FEASIBILITY STUDY OF A LIFTING WORK PLATFORM WITH ARMS MADE BY COMPOSITE MATERIALS

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Keywords: composite materials, carbon fiber, lifting platform

Abstract

Elevating work platforms are hoists equipment that are increasingly used for example in the construction industry and in the field of maintenance. For example, the maintenance of the hub of the wind turbines can be done through the use of the working platform. These structures are required to reach great heights and obviously they have to satisfy the constraints induced by the highway standards, like the maximum axle load and the maximum machine size.

The load increase is usually not a fundamental parameter because the load applied to the arms of the platform is correlated to its basket in which the number of people is usually equal to two. To satisfy these requests the material of the structures changed from the classic steel (S235 JR to S355JR) to high strength steel (S700 to S1100).

The idea of this paper is to evaluate the potential offered by a composite material for the construction of the arms of the platform in order to reduce the global weight of the machine. It is important to note that actually a very limited part of the jib (the last part of the telescopic arm) is made of plastic material, especially in the platforms used for the maintenance of electrical lines, in order to introduce an electrical insulator between the operator (which is present in the basket) and the rest of machine.

The initial analyses show the technical possibility to change the material of the arms with composite materials and this produces a significant reduction of the weight of the machine components, about 50%. Being a feasibility study, still remain open some problems such as the mechanical behavior of the used composite materials (fatigue , environment effect , etc..).

1 Introduction

The goal of this work is a preliminary design of a work platform with some arms made by composite materials and its comparison it with the a platform made by high strength steel. The analysis platform is designed to work at great heights (85 meters); machines with these performances has not yet been manufactured. There are prototypes constructed using for the different components (arms, cylinders, joints) metallic materials, mostly steel alloys, which show great problems due to the great weight and also to the transport of the platform structure. The ultimate goal is to reduce considerably the weight of the system, thus allowing to increase the load capacity and to reduce the mass which has to be transported by the handling truck, allowing also the transport of the entire machine in accordance with the road standards. Starting from a preliminary geometry and design specifications k the paper deals with all the major issues related to the implementation of composite structures.

2 Materials and testing methods

2.1 Design specifications

The platform has to be connected with a truck and has to reach the maximum height of about 85 m; at the extremity of the arm there is a device called JIB used for the fine movement of the platform; the operating range of the platform is shown in figure 1.

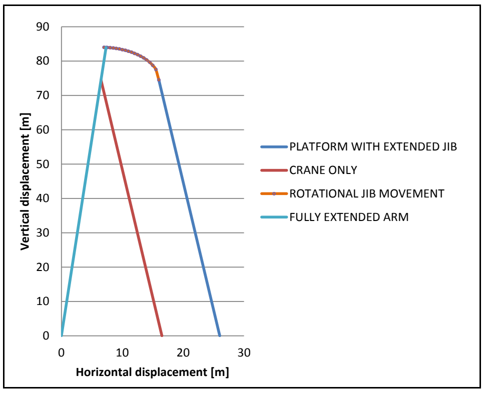

Figure 1. Total operating range of the platform

The platforms with these characteristics that are commercially available are composed by 7 telescopic arms at which end is connected the JIB structure.

2.2 Main characteristics of the new platform

The new structure of the platform is conceived using both composite material (carbon fiber and epoxy matrix) and steel (essentially for the arm joint devices) in order to reduce the weight: the length of each arm is 12 meters, except the JIB which is 10 meters long; the supporting structure (crane) is divided in two functional groups: the first 4 telescopic arms are composed by high strength steel, similar as in the existing steel platform, the second consist of four reclosable arms; this choice is based on several considerations:

- the costs of carbon fiber is much higher than that of steel, it is also necessary to use the first one for the parts which mostly magnify the material characteristics, essentially the weight: the stresses in the structure depend not only from the weight, but also from the lever arm, which is much higher as you get closer to the basket;
- the carbon fiber, like other composite materials, has a low sliding resistance in case of using sliding blocks for the telescopic arms, has also a low contact fatigue resistance if compared with steel alloys in case of the use of rolls.

The fibers used for this machine are the long ones, which make the composite oriented, able to optimize the resistance in the main load direction; the use of long fibers instead of short ones is also justified because the work technique allows to realize the arms using specific molds; the short fibers also have a lower fatigue resistance and are more difficult to joint with steel components.

