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Substituting conventional steel alloys by carbon fibre composites in structural parts of an existing laser cutting equipment

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

[*]Mechanical Engineering Dept., Minho University, Campus de Azurem, Guimaraes, Portugal; E-mail: danielgpvieira@gmail.com;

Tlf.: 00351 912 914 094; Fax.: 00351 253 516 007

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

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

[3]Department of Mechanical Engineering, Faculty of Engineering, University of Porto, R. Dr. Roberto Frias, Porto, Portugal.

ABSTRACT

In the present work, a finite element (FE) analysis 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 the current laser equipment precision and cutting speed. The main objective was 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 presents, compares and discusses the mechanical and dynamical behaviour obtained in the FE 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 is 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) are discussed.

Keywords: Finite element analysis; steel; carbon fibre; composite; laser cutting equipment

1 Introduction

Nowadays, the global and very competitive market we live in, forces machinery industries to build with very short conception time, equipments with much better performances at lower costs. To achieve market competiveness it 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 are an asset to structural engineering [1]. Carbon fibres are widely used in highly advanced structural equipments and begin 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 most 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 to an important economy of energy but also to a much higher performance of equipments.

Carbon fibre composites, which are 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 to 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 is always a good challenge for trying to use composite materials. To do that, it is necessary to identify and analyse 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?) [2]; 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 to withstand all specific service loads and perform all specific tasks in the best conditions (What is the best structure to take the load?) [2]. Fig. 1 shows the main steps used to achieve a final optimal design of an engineering structure by taking in consideration the conditions imposed by the project.

Today, finite element (FE) analysis is the best, most convenient and indispensable tool to quickly achieve the optimal design of complex engineering structures. The advance of science and development of mathematical models allows simulating and modeling in a very realistic and reliable way the behaviour of real engineering structures through the use of the FE methods. Such numerical methods, even though they not give exact solutions, permit more advantageous, more economic and quicker analysis of the behaviour of structures in service than any other analysis made by physical theoretical models [4]. For these reasons, the FE method 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 FE simulations and results. The FE method is an efficient and numerical tool widely used to solve continuous media problems and to simulate and analyse the behaviour of engineering structures submitted to service loads [5].

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 Fig. 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 [6]. By considering Fig. 2, both structural walls present the same equivalent stiffness when:

$$E_{steel} \times I_{steel} = E_{steel} \times \frac{t_{steel}^{3}}{12} \times b \qquad \textbf{Eq. 1}$$

where *E*, *I*, *t* and *b* are the materials Young’s modulus and wall inertia moment, thicknesses and width, respectively. Thus, the equivalent sandwich composite wall in terms of stiffness may be calculated by:

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

Equating the rigidity of the steel wall to wall with composite foam core, with b = 1, we obtain, Fig. 2:

$$E_{steel} \times \frac{t_{aço}^{3}}{12} = E_{fiber} \times \left(\frac{t_{1fiber}^{3}}{12} + t_{1fiber} \times (h_1^2) \right) + E_{foam} \times \frac{t_{foam}^{3}}{12} + E_{fiber} \times \left(\frac{t_{2fiber}^{3}}{12} + t_{2fiber} \times (h_2^2) \right) \qquad \textbf{Eq. 3}$$

In this case the, same thickness for the two layers of carbon fiber ($t_{1fiber}=t_{2fiber}$ and $h_1=h_2$) was used. Thus, it is possible to write Eq. 3 as:

$$2 \times t_{1fiber} \times \left(\frac{t_{1fiber}^{2}}{12} \times (h_1^2) \right) = \frac{E_{steel} \times \frac{t_{steel}^{3}}{12} - E_{foam} \times \frac{t_{foam}^{3}}{12}}{E_{fiber}} \qquad \textbf{Eq. 4}$$

where:

$$h_1 = \frac{t_{1fiber} + t_{foam}}{2} \qquad \textbf{Eq. 5}$$

By using Eq. 1 to Eq. 5, the sandwich composite symmetrical wall laminate [(0º, 90º,±45º), foam], using a polyester foam having the thickness of 3mm, 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 FE calculations [7, 8]:

$$F_1 \cdot \sigma_1 + F_2 \cdot \sigma_1 + F_{11} \cdot \sigma_1^2 + F_{22} \cdot \sigma_2^2 + F_{66} \cdot \tau_{12}^2 + 2 \cdot F_{12} \cdot \sigma_1 \cdot \sigma_2 = 1 \qquad \textbf{Eq. 6}$$

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 [6]. The major difficulty in using this criterion is the experimental determination of the factor F_{12}. In fact, it is necessary to preform bi-axial tensile tests to determine the value of F_{12}. Such biaxial tests are not easily available in common laboratories because they require the use of double head universal testing machines. Many authors apply often in their calculations an estimated value of $F_{12} = 0$.

All other factors may be determined easily. For example, F_1 and F_{11} can be determined by performing tensile and compressive tests on the laminate in the fibers direction of fibers. In this case, assuming $\sigma_2 = \tau_{12}^2 = 0$, it is possible to write:

- For tensile testing:

$$F_1 \cdot X_t + F_{11} \cdot X_t^2 = 1 \qquad \textbf{Eq. 7}$$

- For compressive testing

$$F_1 \cdot X_c + F_{11} \cdot X_c^2 = 1 \qquad \textbf{Eq. 8}$$

which allows determining F_1 and F_{11} as:

$$F_1 = \frac{1}{X_t} + \frac{1}{X_c}$$ **Eq. 9**

$$F_{11} = -\frac{1}{X_t \cdot X_c}$$ **Eq. 10**

In a similar way F_2 and F_{22} are given by:

$$F_2 = \frac{1}{Y_t} + \frac{1}{Y_c}$$ **Eq. 11**

$$F_{22} = -\frac{1}{Y_t \cdot Y_c}$$ **Eq. 12**

F_6 is:

$$F_{66} = \frac{1}{S^2}$$ **Eq. 13**

and F_{12}:

$$F_{12} = \frac{1}{2 \cdot \sigma^2} \cdot \left(1 - \left(\frac{1}{X_t} + \frac{1}{X_c} + \frac{1}{Y_t} + \frac{1}{Y_t} \right) \cdot \sigma + \left(\frac{1}{X_t \cdot X_c} + \frac{1}{Y_t \cdot Y_c} \right) \cdot \sigma^2 \right)$$ **Eq. 14**

3 Laser cutting runway frame under study

The laser cutting machine is manufactured by ADIRA. ADIRA is a leading Portuguese manufacturer and global supplier of sheet metal working machinery, specialized in the production of laser cutting machines, hydraulic press brakes, shears, robotized bending cells and automatic sheet metal transforming systems.

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 Fig. 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 also be reduced to avoid lack of precision.

Fig. 4 presents the currently produced steel beam. This is the beam that equips the cutting machine laser illustrated in Fig. 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. All these plates are assembled and connected together by multi-point welding in almost all cases and also by continuous welding.

4 Materials properties

Naturally, the composite material presents good structural characteristics only when the fibers and matrix are well combined so that they can properly support the loads that are restricted [2]. Because of this, it was proposed that the new beam was made from carbon fibers with an epoxy matrix and a polyester foam core (see Table 1, for mechanical properties).

Carbon fibers are typically applied in composites with high mechanical performance in areas such as aeronautics and space industry [1]. They can withstand extremely high temperatures without loss of much strength and stiffness [7]. Carbon fibres are produced in a variety of tensile strengths and tensile moduli. They are accordingly designated as ultrahigh, very high, high or intermediate modulus and high strength. The tensile strength and tensile modulus of carbon fibres may be as high as 5600 MPa and 500 GPa, respectively [7]. The fibers are usually very thin, with diameters on the order of 5 to 8 microns, so that they can be folded and easily handled. Thus, the carbon fibers can be worked so that they can result in groupings known as fabrics [2]. Another feature of carbon fibers is that they have longitudinal coefficient of expansion negative or near to zero. Regarding the matrix, the main advantages of an epoxy matrix are high mechanical strength, abrasion resistance, chemical resistance, the curing process without release of volatiles, great dimensional stability as a result of its low concentration (2-3%), low absorption water [1], operating temperatures typically between 90 and 120 °C but as high as 205 °C [3] and good adhesion properties to a wide variety of substrates [2]. Another advantage is that these resins have good processability, although less than that of polyester resins, due to higher initial viscosity and long curing times [1].

