Substituting Conventional Steel Alloys by Carbon Fibre Composites in Structural Parts of an Existing Laser Cutting Equipment

D. G. Vieira[1], C.D. J. F. Meireles[1], J. P. Nunes[2], L. F. Silva[3]

[1]Mechanical Engineering Dept., Minho University, Campus de Azurem, Guimaraes, Portugal.

[2]Polymer Engineering Dept. Minho University, Campus de Azurem, Guimaraes, Portugal.

[3]Mechanical Engineering Dept., FEUP, Porto University, R. Dr. Roberto Frias, Porto, Portugal.

ABSTRACT

In the present work, Finite Element Analysis (FEM) was employed to validate the use of advanced carbon fibre composites as replacement of traditional low-alloy steel in the construction of the main runway frame structure of a laser cutting equipment currently available in the market. This new composite solution was adopted to increase considerably the current laser equipment precision and cutting speed. The main objective is to enhance the machine cutting performance by using much stiffer and lighter main structural runway frames to support the machine cutting head and all major laser beam mirrors and lens, which allows decreasing dramatically the inertial and vibration efforts developed in service through the use of carbon fibre composites.

The paper will present, compare and discuss the mechanical and dynamical behaviour obtained in the FEM simulations made by using both solutions, the current one based on a steel frame and the new innovative composite adopted structure. The processing method to be used in the production of the innovative composite structure will be also proposed. Finally, as production costs may also have an important impact on final equipment commercial price and acceptation, an economical study considering both manufacturing situations (currently used and new one) will be discussed.

Keywords: FEM; carbon fibre; composite; laser cutting equipment

1. Introduction

Nowadays, the global and very competitive market we live forces machinery industries to build, with very short conception time, equipments with much better performances at lower costs. To achieve market competiveness is therefore necessary to invest in innovative technologies that may have higher upfront costs and able to become part of the company know-how at medium/long term. The selection of new and more competitive materials as well as the renewal of existing structures design, by making them more rigid and lighter and also able to attain higher cutting speeds and energy savings, performs a main rule in this matter.

Based on the above mentioned reasons, the work carried out in this paper is a real attempt to replace traditional materials by more innovative composite ones in the manufacture of an already existing machine. Today, carbon fibres became an asset to structural engineering [1]. Carbon fibre is widely used in highly advanced structural equipments and begins to be more highly used in civil aviation and ordinary manufacturing industry. Its major drawback continues to be the high cost and the main advantages, the high stiffness and strength, and also its low density.

Composite materials are also known for their high specific strength and stiffness (strength/density and modulus/density ratios), which is superior to mostly other used materials. Composites may have almost the stiffness of steel with a fifth of its weight and much higher stiffness than the aluminium with half of its weight [2]. Being so, they have huge potential for application in commercial and advanced markets, such as, the automotive and aeronautical industries, because the weight reduction they promote is directly related not only with an important economy of energy but also with the much higher performance of equipments.

Carbon fibre composites, which are almost used in high-advanced products and equipments for aerospace, defence and sport markets, begin now being also applied in civil aviation and manufacturing industry.

The replacement of conventional materials by new materials occurs due two major reasons [3]:

1. The need of upgrade and redesign an existing product to achieve higher performance and reliability and/or lower cost and weight, for example.

2. Launch of new products or applications with improved and novel features, capabilities and functionalities.

The design of an engineering structure, regardless the kind of application and material under consideration, it is always a good challenge for trying to use composite materials. To do that, becomes necessary well identifying and analysing the loads and other service requirements and boundary conditions involved in order to achieve the best final structural design. Such process involves two stages: the first includes the analysis and determination of the behaviour exhibited by the structure under the service loads by using different configurations and boundary conditions (What load does the structure take by using different possible configurations?) [4]; and the design stage, that is the time-consuming process where dimensions, shapes, and materials are varied in order to allow finding the optimal structural configuration allow withstand all specific service loads and perform all specific tasks in the best conditions (What is the best structure to take the load?) [4].