2.3 Properties of the materials

The used material for the reclosable arms, chosen as the best compromise between the performance of the material and the related costs, is the carbon fiber with an epoxide matrix; their characteristics of interest are reported in table 1.

Material	***Density ρ [kg/m^3]***	***Young modulus E [MPa]***	***Shear modulus G [MPa]***	***Poisson ratio ν***	***Thermal expansion coefficient α [1/°C]***
Epoxidic resin	1200	4500	1600	0.4	0.00011
Carbon fiber	1750	230000	50000	0.3	0.0000002

Table 1. Mechanical characteristics of the materials composing the used lamina

The fiber percentage of each layer is 60%; with these data is possible to compute the mechanical characteristics of the lamina. The density is:

$$\rho_c = \rho_f V_f + \rho_m V_m = 1530\, kg/m^3 \tag{1}$$

The elastic modulus E_1 along fiber direction and the elastic modulus E_2 normal to fiber direction are:

$$E_1 = E_f V_f + E_m V_m = 139800\, MPa \qquad E_2 = \frac{E_f E_m}{V_m E_f + V_f E_m} = 10929\, MPa \tag{2}$$

The shear module G_{12} is: $G_{12} = \frac{G_f G_m}{V_m G_f + V_f G_m} = 3817\, MPa$ (3)

The major Poisson ratio ν_{12}, defined as $\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1}$, with 1 e 2 principal directions, according to the scheme of figure 2 and the minor Poisson ratio ν_{21}, defined as $\nu_{21} = -\frac{\varepsilon_1}{\varepsilon_2}$ are:

$$\nu_{12} = \nu_f V_f + \nu_m V_m = 0.34 \qquad \nu_{21} = \nu_{12} \frac{E_2}{E_1} = 0.026 \tag{4}$$

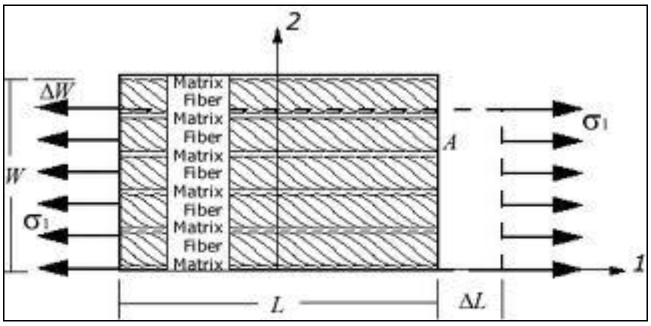

Figure 2. Used direction to define the fiber orientation

2.4 Dimensioning of the arms

The size of the arms depends from several factors:

- The value of the stresses;
- The stacking sequence of the single layers in the laminate.

Each composite arm needs an own mold to be built, it is also allowed to realize arms with a variable section, increasing from its top to the bottom, where the bending stress reaches the maximum value.

The evaluation of the stresses in the arms is obtained by elaboration of a specific program in order to determinate the action between the arms in different positions on the load diagram, once computed the maximum reactions (axial forces and bending moments) the next step regards the definition of the arm sections and also the stresses by using the FEM software ABAQUS.

The stacking sequence of the layers composing the laminate has to comply the following rules:

- the orientation angle of the single layer has to be chosen according to the principal load directions;
- each lamina orientation (0°,45°-45°,90°) should be present in the laminate at least with a percentage of 10%;

- provide a symmetrical distribution of the layers in order to avoid shear-extension and extension-bending couplings which can induce dangerous curvatures in the laminate;
- consider the protection of the primary layers through their collocation in the internal parts of the laminate;
- guarantee a gradual thickness change.

The first arm composing the jib is connected at one end with the basket, at the other with the second arm; to drive the arm is used an hydraulic cylinder; the computation of the reaction forces is made following the schema of figure 3.