The core of the beam is constituted by a polyester nonwoven material with a compression resistant hexagonal cell structure. These pressure-resistant cells, which are separated by channels, contain synthetic micro-spheres. The cells do not absorb resin and therefore limit the total resin up-take. Since these cells are pressure resistant, they create thickness in the laminate even when pressure is applied by vacuum bag. The channels facilitate resin flow and form a pattern of cured resin with good mechanical properties and excellent bonding to the outer skins [9]. Because of these unique properties and characteristics, this polyester foam can be used as:

- Thin core (bulker), adding stiffness, while reducing weight.

- Inter-laminar resin flow medium, eliminating the need for other (disposable) flow media.
- Print blocker (liner), that meets the most demanding cosmetic and finish requirements.

Generally, composite materials reinforced with carbon/epoxy, are treated as linear elastic materials because the essentially linear elastic behavior of fibers provides the most strength and stiffness of the material [2]. To compensate this orthotropic material characteristic, it is usual in its application to distribute the material in successive layers with different directions from each other.

5 The new composite solution

Sandwich materials available are essentially composite materials with a construction where the core of low strength, stiffness and density is placed between two thin layers of dense and resistant materials. The main function of the core is to maintain the outer layers separated and simultaneously to stabilize them. In fact, the faces are responsible for bearing the loads of structural sandwiches, while the core enables the faces to act accordingly. In this context, the role of the matrix is important as it ensures the behaviour of composite sandwich as a whole. If the array fails, the behaviour sandwich is removed and the outer faces behave as two independent thin limbs [7]. For the new solution in composite material a wall of 7 mm is required (see Fig. 5). Of these 7 mm, 4 mm are carbon fiber and the other 3 mm are polyester foam. Fig. 6 illustrates the structure of the selected laminate. As mentioned, the design of a structure is an iterative method. The first approach was to calculate the equivalent stiffness for carbon to steel. Through the analysis in the finite element program and the analysis of the graph shown in Fig. 5, it can be concluded that with the increase in the number of layers, the lens shift focus tends to 0. In other words the strains are smaller. This convergence is justified by the increased stiffness of the beam by increasing the number of layers.

Fig. 7 shows a general view of the beam designed in composite material. Similarly as the steel beam, the beam made of carbon has two box girders type substructures internally reinforced by three types of components. Fig. 8 and Fig. 9 show the allocation of internal components designed to internally improve the beam.

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

The shape of the carbon beam was also optimised in order to allow an easy adhesive bonding between all structural components. Therefore, all reinforcing components present specific surfaces for enabling an easy and good bonding between adjacent components and also their quick positioning and accurate assembly. Fig. 10 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 in its thickness. In this component, all concordance radii were made to be greater than 5 mm to facilitate the placement of fibre fabrics in the mould and facilitate manufacturing.

Fig. 11 illustrates the reinforcing Component 2. Twelve components of this type are used 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 internally components.

The reinforcement shown in Fig. 12, Component 3, is also intended to increase the structure stiffness. It has a "U" shape that allows increasing the beam stiffness in a region of the beam where is not possible to use a bigger reinforcement. Such region must be unobstructed to allow an easy access for assembling equipments that are coupled to the beam like the linear motors. This "U" type reinforcement is adhesively bonded to other components, in particular to Component 2 illustrated in Fig. 11. The final beam has eight components like this.

Finally, the reinforcing component that forms the outer shell of the beam is also represented in Fig. 13, Component 4. All previous components are bonded on this through its outlying areas. Two components of this type are included in the final beam.

Only the length of Component 4 and the number of the other 3 components must be changed when a smaller or a larger framework beam needs to be manufactured. All carbon fiber reinforced polymer (CFRP) components were designed for being used in various machine models currently manufactured by the ADIRA company. Therefore, the same framework beam moulds may be used to produce all of different machine size range. In some cases, only the number of components used in the manufacture is changed.

A possible processing method to perform the beam in carbon fiber with foam core is the vacuum infusion process. This process has lower costs and good reproducibility thus providing its easier industrialization. Furthermore this process can be achieved with low initial investment and the composites can be cured and performed at room temperature or even at lower temperatures [10].

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.

6 Finite element analysis

The study of mechanical models can be made in two ways, i.e, through a physical model (experimental) and/or through a mathematical system. With the advancement of science, the developments of mathematical models that simulate the behaviour of physical systems are increasingly realistic, providing reliable modeling for real engineering cases. These analysis models are much more economic analysis than the analysis of physical models. Although the results of the analysis resulting from an analysis by finite element method are not exact, the counterparts are advantageous [4]. The analysis of mathematical models usually requires the use of numerical methods, among which stands out the finite element method, FE.

Validating the FE results

Usually, the validation of an analysis is made on its results. However, it is impossible to validate the results obtained in this analysis because these are the results of a high initial cost prototype. Therefore, it was decided to validate the procedures for obtaining the results to have confidence in the results obtained from the numerical model. For that, comparisons were carried out between numerical and analytical calculations for the same case. These comparisons are always performed with very simple components.

Because the geometry of the beam is quite complex with components having very small radius, the geometry had to be simplified in some aspects and details, without changing the overall shape. Examples are the contours with very small radius that must be softened to larger radii in order to reduce the number of elements to use. Fig. 14 illustrates a simplified geometric model of the real to an approximate model to facilitate the finite element modeling. As can be seen the image on the left has less areas than the actual image of the same component on the right. This is visible by the number of colors shown in each figure, in which each color represents an area. Through minor modifications of this kind is possible to reduce the number of degrees of freedom, obtaining more reliable results and reduce computing time.

Due to the great number of calculations made by advanced numerical methods, simulations and results obtained from a FE analysis usually present huge discrepancies caused by small differences or errors made during the introduction of the loads, 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 the FE analysis to ensure they are realistic and that the FE software is properly working. In this work, FE results were validated by two different ways. The first summarizes the comparison of the results obtained from FE with very elementary laminate plates with those obtained from a simple computer software widely used in the calculation of laminates, the LAP (Laminate Analysis Program**)** [11]. 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. Once selected the stacking sequence, and the results obtained, these should be compared with results obtained by the analysis of the composite component with other methods such as FE’s, and finally optimising the design by inspecting the laminate behaviour layer by layer [11]. The stresses and strains of a loaded flat composite plate with the layers, with the appropriate properties, calculated using the LAP software were then compared with the results obtained from the FE used software ANSYS with exactly the same laminate.

The second way to validate the FE analysis was to compare the displacements suffered by two plates with the same stiffness, one made of steel and other made of a composite material. The results obtained from the FE simulations of the two plates must show the same displacements in both plates. With this analysis it can be concluded that the calculations performed manually match with the calculations performed by the FE program ANSYS. This proves that the results obtained by the FE program are representative.

The two plates have the same boundary conditions and the same geometry of 0.5×0.1 m recessed at one end and a load of 20 Pa applied. For the plate made of composite material, a displacement of 0.688×10^{-03} m was obtained with a plate 2.7 mm thick, Fig. 15 and 0.689×10^{-03} m was obtained wtih a plate made of steel 2.5 mm thick, Fig. 16. All the mechanical properties of materials are presented in Table 1.

After validating the methodology used in the FE method, the response of the structure submitted to the service loads in working boundary conditions were studied. First, the FE analysis was used to study the static and then the dynamic behaviour of the new composite beam.

Mesh and boundary conditions

For a better understanding of the study, it is necessary to define all axes. Therefore, the y-axis was defined as the axial direction of the beam, or the transverse direction of the laser cutting machine. The car that is coupled to the beam runs in this direction. The x-axis was defined as the direction over the machine, or in other words along the machine. The movements in this direction are basically the translation of the beam. The z-axis was defined as the vertically direction of the laser cutting machine. The only component that moves in this direction is the head that supports the focusing lens of the optical beam.

In composite materials as each layer can have different properties, one must define the properties and the orientations of several layers [8]. The choice of the appropriate element to the analysis in question thus, becomes a key point in the formulation of a structural problem. There are in the library of FE program, ANSYS, various elements with composites modeling capabilities. Element Shell99 was used. This element can be used for applications where the material is disposed in layers and the structural model is a shell (Shell) with a length/thickness of about 10 or greater [8]. This element allows the modeling of materials up to 250 layers and has six degrees of freedom at each node. The most important points to note about this element is that it allows in each layer to insert three essential features in the modeling of composites:

- The material layer;
- The fiber orientation (angle of the element makes with the x-axis);
- The thickness of the layer.

