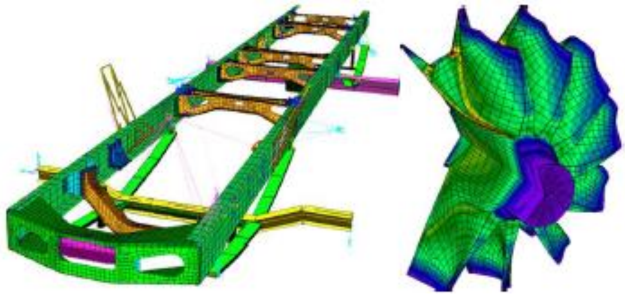

Figure 3. Finite Element Method Application – Subdivision of solid elements

The idea of discretization of a continuous system was initially introduced for implementing structural calculation, because the initial applications of the method have historically been developed for this field of engineering. The deformed configuration of the structure is determined by the displacements of the nodes whatever the shape of the structure and the type of loading. Thus, in this case, the parameters describing the system behavior is the nodal displacement. From these, it is possible to determine the internal forces, tensions and assess, the strength of the analysis object structure, On a more general language, these parameters are also called state variables because govern and describe the structure of the steady state.

Therefore, from the general concept of discretization, there is the definition of the Finite Element Method.

Analysis of nature problems

Establishing a methodology to apply in all cases

Discreet System Standard

⇩

The finite element method is an approximate calculation method of continuous systems, so that:

- **The structure, the mechanical component or, in general, the solid body is subdivided into a finite number of parts (elements), interconnected by discrete points, which are called nodes. The mounting elements constituting the mathematical model, has its behavior specified by a finite number of parameters. In particular, the problems of structural analysis, the parameters are the nodal displacements, which are the unknowns of the problem.**
- **The solution of the system strategy, the assembly of the elements is the same strategy general method for analysis**

g. General Results

The results achieved were satisfactory, even with a hand lay-up, the pressure and heat increase contributed positively and clearly to the standardization process in general. The thickness of the laminate ranged from 0.95mm to 1.0mm. The curing process and the pressing time was the same for the three resins. There were variations in the results, according to the used resins. Table 1 below shows the general data comparing them with other materials.

TABLE I. COMPARATIVE RESULTS BETWEEN MATERIALS

TEST Laminates 4 layers of carbon fiber fabric Twill	*Stress σt (MPa)*	*Density ρ (g/cm³)*	σ_t/ρ
WEFT - SQ 2001	316,459	1,311	241,472
WARP - SQ 2001	390,769	1,311	298,174
WEFT - SQ 2004	342,151	1,296	263,945
WARP - SQ 2004	382,493	1,296	295,066
WEFT -DERAKANE 400	322,176	1,389	231,948
WARP -DERAKANE 400	343,096	1,389	247,009
TRANSVERSAL (55°)- SQ 2004	65,877	1,296	50,819
Carbon Steel - 1020	400,000	7,830	51,086
Aluminum	600,000	2,630	228,137

In this table, the carbon fiber drawn at an angle of 55° was the lowest value obtained, because this kind of structure breaks both the weft and the warp, which becomes brittle laminate and reduces abruptly the tensile strength. On the other hand, a material laminated following the warp orientation with the resin SQ 2001 presented the best mechanical characteristic. The difference between warp and weft becomes obvious.

Comparison among the resins used at this report, SQ 2001 and SQ 2004 epoxy resin (diglycidyl bisphenol A) and Derakane 470 (epoxy vinyl ester), the difference of a resin to another is clear by the results obtained in the tensile and flexural strength. Figure 4 exemplify this comparison.

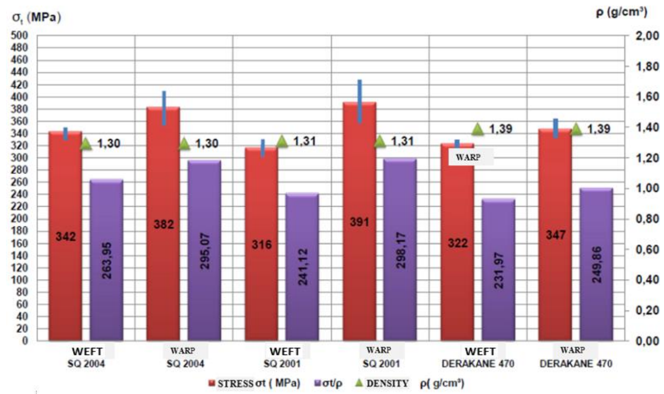

Figure 4. General results of the tensile test in both directions for the three resins.

h. Resins Comparison

The differences between each resin and between the extraction positions of the specimens is explicit in the following figures. The average curves were provided by tensile and bending tests helping to compose the knowledge to differentiate both resin and direction (plot x warp).

