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DYNAMIC ANALYSIS OF A VEHICLE PLATFORM MADE OF COMPOSITE MATERIALS, USING THE FINITE ELEMENT METHOD IN THE DEVELOPMENT OF MATHEMATICAL MODELING

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Abstract. The present work consisted in the discretization of a vehicle platform in finite elements in a simplified way, responsible for representing a generic vehicle, using 12 elements of Kirchhoff Plates (whose thickness is negligible in relation to the other dimensions), with 3 degrees of freedom per node (one vertical displacement and two rotations), aiming at obtaining an adequate mathematical model, determining the natural frequencies and the time responses of the structure. The simulations were performed with three different materials, two composites and 1040 steel. The results obtained show that the structure made with carbon fiber has the highest natural frequencies when compared to the others, a fact that is linked, above all, to the high modulus of elasticity that the material has. Regarding the responses over time, the structure made with e-glass fiber presented the highest amplitudes of oscillation, indicating that the parameters used may not be very suitable to simulate the structure made from this material. In addition, the structure made from carbon fiber proved to be more stable in the simulations, as it returns to the equilibrium situation in a relatively shorter time when compared to the other materials studied.

Keywords: vehicle platform, finite elements, composite materials, suspension

1 Introduction

1.1 Composite materials

Composite materials can be defined as multiphase materials consisting of two phases combined on a macroscopic scale, exhibiting a significant proportion of the properties of the phases that constitute them, as defined by Callister [1]. Thus, these materials have a superior performance to the constituent materials when acting in isolation.

According to Tita [2], the great advantages offered by composite materials are: low weight associated with high rigidity and mechanical strength, great versatility in molding the material and high probability of cost reduction. Due to these characteristics, these materials are increasingly being used in various productive sectors, such as aeronautics, automobiles and civil construction, for example.

Most composite materials have only two phases, called matrix and reinforcement. Generally, according to Campbell [3], the reinforcement (or dispersed phase) is the phase responsible for promoting the properties of hardness and stiffness to the final material, while the matrix (or continuous phase) seeks to hold the reinforcement together and transmit the applied load to it. In addition, composite materials can be classified, according to Callister [1], into three main divisions: particle-reinforced composites, fiber-reinforced composites and structural composites, with subdivisions referring to each branch. Particulate composites are generally weaker and less rigid compared to fiber-reinforced composites, although they are also generally much less expensive, as proposed by Campbell [3]. The composite materials that have the greatest technological relevance for applications in the aeronautical and automotive industries are those that have the dispersed phase in the form of fibers, given that they have high stiffness in relation to weight. This combination of materials is necessary to achieve properties that are not found in conventional materials. Thus, composites reinforced with high strength fibers and presenting relatively high specific modules were produced, using low density materials for the fiber and matrix, generating light structures.

1.2 Fibers

According to Campbell [3], fibers can be defined as a filamentous structure (having lengths much greater than their diameters) in which their orientation is related to the properties of the material. Above all, according to Callister [1], it is known that the mechanical behavior of a fiber-reinforced composite material depends mainly on its properties and on the degree to which loads applied to this material are transferred to the fibers by the bond with their headquarters. Generally, the fibers have lengths much greater than their diameters, as it is in these cases that a significant improvement in strength is noticed.

Elastic properties, such as modulus of elasticity, shear modulus and Poisson's ratio, are extremely important when considering composite materials for design. Although they are fewer common materials, they have more desirable mechanical properties than homogeneous materials in many load design situations. Therefore, for future calculations of this work, it is necessary to determine these properties using the Mixture Rule defined by Vinson and Sierakowski [4].

1.3 Vehicle dynamics

For engineering projects, it is necessary that, in addition to the availability of these materials, analyzes of the dynamic behavior of components manufactured from these materials are carried out. There are, for example, part of the automotive components that, in the test stage, it is verified that they resonate with the rotation range of the system, with the need to increase or decrease mass and/or rigidity to change the natural frequencies. According to Chung [5], these materials with high rigidity can leave the natural frequencies outside the rotation range, considering the design characteristics.

2 Methodology

2.1 Finite Element Method (FEM)

Basically, one can define the analysis of any structure by the Finite Element Method as a numerical technique. From this method, it is possible to build mathematical models of relatively complex mechanical systems. By dividing the system into a finite number of elements (as the name suggests), it is possible to determine the mathematical equation to describe the behavior of the structure, obtaining static and dynamic parameters.

In the Finite Element Method, it is possible to introduce all the complexities that a real problem presents, that is, its geometry, its physical parameters, the acting forces, among others. However, because it is a numerical method, it is worth mentioning that the solutions found are approximations.