The simulation of the beam behavior was carried out under its extreme working conditions. For that, restrictions were applied on the beam extremities, simulating the joints of the linear motors that connect the beam to the structure of the cutting machine. After this, the rest of the components were attached to the beam, the ones that holds the mirrors and the focusing lens laser cutting. Finally, the accelerations were applied. These accelerations correspond to the limits of the linear motors. Thus, an acceleration of 2g's (g = 9,80665 m/s^2) was applied in the direction of the x and y axis and 1g in the direction of z-axis (Fig. 17).

For the modeling of the beam with mounted components, 52257 elements were used totaling 222763 degrees of freedom.

7 Results

Static analysis

A requirement of the project was to 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.

Fig. 18 illustrates the deformation of the beam structure in the z-axis direction. The different displacements obtained correspond to different colours. The colours in the middle of the beam correspond to the points where the structure is more deformed. On the other hand, the extremities colours represent the points where the structure is less deformed. This situation occurs as expected because the maximum moment of a beam occurs when the load is applied at mid-span as it was defined in this simulation. Due to restrictions of movement and rotation, defined in the analysis, the extremities zones were that had lower displacements.

Dynamic analysis

Given the specific application of the studied component, a dynamic analysis should also be performed in this work. In this analysis, the rigid vibration or local modes of vibration modes were not considered, since those are not expected to have significant influence on the overall behaviour of the structure. The simulation was performed between 0 to 500 Hz.

In the first analysis, we determined the dynamic behavior of the complete composite beam with the various components mounted on it. The natural frequencies found for this analysis are presented in Table 2. Twenty three modes of vibration of the beam with the components assembled were calculated. Most of these modes influence the stability of components assembled to the beam. This instability increases the deviations of the laser beam cut-off. Thus, the main causes of the laser beam cut-off deviations are the strains suffered by the components that are assembled to the beam, instead of the strains suffered by the beam. The components assembled on the beam made of steel and aluminium influence the accuracy of the machine and should be optimized (see Fig. 18).

Examining the isolated beam, both in composite and the existing solution in steel, we obtained the natural frequencies shown in Table 3. The composite beam has seven modes of vibration while the currently produced steel has four modes of vibration. The values found for the first natural frequencies are relatively high, which means that both solutions are acceptable. The natural frequencies obtained for the composite component studied compared with the natural frequencies of the steel beam currently produced and that equips the laser cutting machine, lead to the conclusion that the dynamic behaviour of the component must be optimized.

Fig. 19 illustrates the vibration Mode 7 at frequency of 153 Hz. This mode is primarily characterized by a flexion of the beam. This is the first vibration mode and only appears at 153 Hz, which corresponds to a structural component and got quite dynamically, but not better than de steel beam. The first mode of vibrations of the steel beam only appears at appears at 241 Hz, which corresponds to a very high frequency of a structure of this kind (see Fig. 20).

8 Conclusions

In this work, a totally new composite main runway frame beam was developed to replace the steel currently used one, in order to improve significantly the performance of laser cutting machines that are manufactured by the company. The static and dynamic mechanical behaviour of the new composite framework structure was studied by FE analysis.

Dynamically, the behaviour of some components that are assembled on the beam, should be revised and optimised because like it was demonstrated they present some worrying behaviour at frequencies in the possible machine working range. Regarding to the new composite framework beam, this has not shown to present better dynamic behaviour than the currently one made of steel. This can be concluded by the analysis of Table 3, where it is visible that for the same range of study, the beam made of composite presents more modes of vibration and the first is at 153Hz, a frequency that is very possibly within the range of frequency of the machine work. On the other hand, the first natural frequency of vibration of steel beam only appears at 241Hz, which is a frequency that is already outside the range frequencies of machine work. However, by the analysis of the steel beam and because of the internal reinforcement components have many free surfaces and edges (i.e. “X” reinforcement illustrated in Fig. 4 b)) there are many local vibration modes that can be avoided using the new composite solution.

The reducing of the weight of the beam can result that, with the same linear motors it can be increased the acceleration of the machine and consecutively its cutting speeds.

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

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References

[1] M. F. S. F. Moura, A. B. Morais, A. G. Magalhães, *Materiais Compósitos: Materiais, Fabrico e Comportamento Mecânico,* Publindústria, **2005**

[2] R. M. Jones, *Mechanics of composite materials* (2^a ed.), Taylor & Francis, **1999**

[3] S. K. Mazumdar, *Composites manufacturing: materials, product, and process engineering.* CRC Press LLC, **2002.**

[5] H. L. Soriano, S. S. Lima, *Método dos Elementos Finitos em Análise se Estruturas* (Vol. 48), EdUSP, **2003.**

[7] P. K. Sinha, *Composite Materials and Structures,* Department of Aerospace Engineering, I.I.T., Kharagpur, **2004.**

[8] *ANSYS user's manual.* Swanson Analysis Inc. **1992.**

Thesis

[4] J F. B. Meireles, *Análise Dinâmica de Estruturas por Modelos de Elementos Finitos Identificados Experimentalmente*, PhD Thesis, Minho University, Guimarães, Portugal, **2007.**

[6] J. P. Nunes, *A Study of the Processing and Properties of Sheet Molding Compounds and Unidirectional Carbon Fibre Towpregs*, PhD Thesis, Minho University, Guimarães, Portugal, **1998.**

Websites

[9] http://www.lantor.nl/index.php/id_structuur/10599/soric.html, **2011.**

[10] http://www.netcomposites.com/education.asp?sequence=61, **2010.**

[11] http://www.anaglyph.co.uk/LAP.htm, **2010.**

List of Table Captions

Table 1 – Mechanical properties of the main materials used

Carbon Fiber/Epoxy Resin	
Young’s Modulus, E_x (GPa)	135
Young’s Modulus, $E_y= E_z$ (GPa)	10
Poisson’s Ratio, $PR_{yz} = PR_{xz} = PR_{xy}$	0.3
In –plane Shear Modulus, $G_{yz} = G_{xz} = G_{xy}$ (GPa)	5
Density, ρ (kg/m^3)	1600
Ultimate Tensile Strength, σ_{xt} (MPa)	1500
Ultimate Compression Strength, σ_{xc} (MPa)	1200
Ultimate Tensile Strength, $\sigma_{yt} = \sigma_{zt}$ (MPa)	50
Ultimate Compression Strength, $\sigma_{yc} = \sigma_{zc}$ (MPa)	250
Ultimate In –plane Shear Strength, $G_{yz} = G_{xz} = G_{xy}$ (MPa)	70
Polyester foam	
Young’s Modulus, E (GPa)	0.8
Poisson‘s Ratio, PR	0.3
Density, ρ (kg/m3)	600
Steel	
Young’s Modulus, E (GPa)	170
Poisson’s Ratio, PR	0.3
Density, ρ (kg/m3)	7111

Table 2 – Natural frequencies and vibration modes for the composite beam with components assembled (20 of 23 modes calculated)

Vibration mode	Natural frequency [Hz]	Vibration mode type (description)
Mode 7	46.49	Flexion
Mode 8	66.06	Flexion
Mode 9	81.36	Torsion
Mode 10	88.46	Flexion
Mode 11	96.79	Flexion
Mode 12	119.14	Torsion
Mode 13	151.32	Flexion
Mode 14	177.93	Flexion
Mode 15	239.39	Flexion
Mode 16	247.75	Torsion
Mode 17	254.89	Flexion
Mode 18	302.72	Flexion
Mode 19	308.01	Flexion
Mode 20	331.97	Flexion
Mode 21	334.84	Flexion
Mode 22	357.89	Flexion
Mode 23	400.07	Flexion
Mode 24	402.38	Flexion
Mode 25	417.75	Flexion
Mode 26	434.49	Flexion

Table 3 - Natural frequencies and vibration modes for the composite and steel beams

Vibration Mode	Natural frequency [Hz]	Vibration mode type (description)
	Composite beam	
Mode 7	153.15	Flexion
Mode 8	202.64	Flexion
Mode 9	253.96	Torsion
Mode 10	321.36	Flexion
Mode 11	390.70	Flexion
Mode 12	466.83	Torsion
Mode 13	485.05	Flexion
	Steel beam	
Mode 7	241.71	Flexion
Mode 8	336.61	Flexion
Mode 9	414.23	Torsion
Mode 10	489.71	Flexion