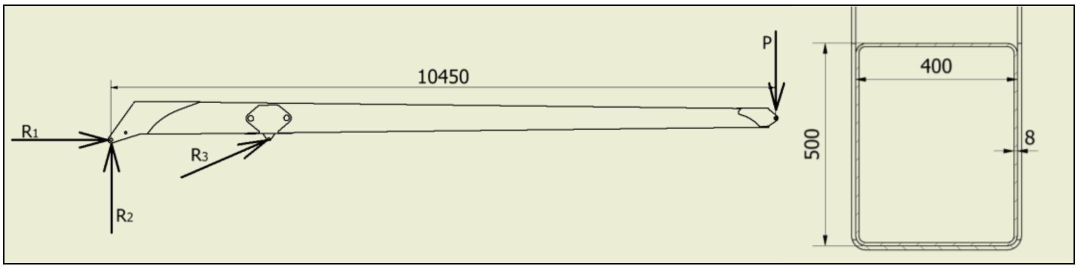

Figure 3. Schema for the computation of the reaction forces in the structure and major section of the arm (dimensions in mm)

The greatest stress, caused by the bending moment, occurring when the element is in the horizontal position, is equal to 108000 Nm; the computation of the stresses is made following the classical composite theory for two-dimensional laminates; the considered stacking sequence is $(90,45,-45,0)_s$; with the layer thickness reported in table 2.

Layer orientation	*90°*	*45°*	*-45°*	*0°*
Thickness [mm]	1	0.5	0.5	2

Table 2. Thickness of each layer composing the laminate

Introducing a reference system with the first two axis on the lamina and neglecting the deformation ε_3 perpendicular to the lamina plane is possible to compute the deformations with the following formula:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{5}$$

The S_{ij} components form the compliance matrix are computed starting from the elastic constants of the lamina:

$$S_{11} = \frac{1}{E_1} \qquad S_{12} = -\frac{\nu_{12}}{E_1} = -\frac{\nu_{21}}{E_2} \qquad S_{22} = \frac{1}{E_2} \qquad S_{66} = \frac{1}{G_{12}} \tag{6}$$

To compute the stresses starting from the deformations is necessary to use the stiffness matrix, the inverse of the compliance one:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{7}$$

These formulas are usable with laminae having the fiber reinforcement aligned with the principal axis direction , if there is a relative angle is necessary to use the rotational matrix T:

$$T = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \tag{8}$$

where $c^2 = \cos^2\theta,\ s^2 = sen^2\theta$, moreover:

$$[\bar{S}] = [T]^T [S][T]\ [\bar{Q}] = [T]^{-1}[Q][T]^{-T} \tag{9}$$

The expression usable for the computation of the stresses in a generic lamina becomes also:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{10}$$

In case of a laminate composed of a certain number of laminae is possible to compute the forces and the moments:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{11} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{bmatrix} \tag{11}$$

Were ε_i^0 e k_{ij} are respectively the deformations and the bendings of the laminate in the principal directions, in compact form:

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ k \end{bmatrix} \tag{12}$$

The components of the ABBD matrix are computable in the following way:

$$A_{ij} = \sum_{k=1}^{N} \left(\bar{Q}_{ij}\right)_k (z_k - z_{k-1})\ B_{ij} = \frac{1}{2}\sum_{k=1}^{N} \left(\bar{Q}_{ij}\right)_k (z_k^2 - z_{k-1}^2)\ D_{ij} = \frac{1}{3}\sum_{k=1}^{N} \left(\bar{Q}_{ij}\right)_k (z_k^3 - z_{k-1}^3) \tag{13}$$

With z_i position of the layer, as shown in figure 4.

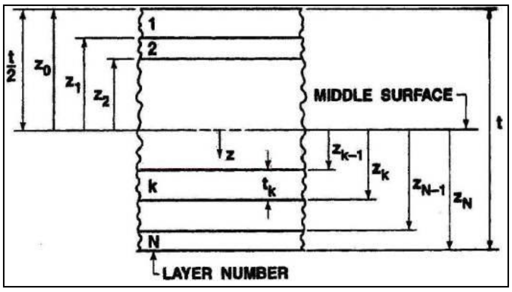

Figure 4. Schema for the computation of the stiffness characteristics of the laminate

In the laminate of interest the values of the ABBD matrix components are:

$$\begin{bmatrix} 632917 & 66083 & 0 & 0 & 0 & 0 \\ 66083 & 353317 & 0 & 0 & 0 & 0 \\ 0 & 0 & 162702 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7274861 & 2511161 & -524250 \\ 0 & 0 & 0 & 2511161 & 113152442 & -524250 \\ 0 & 0 & 0 & -1048499 & -1048499 & 5999461 \end{bmatrix} \qquad (14)$$

The components of the B matrix, as the components A_{16}, A_{26} are quite equal to 0 because the laminate is balanced and symmetric.