To perform the computer simulations, the plate was modeled by Finite Elements of Kirchhoff plates (when the dimensions are considerably high in relation to the thickness). According to Dawe [6], the mass matrix [M] of this plate element is given by eq. (1).

$$[M] = \frac{\rho \cdot h \cdot a \cdot b}{6300} \cdot \begin{bmatrix} m_{1,1} & & & & & & & & & & & \\ m_{2,1} & m_{2,2} & & & & & & & & & & \\ m_{3,1} & m_{3,2} & m_{3,3} & & & & & & & & & \\ m_{4,1} & m_{4,2} & m_{4,3} & m_{1,1} & & & & \text{Simetric} & & & & \\ m_{4,2} & m_{5,2} & m_{5,3} & m_{2,1} & m_{2,2} & & & & & & & \\ -m_{4,3} & -m_{5,3} & m_{6,3} & -m_{3,1} & -m_{3,2} & m_{3,3} & & & & & & \\ m_{7,1} & m_{7,2} & m_{7,3} & m_{10,1} & m_{10,2} & -m_{10,3} & m_{1,1} & & & & & \\ -m_{7,2} & m_{8,2} & m_{8,3} & m_{11,1} & m_{11,2} & -m_{11,3} & -m_{2,1} & m_{2,2} & & & & \\ -m_{7,3} & m_{8,3} & m_{9,3} & -m_{12,1} & -m_{12,2} & m_{12,3} & -m_{3,1} & m_{3,2} & m_{3,3} & & & \\ m_{10,1} & m_{10,2} & m_{10,3} & m_{7,1} & m_{7,2} & -m_{7,3} & m_{4,1} & -m_{4,2} & -m_{4,3} & m_{1,1} & & \\ -m_{10,2} & m_{11,2} & m_{11,3} & m_{8,1} & m_{8,2} & -m_{8,3} & -m_{5,1} & m_{5,2} & m_{5,3} & -m_{2,1} & m_{2,2} & \\ m_{10,3} & -m_{11,3} & m_{12,3} & -m_{9,1} & -m_{9,2} & m_{9,3} & -m_{6,1} & m_{6,2} & m_{6,3} & m_{3,1} & -m_{3,2} & m_{3,3} \end{bmatrix} \quad (1)$$

Being ρ the density of the material, h the thickness of the plate, and finally the two sub-indices of the elements within the matrix, first indicates the row, and the column for the second. Being that: $m_{1,1}$ = 3454, $m_{2,1}$ = 922b, $m_{2,2}$ = 320b^2, $m_{3,1}$ = 922a, $m_{3,2}$ = 252ab, $m_{3,3}$ = 320a^2, $m_{4,1}$ = 1226, $m_{4,2}$ = 398b, $m_{4,3}$ = 548a, $m_{5,2}$ = 160b^2, $m_{5,3}$ =168ab, $m_{6,3}$ = -240a^2, $m_{7,1}$ = 394, $m_{7,2}$ = 232b, $m_{7,3}$ = 232a, $m_{8,2}$ = -120b^2, $m_{8,3}$ = -112ab, $m_{9,3}$ = -120a^2, $m_{10,1}$ = 1226, $m_{10,2}$ = 548b, $m_{10,3}$ =398a, $m_{11,2}$ = -240b^2, $m_{11,3}$ = -168ab, $m_{12,3}$ = 160a^2.

Furthermore, still according to Dawe [6], the stiffness matrix of this element [K] is given by eq. (2).

$$[K] = \frac{D}{60ab} \cdot \begin{bmatrix} k_{1,1} & & & & & & & & & & & \\ k_{2,1} & k_{2,2} & & & & & & & & & & \\ k_{3,1} & k_{3,2} & k_{3,3} & & & & & & & & & \\ k_{4,1} & k_{4,2} & k_{4,3} & k_{1,1} & & & & \text{Simetric} & & & & \\ k_{4,2} & k_{5,2} & 0 & k_{2,1} & k_{2,2} & & & & & & & \\ -k_{4,3} & 0 & k_{6,3} & -k_{3,1} & -k_{3,2} & k_{3,3} & & & & & & \\ k_{7,1} & k_{7,2} & k_{7,3} & k_{10,1} & k_{10,2} & -k_{10,3} & k_{1,1} & & & & & \\ -k_{7,2} & k_{8,2} & 0 & k_{11,1} & k_{11,2} & -k_{11,3} & -k_{2,1} & k_{2,2} & & & & \\ -k_{7,3} & 0 & k_{9,3} & -k_{12,1} & -k_{12,2} & k_{12,3} & -k_{3,1} & k_{3,2} & k_{3,3} & & & \\ k_{10,1} & k_{10,2} & k_{10,3} & k_{7,1} & k_{7,2} & -k_{7,3} & k_{4,1} & -k_{4,2} & -k_{4,3} & k_{1,1} & & \\ -k_{10,2} & k_{11,2} & 0 & k_{8,1} & k_{8,2} & -k_{8,3} & -k_{5,1} & k_{5,2} & k_{5,3} & -k_{2,1} & k_{2,2} & \\ k_{10,3} & 0 & k_{12,3} & -k_{9,1} & -k_{9,2} & k_{9,3} & -k_{6,1} & k_{6,2} & k_{6,3} & k_{3,1} & -k_{3,2} & k_{3,3} \end{bmatrix} \quad (2)$$