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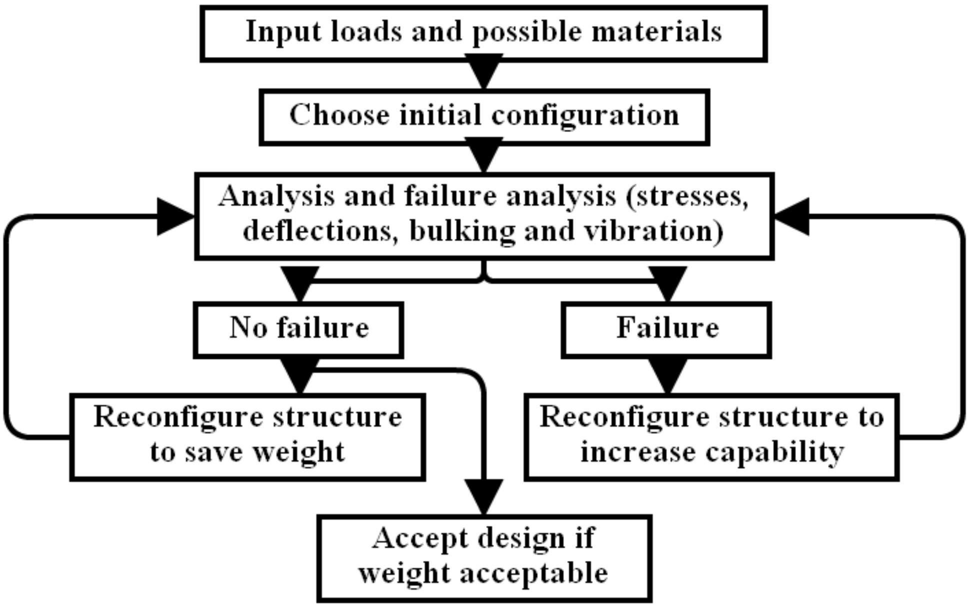

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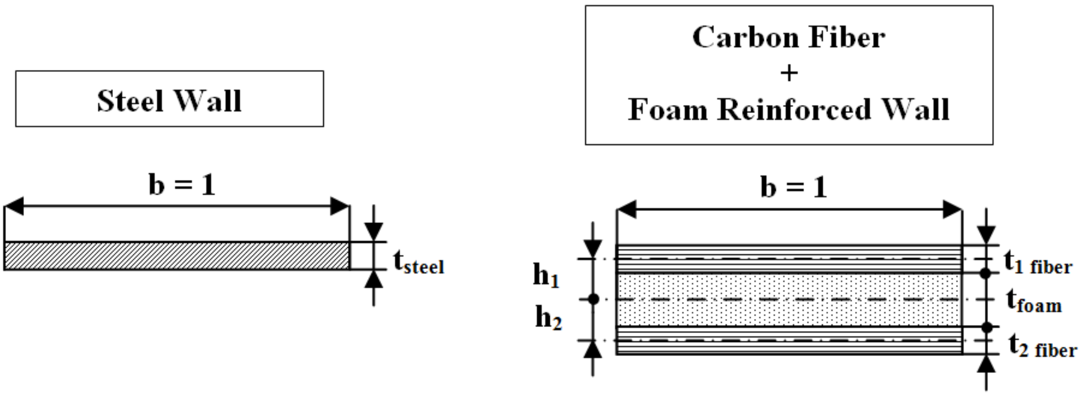

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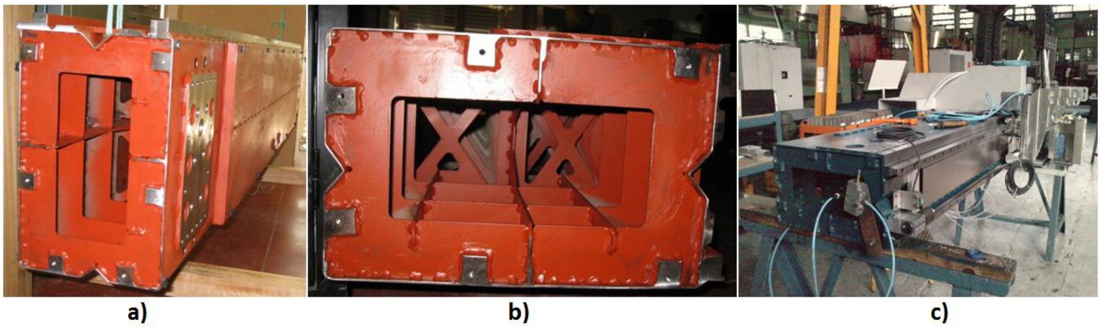

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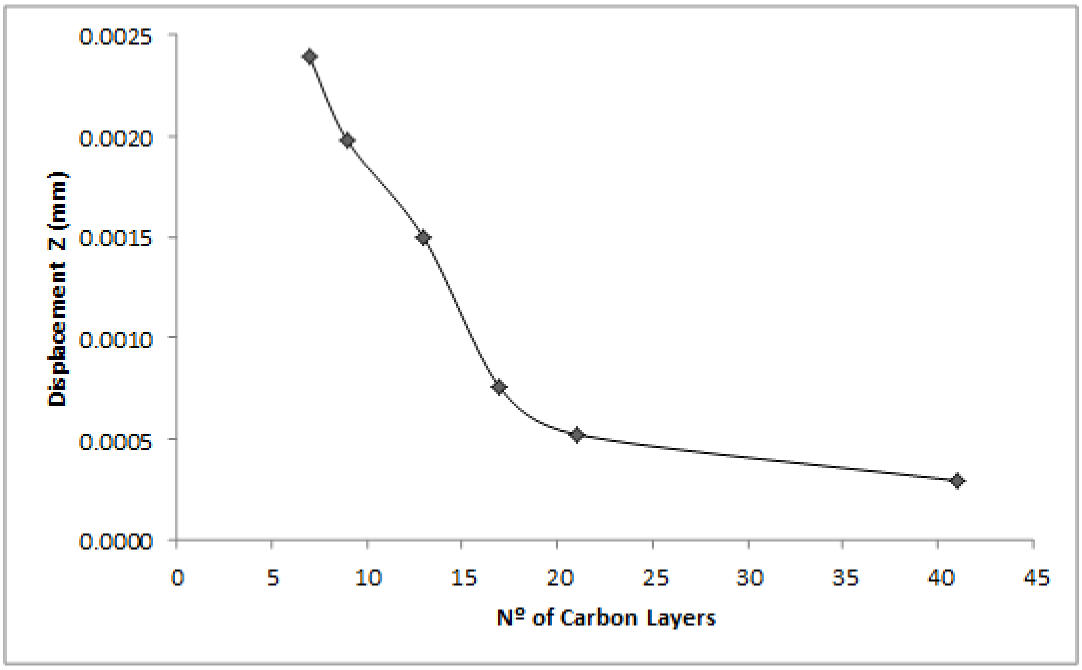

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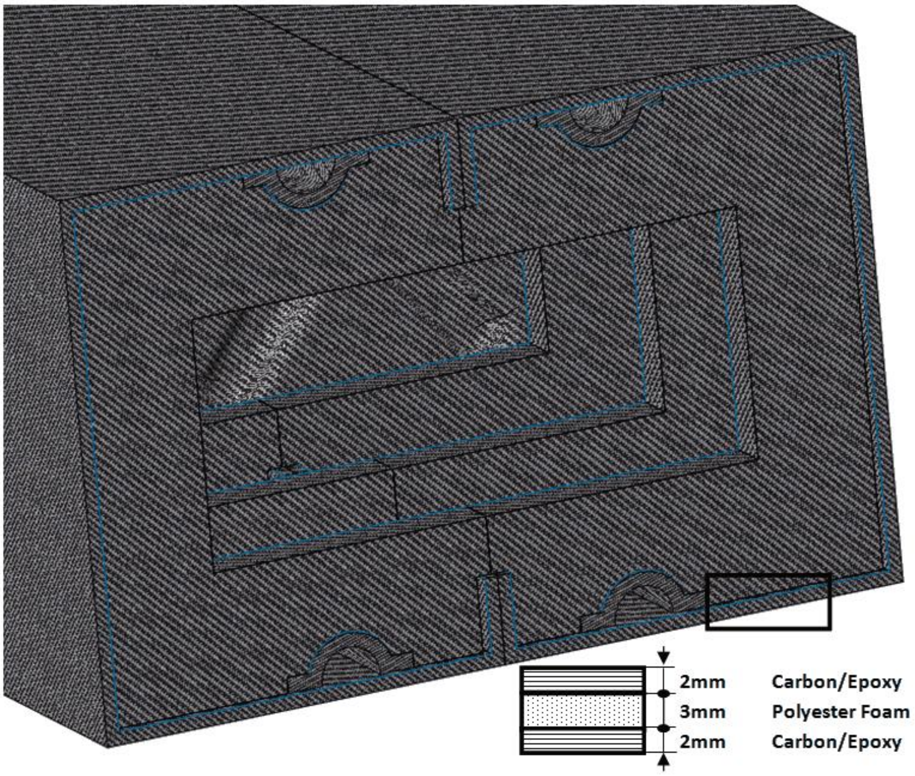