Today, finite element (FE) analysis is the best, most convenient and a indispensable tool to quickly achieve the optimal design of complex engineering structures. The advance of science and development of mathematical models allows simulating and modelling in a very realistic and reliable way the behaviour of real engineering structures through the use of the finite element methods (FEM). Such numerical methods, even though they not give exact solutions, permit much advantageous, economic and quick analysis of the behaviour of structures in service than any other analysis made by physical theoretical models [5]. For these main reasons FEM was the tool chosen to model and simulate the behaviour of the structure studied in this work. The software ANSYS was used to generate the FEM simulations and results.

The Finite Element Method is an efficient and numerical tool widely used to solve continuous media problems and to simulate and analyse the behaviour of engineering structures submit to load service charges [6].

The diagram in Figure 1 shows the main steps used to achieve a final optimal design of a engineering structure by taking in consideration the conditions imposed by the project.

2. Composite Laminate Construction

Sandwich construction is an efficient and widely used method to increase the stiffness of composite laminates walls. Usually, it consists in introducing a lightweight and low cost foam between the higher strength and stiffness layers located in the internal and external surfaces of the composite wall in order to increase its moment of inertia and, consequently, overall wall stiffness (see Figure 2). Such technique was used in the present work to allow quickly obtaining a composite structural wall to be used with the same equivalent stiffness, as replacement of the currently steel one used in the main runway frame of the laser cutting equipment under study.

The Steiner's theorem was used to calculate the initial configuration of the composite structural wall [7].

By considering Figure 2, both structural walls present the same equivalent stiffness when:

$$E_{steel} \times I_{steel} = E_{steel} \times \frac{t_{steel}^3}{12} \times b \tag{1}$$

where *E*, *I*, *t* and *b* are the materials Young' modulii and wall inertia moment, thicknesses and width, respectively.

Thus, the equivalent sandwich composite wall in terms of stiffness may be calculated by:

$$E_{fiber} \times \left(\frac{t_{1fiber}^3}{12} \times b + t_{1fiber} \times b \times (h_1^2) \right) + E_{foam} \times \frac{t_{foam}^3}{12} \times b + E_{fiber} \times \left(\frac{t_{2fiber}^3}{12} \times b + t_{2fiber} \times b \times (h_2^2) \right) \tag{2}$$

where:

$$h_1 = \frac{t_{1fiber} + t_{foam}}{2} \tag{3}$$

By using Eqs. 1 to 3, the sandwich composite symmetrical wall laminate [(0º, 90º,±45º), foam], using a polyester foam having the thickness of 7 mm, was selected to be applied in the structural wall of the main runway framework beam of the laser cutting equipment. Unidirectional carbon fibres reinforced epoxy layers were selected for being used in the external wall layers due to carbon fibre high stiffness. A thickness of 3 mm was used in each external carbon fibre reinforced epoxy layers.

To predict the failure of layers in any different direction, the following interactive Tsai-Wu criterion was used in the FEM calculations [7, 8]:

$$F_1 \cdot \sigma_1 + F_2 \cdot \sigma_1 + F_{11} \cdot \sigma_1^2 + F_{22} \cdot \sigma_2^2 + F_{66} \cdot \tau_{12}^2 + 2 \cdot F_{12} \cdot \sigma_1 \cdot \sigma_2 = 1 \qquad (4)$$

where σ_1 and σ_2 are the normal stresses in the fibre and transverse to the carbon fibre directions, respectively, τ_{12} is the shear stress and F_1, F_2, F_{11}, F_{22}, F_{66}, F_{12} are layer characteristics experimentally determined by mechanical testing [7].

3. Laser Cutting Runway Frame Under Study

The laser cutting machine has four linear motors (two on the ends of the beam and two mounted in the car where the cutting head is) and a laser beam of high concentration that is directed through the focusing lens that is mounted on the car that slips in the axial direction of the beam (see Figure 3).