The sub-indices are analogous to the mass matrix. Also, the values of k are (being ν the Poisson's coefficient): $k_{1,1}$ = 60p + 60p^{-1} + 42 -12ν, $k_{2,1}$ = b(60p + 6 + 24 ν), $k_{2,2}$ = b^2(80p + 16 - 16ν), $k_{3,1}$ = a(60p^{-1} + 6 + 24 ν), $k_{3,2}$ = 60νab, $k_{3,3}$ = a^2(80p^{-1} + 16 - 16 ν), $k_{4,1}$ = 30p – 60p^{-1} – 42 +12 ν, $k_{4,2}$ = b(30p – 6 - 24 ν), $k_{4,3}$ = a(-60p^{-1} -6 + 6 ν), $k_{5,2}$ = b^2(40p - 16 + 16 ν), $k_{6,3}$ = a^2(40p^{-1} - 4 + 4 ν), $k_{7,1}$ = -30p – 30p^{-1} + 42 - 12ν, $k_{7,2}$ = b(-30p + 6 - 6 ν), $k_{7,3}$ = a(-30p^{-1} + 6 - 6 ν), $k_{8,2}$ = b^2(20p + 4 - 4 ν), $k_{9,3}$ = a^2(20p^{-1} + 4 - 4 ν), $k_{10,1}$ = -60p + 30p^{-1} - 42 + 12ν, $k_{10,2}$ = b(-60p - 6 + 6 ν), $k_{10,3}$ = a(30p^{-1} - 6 - 24 ν), $k_{11,2}$ = b^2(40p - 4 + 4 ν), $k_{12,3}$ = a^2(40p^{-1} -16 + 16 ν).

The parameters p and D are presented in eq. (3) and eq. (4), respectively.

$$p = \left(\frac{a}{b}\right)^2 \quad (3)$$

$$D = \frac{E \cdot h^3}{12 \cdot (1 - \nu^2)} \quad (4)$$

In order for the element to be represented in this way, some considerations were taken: the plate thickness is insignificant when compared to the length and width dimensions; the deflection of the plate is minimal compared to the thickness of the plate, and the slope of the deflected midplane is small compared to unity; the deformation of the plate is such that straight lines that are initially normal to the middle surface remain straight and normal to the middle surface in the loaded structure; and there are no stresses on the middle surface of the plate.

To carry out the simulations, the vehicle platform system was divided into 12 plate elements, containing 20 nodes and presenting three degrees of freedom per node (one vertical displacement and two rotations). Furthermore, the 4 degrees of freedom of the wheels were considered, thus totaling 64 degrees of freedom. Figure 1 presents a representation of the system used in the simulations. It is worth mentioning that all simulations were performed using the MATLAB software.

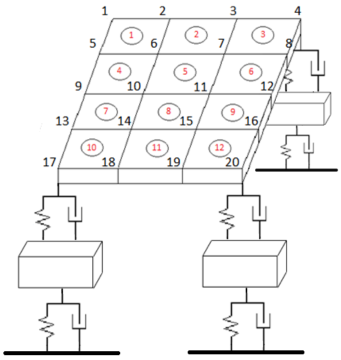

Figure 1. System discretized by the Finite Element Method.

2.2 Idealization of materials

To carry out the simulations using composite materials, initially, the properties of a matrix with two different types of fibers were calculated. In this case, the two materials studied were the Epoxy Resin with the E-Glass fiber and the same resin with the Carbon fiber. The determination of these properties was performed using the Mixture Rule, proposed by Vinson and Sierakowski [4], considering an ideal component (orthotropic, homogeneous, perfect adhesion, plane stress state in the laminae and properties according to the orientation of each lamina).