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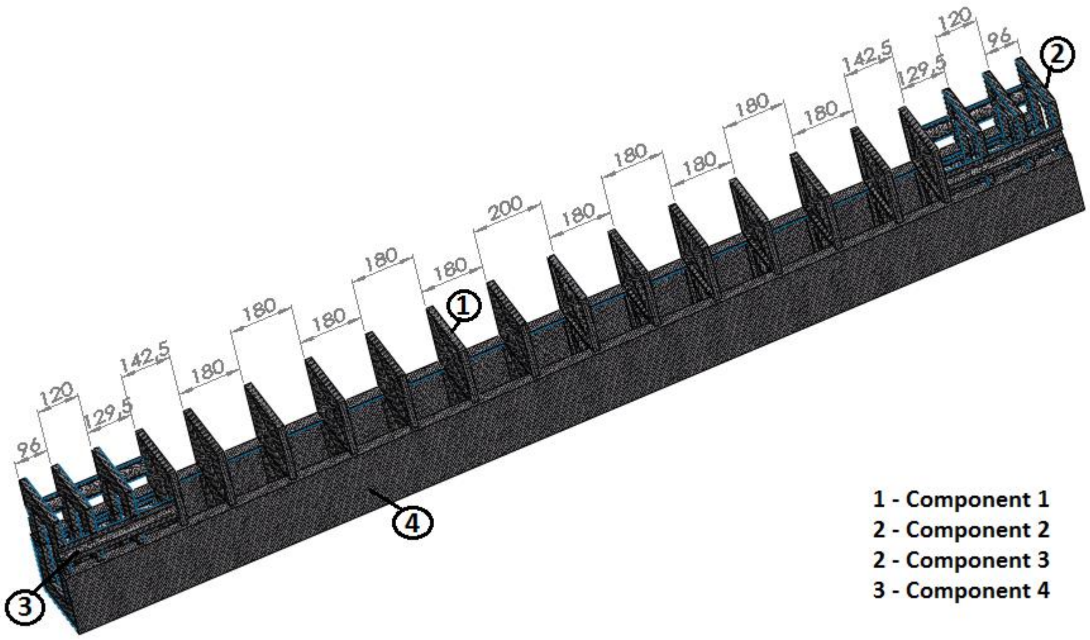

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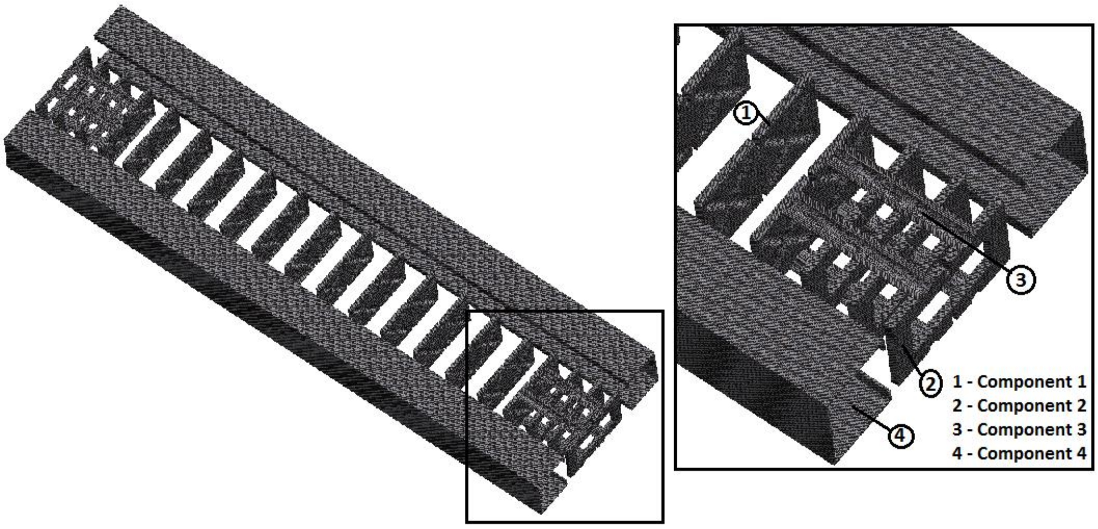

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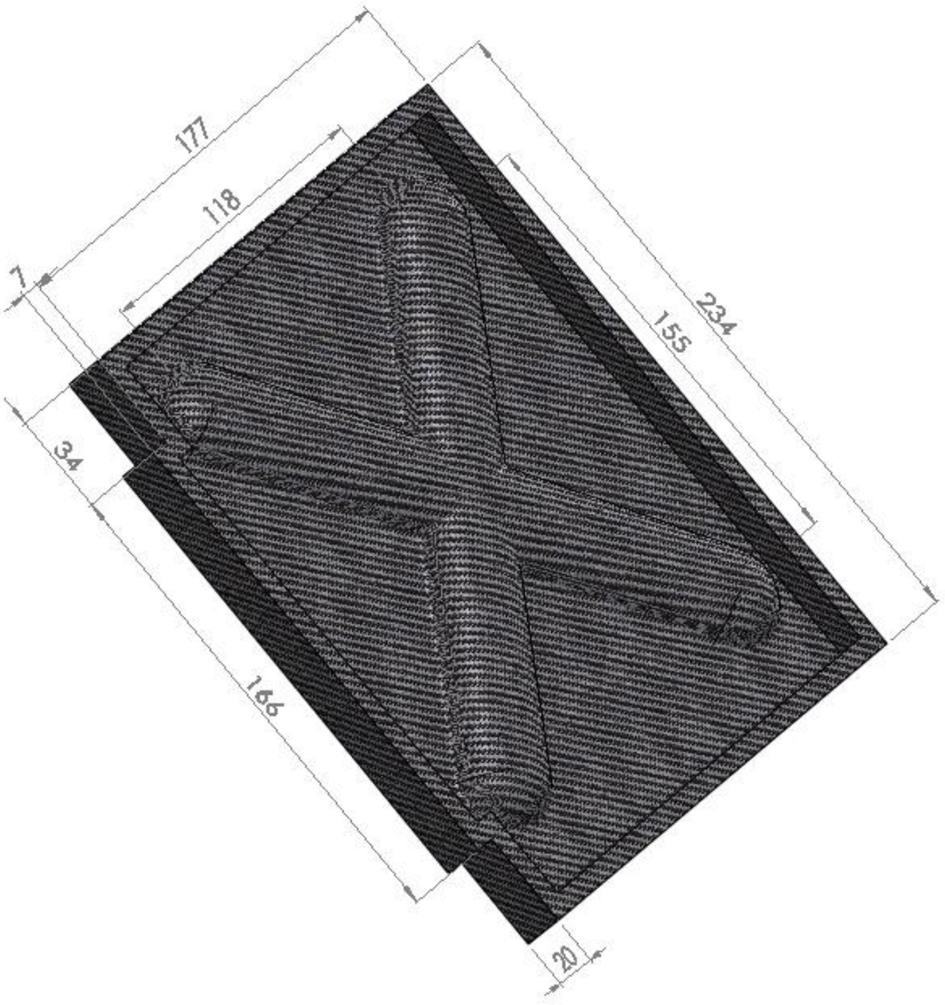