This beam ensures the major movements of the cutting head and it is a key component of the machine. It must also withstand high mechanical loads and all deformations it suffers are reflected in deviations of the beam cut-off, which consequently reduces the machine cutting precision. Thus, cutting speeds must be also reduced to avoid lack of precision.

Figure 4 presents the currently produced steel beam. This is the beam that equips the cutting machine laser illustrated in Figure 3. The photos show the external aspect of the beam and the reinforcement components existing in its interior.

Regarding the architecture of the beam and method of manufacture, the current beam is composed by two box girder type substructures. These two box girder structures are internally supported by plates having forms of "X", "C" and other components. In the box girder with guides coupled plates having form of "V" are used to reinforce the wall where such guides exist. All these plates are assembled and connected together by multi-point welding in almost of cases and also by continuous welding.

4. The New Composite Solution

All four composite components that form the beam were design in order to be symmetric and capable of being processed by vacuum/infusion. This allowed optimising and reducing to a minimum possible, the number of different moulds to be used to produce the all entire composite structure. Such optimisation was important because the final price of the final composite runway frame is largely affected by the number of moulds to be manufactured.

The shape of the carbon beam has been also optimised in order to allow an easy glue bonding between all structural components. Therefore, all reinforcing components present specific surfaces with enough good areas for enabling an easy and good bonding between adjacent components and also their quick positioning and accurate assembly. Figure 5 shows the reinforcing component 1. Twenty-eight components like this are needed in the final runway beam frame. As can be seen, a “X” shape was introduced inside the component to improve the torsion strength. This shape allows increasing the component torsional stiffness without oversize its thickness. In this component, all concordance radii was made to be greater than 5 mm to facilitate the placement of fibre fabrics in the mould and facilitate manufacturing.

In Figure 6 is illustrated the reinforcing component 2. Twelve components of this type are use in the final beam. It has a form of “C” to increase the overall structure stiffness in the beam extremities while also maintaining the necessary openings that allow an easy access to mount equipments in these locals.

The reinforcement shown in Figure 7 a) is also intended to increase the structure stiffness. It has the shape of "U" that allow increasing the beam stiffness in a region of the beam where is not possible to use a bigger reinforcements. Such region must be unobstructed to allow an easy access for assembling equipments coupled to the beam. This "U" type reinforcement is glued to other components, with particular to the type "C" component illustrated in Figure 6. The final beam has eight components like this.

Finally, the reinforcing component that forms the outer shell of the beam is also represented in Figure 7 b). All previous components are glued on this through its outlying areas. Two components of this type are included in the final beam. Such component is the only one that has to change its length when smaller beams are manufactured. In the design of this new carbon fibre beam has been always taken into account the possible of using all components in all different laser cutting machine models that are currently produced by ADIRA S.A.. Therefore, the same mould is always used to manufacture all sizes of this component used in the all different machine models currently produced by ADIRA S.A.. In some cases only the number of necessary components vary in the different produced models of the laser cutting equipment.

The total weight of the new composite beam structure is 62 kg, which corresponds to a reduction of 64% relatively to the currently produced steel beam.

5. Validating the FEM Results

Due to the great number of calculations made by advanced numerical methods, simulations and results obtained from FEM usually present huge discrepancies caused by small differences or errors made during the introduction of load charging, boundary conditions, layers and/or materials properties and/or also through the mesh generation. Thus, it is always convenient that designers validate the results obtained from FEM to ensure they are realistic and that the finite element software is properly working.

In this work, FEM results were validated by two different ways. The first summarizes the comparison of the results obtained from FEM in very elementary laminate plates with those obtained from a simple computer software widely used in the calculation of laminates, the LAP (Laminate Analysis Program**)** [9]. The flat laminate has no fixed size apart from its thickness, so that the analysis can be applied to any composite component, at a location where loadings or deformations are known. Typically, the software (LAP) is used in preliminary design for tailoring a stacking sequence, then analysing the composite component with other methods such as finite elements, and finally optimising the design by inspecting the laminate behaviour layer by layer [9].