Due to the moment present in the section shown in figure 3 is generated a force in the upper and lower platbands equal to:

$$N = \frac{M_f}{H} = 225\,kN \qquad (15)$$

Which determines a linear stress of:

$$N_x = \frac{N}{L} = 562\,\frac{N}{mm} \qquad (16)$$

Is now possibly to compute the deformations and the bendings using the inverse ABBD matrix:

$$\begin{bmatrix} \varepsilon^0 \\ k \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} N \\ M \end{bmatrix} \qquad (17)$$

Due to the balanced and symmetrical disposition of the layers are obtained equal deformations in the laminae and bendings equal to 0; the greatest stresses are located in the 0° lamina and reach the value of about 100 MPa, significantly below the breaking limit, for this material equal to about 1300 MPa.

Following this procedure are determined all the sections of the arms, which are realized with a variable section in order to optimize the flexional resistance by increasing the section dimensions where the bending moment is higher; this characteristic, very difficult to obtain with metal arms, is practicable with composite materials realizing a suitable mold.

In order to determine the global stresses in the structure is necessary to execute several analyzes using a finite element program.

2.5 FEM analysis

The FEM analysis is performed using the ABAQUS STANDARD code; the composite arms are modeled as shell elements while the metallic parts are modeled as 3D parts; to each arm is given the defined stacking sequence of the laminate with the correspondence thickness of each layer; to improve a correct behavior is given a local orientation for each arm, as reported in figure 5:

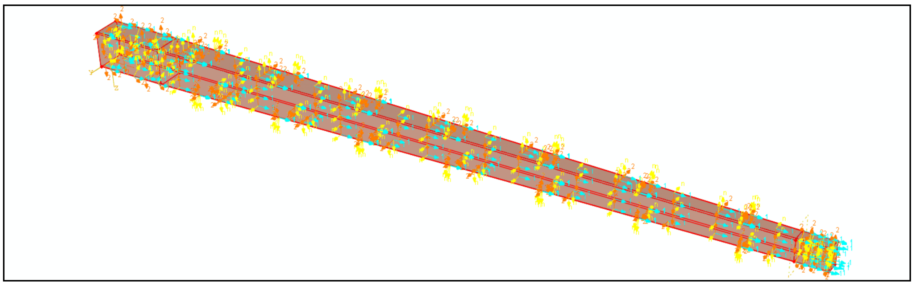

Figure 5. Application of the local reference system for the arm

Once computed the stresses is possibly to apply a failure criterion for the structure, like the Tsai-Hill one, as shown in figure 6.

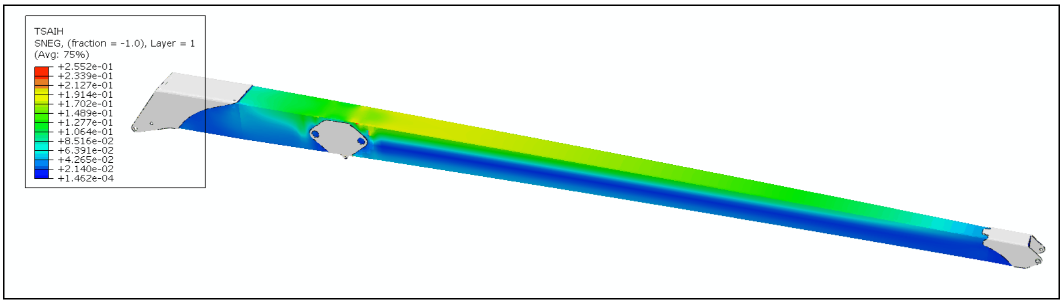

Figure 6. Values of the stresses in the first arm

Is also possible to inspect the stresses in the laminate varying the position along the thickness; the founded values are significantly different for each lamina, due to the variation of the orientation; the greatest stress value is findable in the 0° lamina, as reported in figure 7:

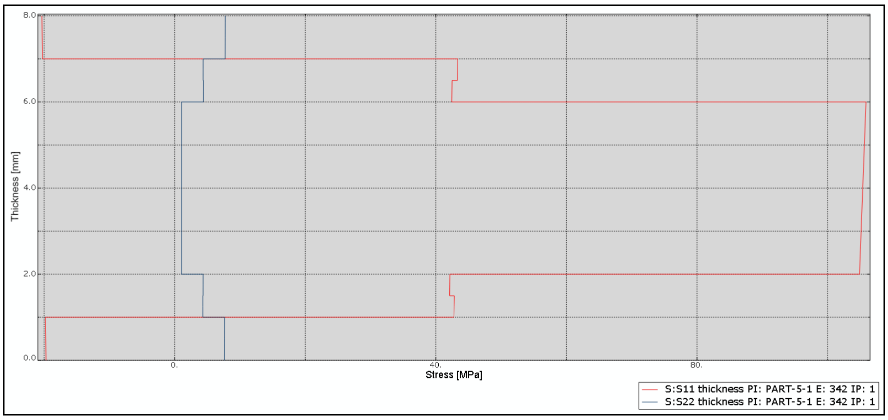

Figure 7. Stress trend for each lamina in one of the most solicited regions of the laminate

2.6 Final aspect of the structure

The final structure is composed by four reclosable composite arms and four telescopic steel arms, the aspect is reported in figure 8. In order to minimize the height the steel and the composite arms are connected in a staggered arrangement.

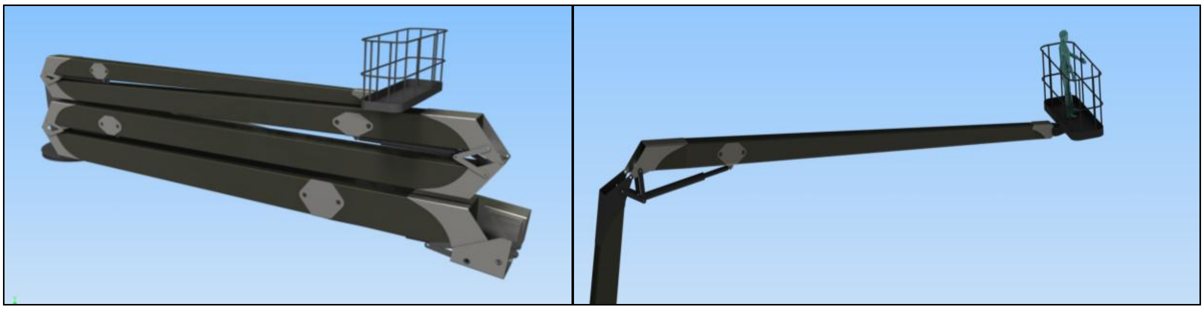

Figure 8. View of the entire structure in the reclosed position and particular of the JIB.

The analyses were conducted focusing on the JIB: they show a great weight reduction due to the material change (the density of the carbon fiber is 5 times lower than the density of steel); the weight of the structural devices will conversely increase, but globally there is a significant weight reduction, as reported in table 3. Reprocessing the same numerical methodology for the other three arms in composite material, the weight reduction is quite the same percentage as in the JIB, close to 50%.

Machine	*Arm weight [kg]*	*Devices weight [kg]*	*Total weight [kg]*
Steel platform	632	160	792
Composite platform	170	180	350
Percentage variation	-73%	+12%	-56%

Table 3. Weights of the steel and the composite JIB

3 Conclusions

This paper remarks the feasibility of a new typology of platforms, able to optimize the most important characteristics; for this purpose was studied the possibility to replace the steel arms of a platform using composite materials, this required a new type of design; analyzing the possibilities given by various materials the choice fell on a long-fiber composite reinforced by carbon fiber. The first analyses show that this substitution, combined with new handling systems, allows a significant weight reduction of almost 50%. This permits the implementation and use in extremely high platforms (mainly used in wind power systems, where the dimensions are increasingly growing) that otherwise would not be employable and drivable on the road network. There remain some open issues to be addressed such as fatigue and local buckling and the interaction with the environment. The final aspect is related to the costs, which increase significantly in comparison with the steel, but globally will be profitable if compared to a machine that could not travel on the road due, for example, to the excessive weight.

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