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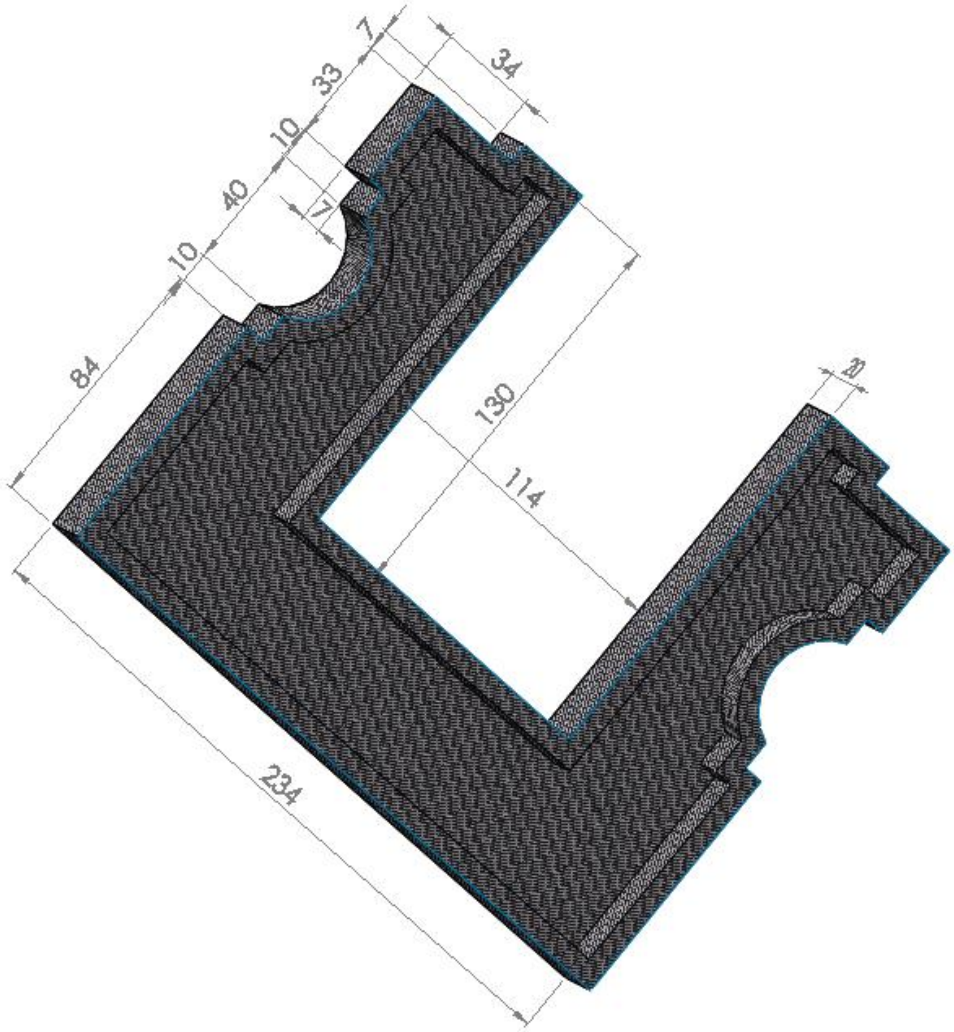

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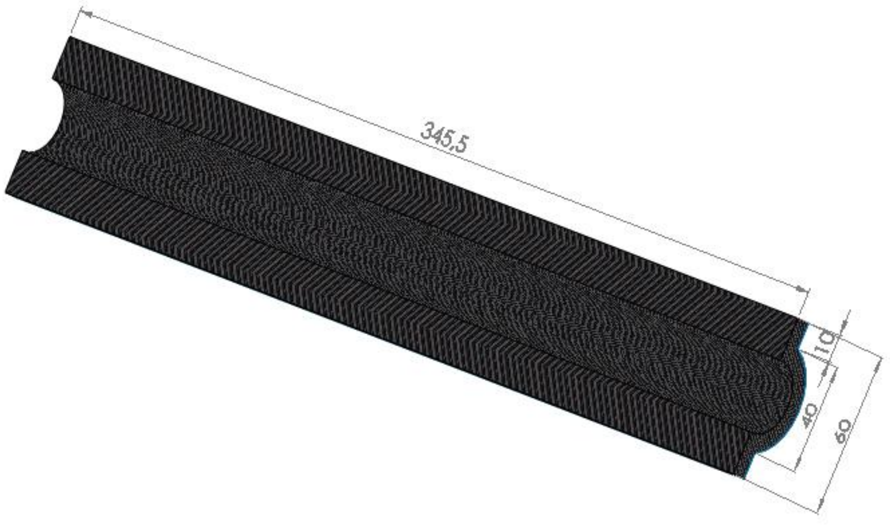

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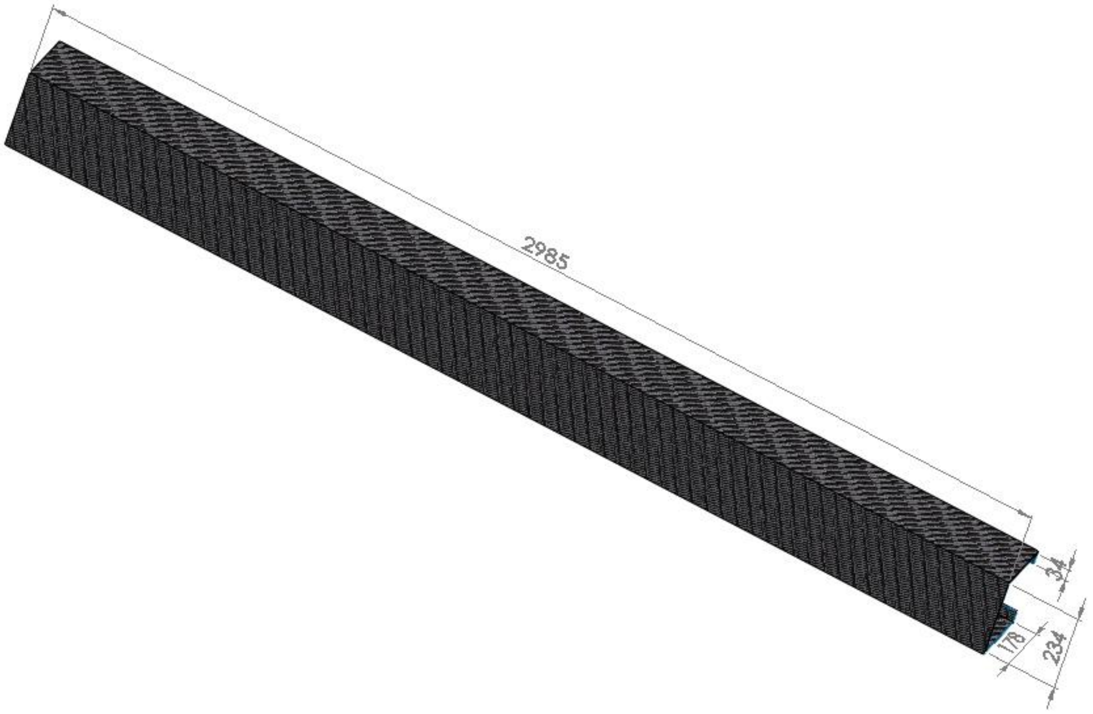

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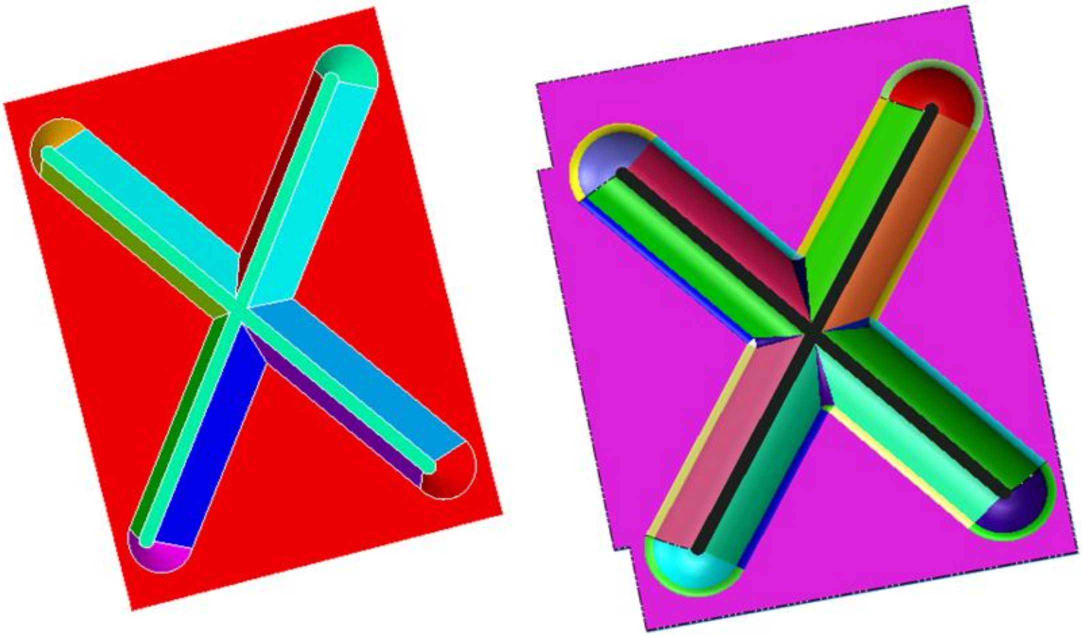