The stresses and strains of a load charged flat composite plate having the layers, with the appropriate properties, calculated using the LAP software were then compared with the results obtained from finite element used software ANSYS exactly the same laminate.

The second way to validate the FEM is to compare the displacements suffered by two plates with the same stiffness, one made of steel and other in composite. The equivalent stiffness of the two plates has been calculated by Eq. 3. The results obtained from the FEM simulations of the two plates must show the same displacements in both plates.

6. Mechanical and Economic Analysis

After validating the methodology used in the finite element method, the response of the structure submitted to the service charges in working boundary conditions has been studied. First, the FEM analysis was used to study the static behaviour of the new composite beam and determined the deformations it suffers. A requirement of the project was ensure that the displacements obtained in any direction cannot cause a deviation in the cutting optical beam greater than 0.018°. For the new carbon fibre composite solution having polyester foam core, deviation values of 0.017° were obtained in the optical beam, which fulfil the project requirements.

Figure 8 illustrates the deformation of the beam structure in the XX direction. The different displacements obtained correspond to different colours. The colours in the extremities of the beam correspond to the points where the structure is more deformed. On the other hand the middle colours represent the points where the structure is less deformed.

Regarding the dynamic analysis, which not consider rigid vibration modes (6 first modes), the resonance occurs in the composite and steel beams at the frequencies shown in Table 2. This table only shows some of the modes of vibration. The simulation was performed between 0 to 500 Hz.

In terms of dynamic results, the composite beam has shown seven modes of vibration and the currently produced steel beam that equips the cutting laser machines has shown 47 modes of vibration.

Regarding costs involved, the manufacture of the new proposed composite framework sandwich structure, using CFRP outside layers involving a polyester foam core, seems present much higher cost than the one associated to the production of the currently produced steel structure. The initial predictions done make expect that the new composite framework beam could be about 6.6 times more costly than the currently steel one used. However, deeply studies concerning the impact caused in the market by the launch of the new laser cutting machine, that presents much higher performance in terms of speed and precision, and also the benefits for the manufacturing company that may result from the technological advanced knowledge acquired should be made in order to take definitive conclusions about the economic final profits and losses obtained.

7. Conclusions

In this work a totally new composite main runway frame beams were developed to replace the steel currently used ones in order to improve significantly the performance of laser cutting machines that are manufactured by a company. The static mechanical behaviour of the new composite framework structure was validated by FEM. Dynamically, the behaviour of the new composite framework beam behaviour should be revised and optimised because it has demonstrated, when having all its components attached, to present some worrying behaviour at frequencies in the possible machine working range. However, the new composite framework beam has clearly shown to present much better dynamic behaviour than the currently one made of steel.

This new type of materials and technologies could bring benefits to ADIRA S.A., not only in terms of the better performance of the laser cutting equipments but also because of technological advantage it may take over all other market competitors.

Acknowledgement

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Table 1 - Natural frequencies and vibration modes for the composite and steel structures

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Table 1 - Natural frequencies and vibration modes for the composite and steel structures

Vibration Mode	Natural Frequency [Hz]	Vibration Mode Type	Vibration Mode	Natural Frequency [Hz]	Vibration Mode Type
Composite Structure			**Steel Structure**		
Mode 7	153,15	Flexion	Mode 7	18,26	Flexion
Mode 8	202,64	Flexion	Mode 8	20,13	Flexion
Mode 9	253,96	Torsion	Mode 9	125,36	Flexion
Mode 10	321,36	Flexion	Mode 10	208,79	Flexion
Mode 11	390,70	Flexion	Mode 11	209,13	Flexion
Mode 12	466,83	Torsion	Mode 12	209,38	Flexion