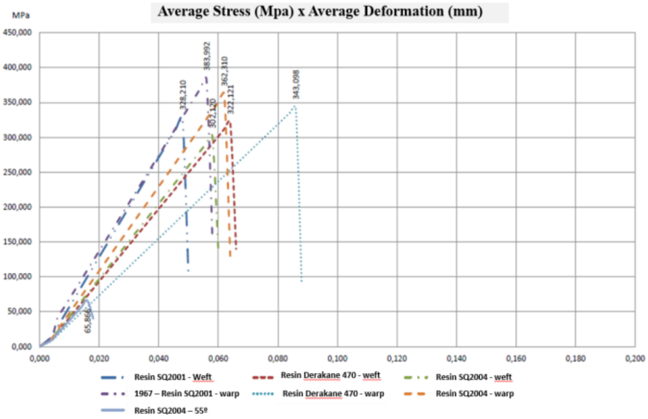

Figure 5. Curves of tensile tests with general results of resins and orientation extraction of the specimens

The chart presents all the curves extracted from tensile tests and show several features: from higher voltage to even greater deformations. These data help to form a horizon on which resin is more interesting and which is the best lamination direction, as these factors influence directly the mechanical properties and consequently can have better conditions to define structural dimensioning.

SQ 2004 resin presented the best result in the weft direction followed by SQ 2001 and subsequently Derakane 470. The difference between SQ 2001 and SQ 2004 resin is 7.80%, as compared with the resin Derakane 470, the difference between SQ 2004 is 6.01%, in percentage ratio both have enough distinction. At this point, the resin Derakane 470 is the intermediate whereas SQ 2001 resin is the last.

When analyzed towards the warp, the differences become even more interesting. After all, the best result was with the SQ 2001 resin followed by SQ 2004 resin and finally, with considerably less value, Derakane 470 resin. However, the rupture values are higher in the warp direction than in the weft direction. In the range percentage comparison among the resins, the difference between the SQ 2001 and SQ 2004 is 2.14%, between SQ 2001 resin and Derakane 470 the difference is around 12.99% whereas the difference between SQ2004 and Derakane is 10.85%.

i. Virtual Results

Initially specimens was designed to obtain the mechanical properties of Epoxy Resins SQ 2001, SQ2004 and Vinyl Ester Resin Derakane. It was laminate by 4 layers of carbon fiber of twill and each of the resins. Following by the proper procedures to cure the specimens and cut according the standard ASTM 3039 and standard ASTM D7264 and subjected to tensile and bending tests. Afterwards modeled in software FEMAP NX Nastran, a specimen identical with the actual format and put aside to suffer the traction test requests (figure 1) and bending, using the values presented in the literature as input parameters. These analyzes was made by the method of nonlinearity in two ways: first using the software tools in fiber composites analysis with each resin and second displaying the stress-strain curve of materials studied and compared with the plastic deformation of the steel.

The arrangement of threads interferes the ultimate strength of the resin, being higher in the warp than the weft, hence using the results obtained in the direction of the warp, which reached a stress of 383 MPa.

Using finite element modeling the result obtained was a stress of 11.19 kgf / mm² by fiber layer equivalent to 438.91 MPa in the laminated, as shown in Figure 6.

The difference between the results obtained experimentally and obtained by the software was 55.91 MPa equivalent to an error of 13.9%, which is permissible since the manual lamination may have presented small unfilled volume promoting the decreased resistance.

Figure 6 schematic diagram shows the locations of major and minor stress, showing the exact location of the specimen's rupture, also seen in Figure 7.

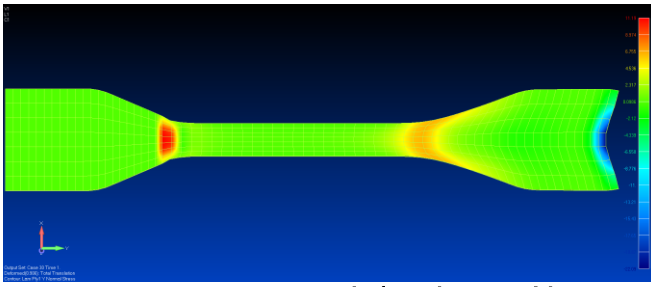

Figure 6. Fracture Region in the finite element model

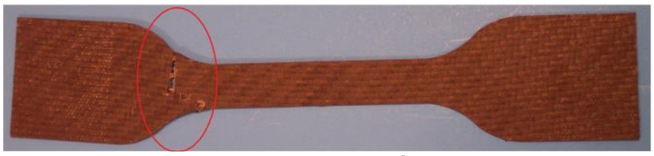

Figure 7. Fracture Region in the specimen

j. Conclusions

The fracture position is consistent with the result test data.

The experimental results are consistent with the virtual, for the ultimate strength values was 13.9% higher than the experimental data which makes reliable the data obtained, it is because the model generated by the software is close to ideal, not predicting unfilled volume and lack of impregnation of the resin.

Acknowledgment

The authors would like to thank the following entities:

AES BRASIL

FUNDEB - The foundation for development of the City of Bauru – Sao Paulo State – Brazil

References

[1] A. Filho. Avelino, "Elementos Finitos – A Base da Tecnologia CAE" , 1ª Edição, Editora Erica. São Paulo, Brazil, 2007.

[2] A. Filho. Avelino, "Elementos Finitos – A Base da Tecnologia CAE – Analise não Linear" , 1ª Edição, Editora Erica. São Paulo, Brazil, 2012.

[3] Marinucci,G – Materiais compósitos poliméricos: fundamentos e tecnologia – Editora Artliber, pg 70, 2011.

[4] REZENDE, M.C;BOTELHO,E.C.O. **Uso de compósitos estruturais na indústria aeroespacial**. Polímeros: Ciência e Tecnologia, vol 10, nº 2, 2000.

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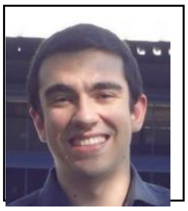

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