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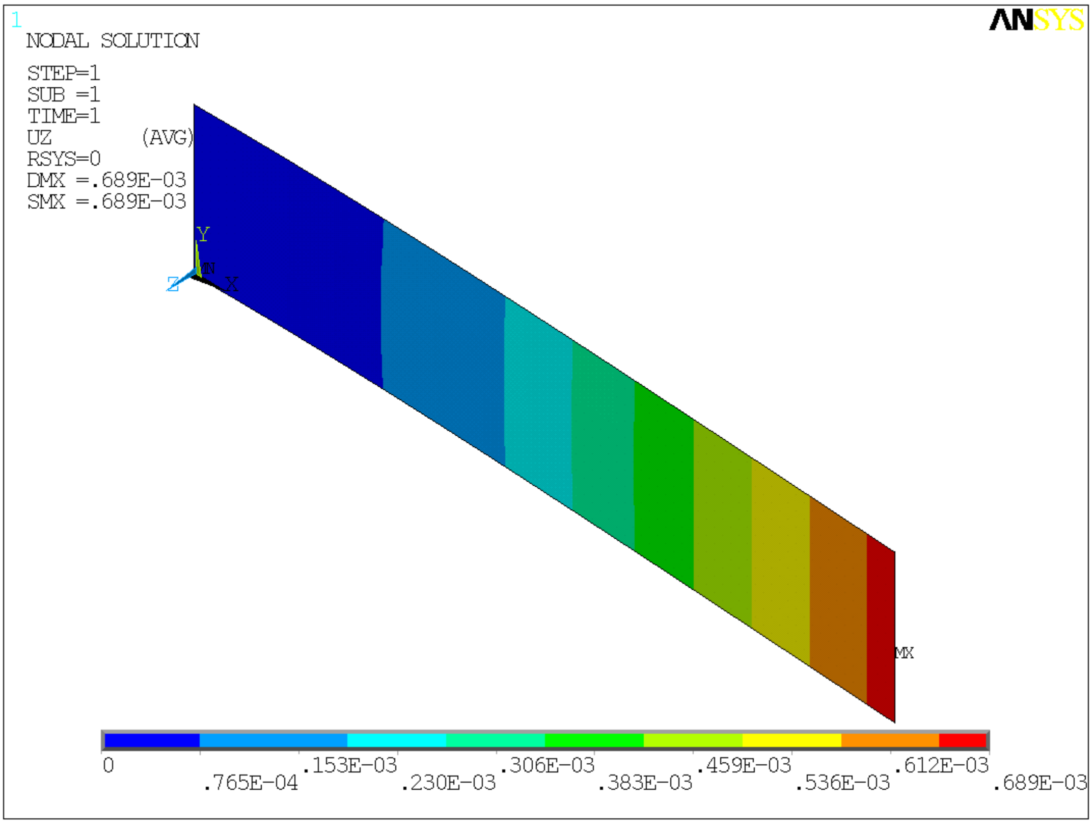

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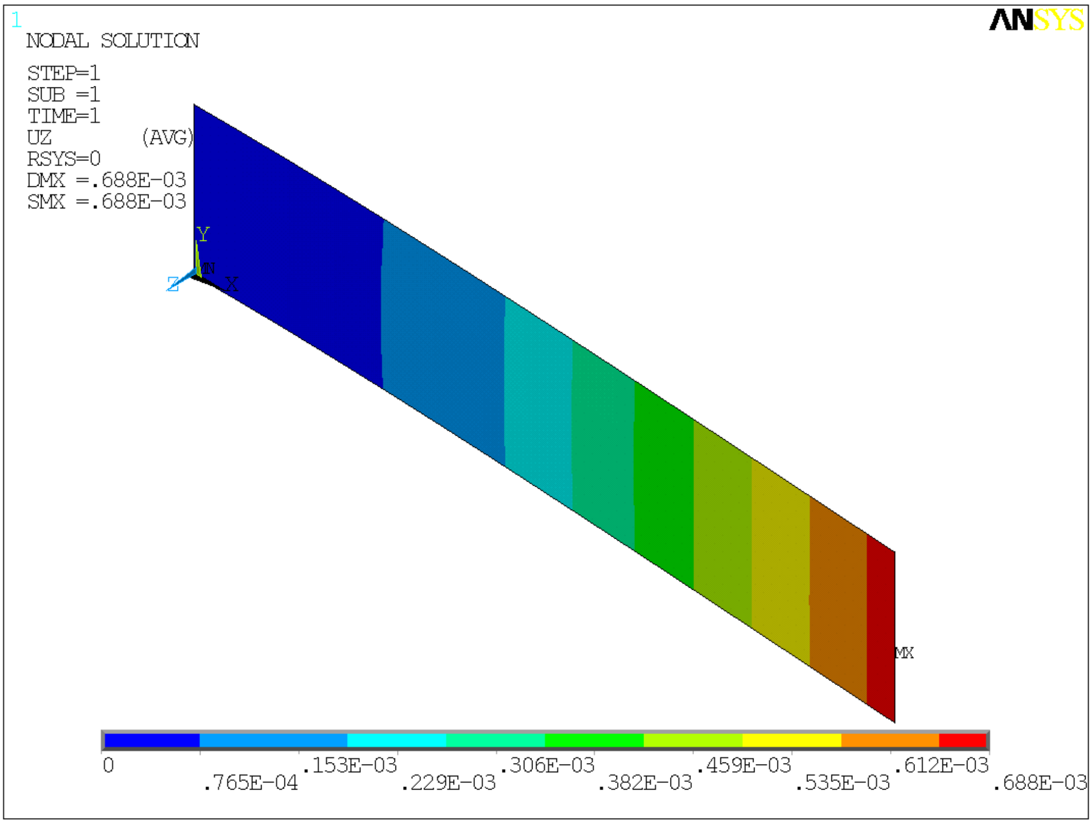

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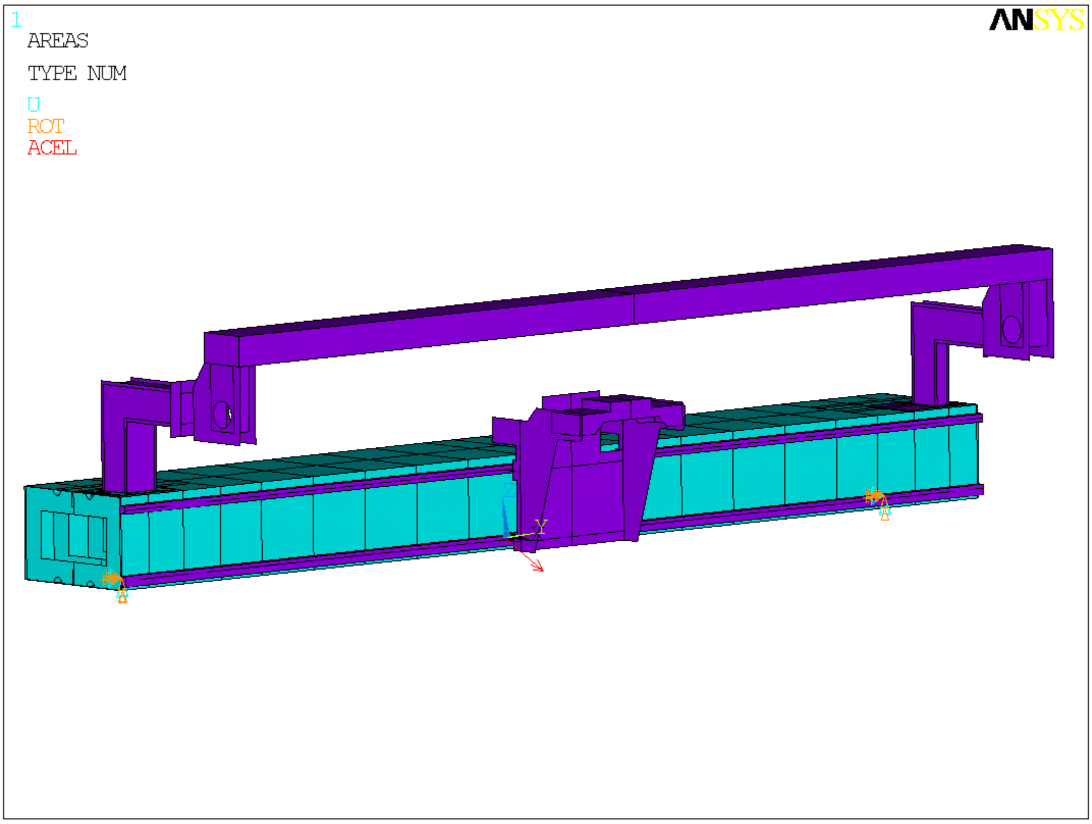