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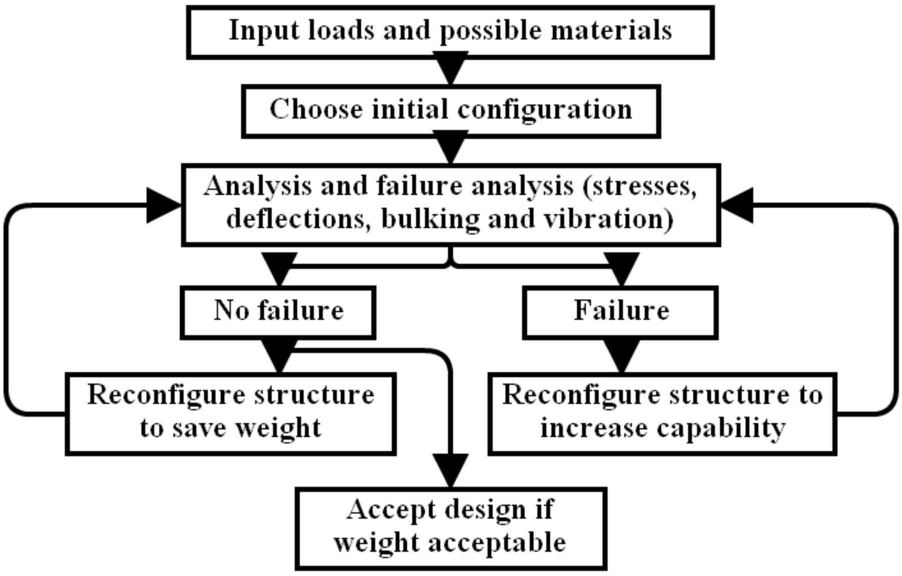

Figure 1 – Stages involved in the design of an engineering structure [4]

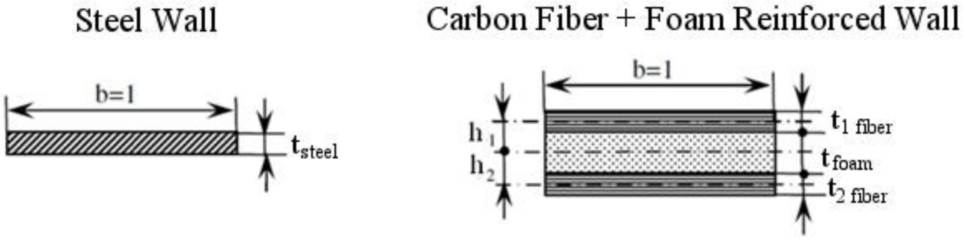

Figure 2 – Diagram of a sandwich type composite material structure

Figure 3 – Laser beam of the laser cutting machine (running a cut)

Figure 4 – Details of the construction of the currently used steel beam

Figure 5 - Component 1

Figure 6 - Component 2

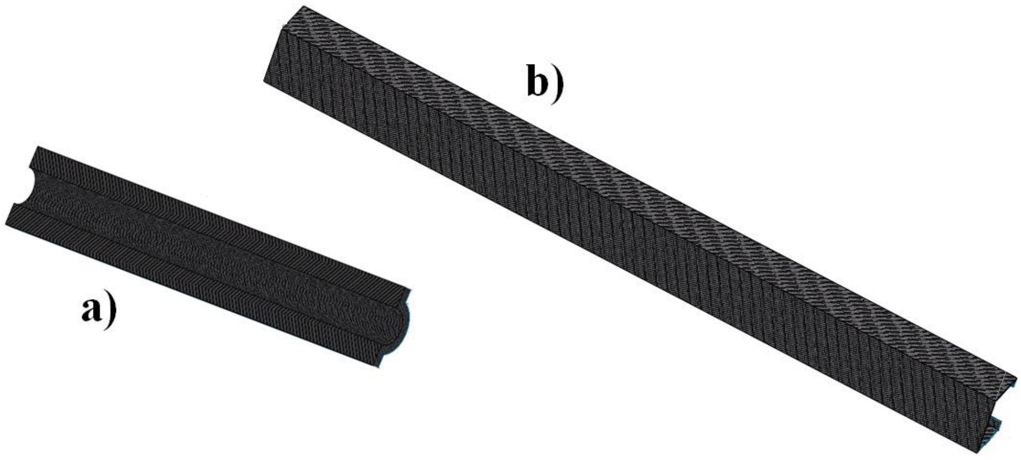

Figure 7 – a) Component 3; b) Component 4

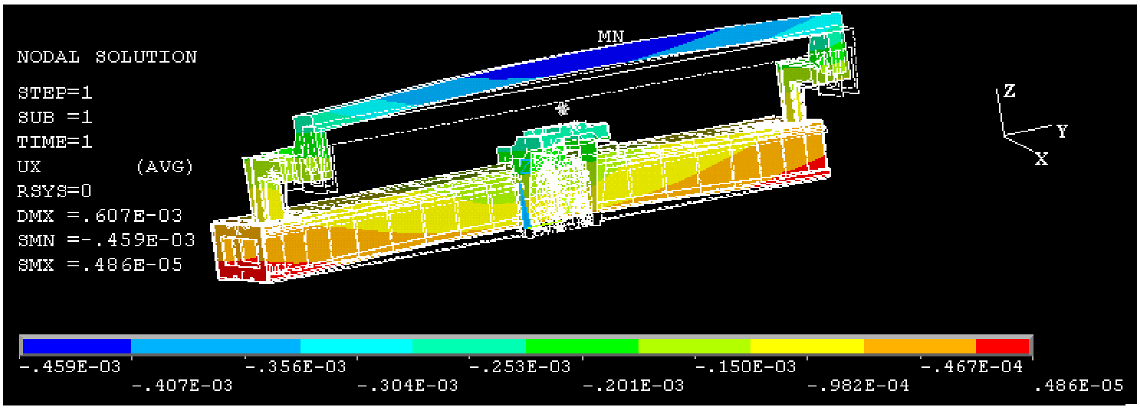

Figure 8 – Displacement in XX direction [m]

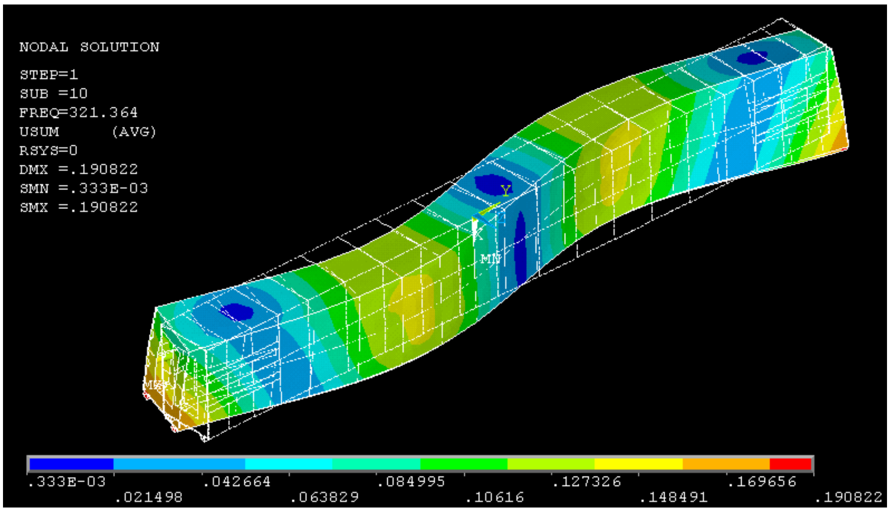

Figure 9 – Vibration Mode 10