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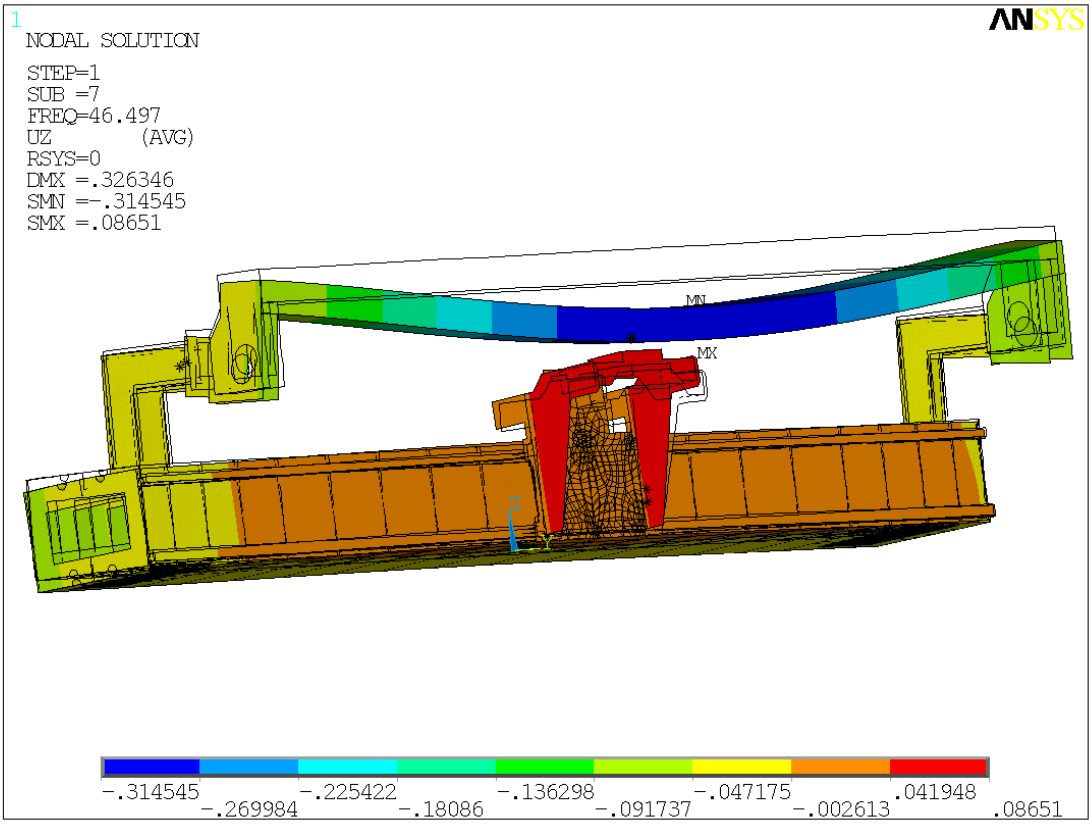

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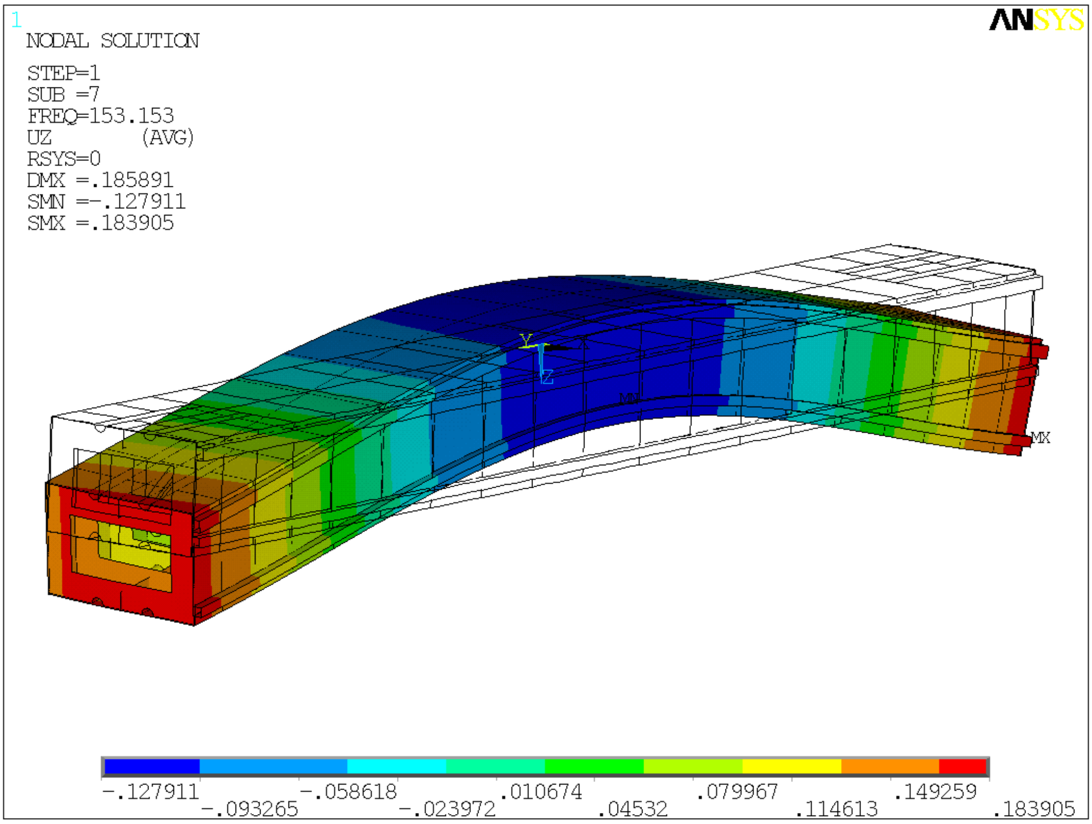

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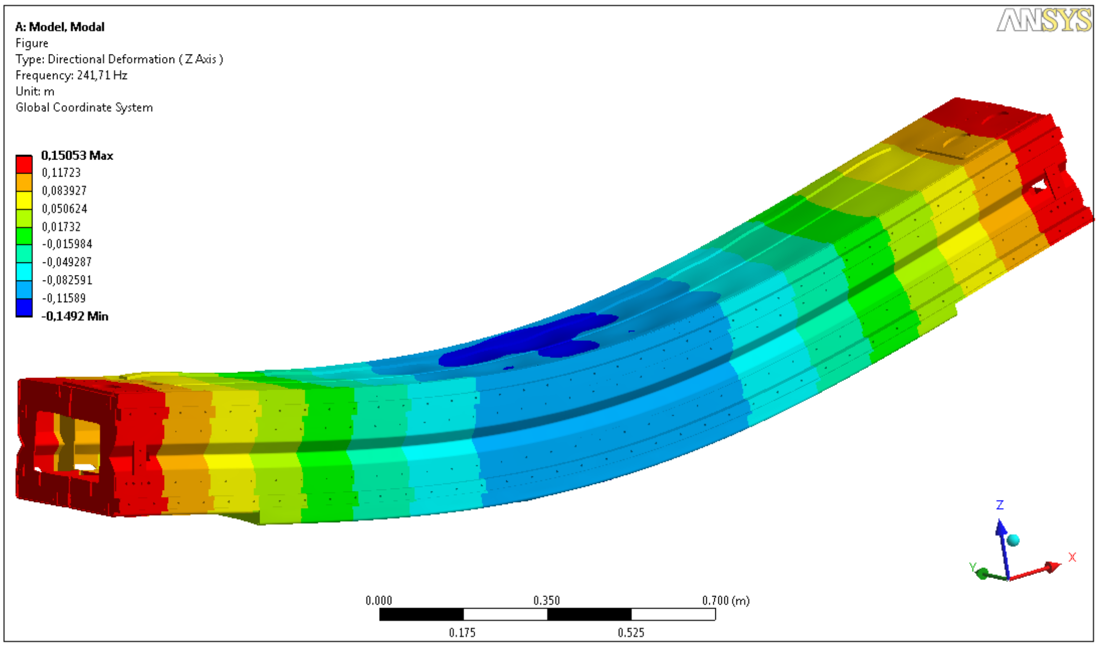

Fig. 20 – Displacement in the z-axis direction at 241 Hz (dimensions in m). Mode 7 of the steel beam.