For the two composite materials studied, a matrix volumetric fraction V_m of 0.4 was used and for the fiber V_f of 0.6. The properties calculated for each of these composite materials are found in Tab. 1.

Table 1. Properties of composite materials from the Mixture Rule.

Property	Epoxy Resin + Glass Fiber E	Epoxy Resin + Carbon Fiber
Longitudinal E [GPa]	46.2	139.8
Transversal E [GPa]	12.4	7.3
G [GPa]	5.34	5.72
ν	0.31	0.34
ρ [g/cm³]	2.04	1.53

According to Hull and Clyne [7], high-performance polymer composites consist of laminates stacked in a predetermined arrangement. To carry out this work, it was assumed that these laminates are homogeneous and that the entire fiber arrangement is uniform. In addition, it was considered that there is also a perfect adhesion between the matrices and fibers, in other words, the presence of imperfections or discontinuities between both constituent materials was disregarded. In addition, for comparative purposes, 1040 steel was also used in the simulations.

3 Results and Discussion

Initially, to carry out the numerical simulations, the parameters regarding the vehicle platform were defined, as shown in Fig. 2.

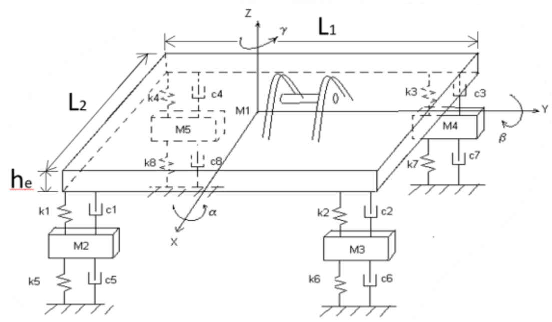

Figure 2. Vehicle platform model.

Table 2 presents the values of each of these parameters. As can be seen from the values shown in it, the use of Kirchhoff Plates for the discretization of the plate in Finite Elements is adequate, considering that the plate thickness is much smaller when compared to the other two dimensions.

Table 2. Properties of composite materials from the Mixture Rule.

Parameter Value	Parameter Value
$L1$	1 m
$L2$	0.6 m
he	0.01 m
$m2 = m3 = m4 = m5$	0.6 kg
$k1 = k2 = k3 = k4$	5000 N/m
$c1 = c2 = c3 = c4$	80 N.s/m
$k5 = k6 = k7 = k8$	5000 N/m
$c5 = c6 = c7 = c8$	50 N.s/m

Furthermore, the existence of an unbalance force in the system of the type $F = m_o e\, \Omega^2 sin(\Omega t)$ was considered, being applied to node 10 of the structure shown in Fig. 1. The amount of unbalance in the system was considered equal to 10 kg.m and with an angular velocity equal to 2 rad/s.

3.1 Natural frequencies

Initially, the first five natural frequencies were calculated for each vehicle platform composed of a composite material. In addition, it was compared with the natural frequencies of the same structure, however composed of 1040 steel material. Table 3 presents the results obtained.

Table 3. Natural frequencies of the materials studied.

Material	1st Natural Frequency (Hz)	2nd Natural Frequency (Hz)	3rd Natural Frequency (Hz)	4th Natural Frequency (Hz)	5th Natural Frequency (Hz)
Epoxy Resin + Carbon Fiber	6.20	11.14	25.78	49.33	65.09
Epoxy Resin + Glass Fiber E	4.13	8.59	15.75	18.14	28.97
1040 steel	2.86	5.25	14.16	15.44	30.72

The analysis of Tab. 3 shows that the vehicle platform composed of the composite material from Carbon Fiber is the structure that presents higher natural frequencies when compared to the Glass Fiber – E composite material. This is mainly due to the high modulus of elasticity that this material has. The determination of these natural frequencies is important in order to avoid the phenomenon of resonance. Thus, from these values and the excitation of the system that the developed project will be used, changes can be made in the mass and rigidity values of the system so that it stays outside the rotation ranges. This can be done, for example, by adding elements of other materials at specific points located along the platform, in order to change the global matrices [K] and [M], which will also affect the values of the natural frequencies of the structure.

3.2 Responses over time

Considering the existence of an imbalance in the system as mentioned above, the time responses for each vehicle platform made up of the different materials studied were analyzed. To carry out these simulations, a time span of ten seconds was used, starting from zero. In addition, the time interval between each graphically generated point was less than 0.01 seconds, totaling 1024 steps. Figure 3 presents the results obtained for Carbon Fiber, Glass Fiber – E and 1040 steel.

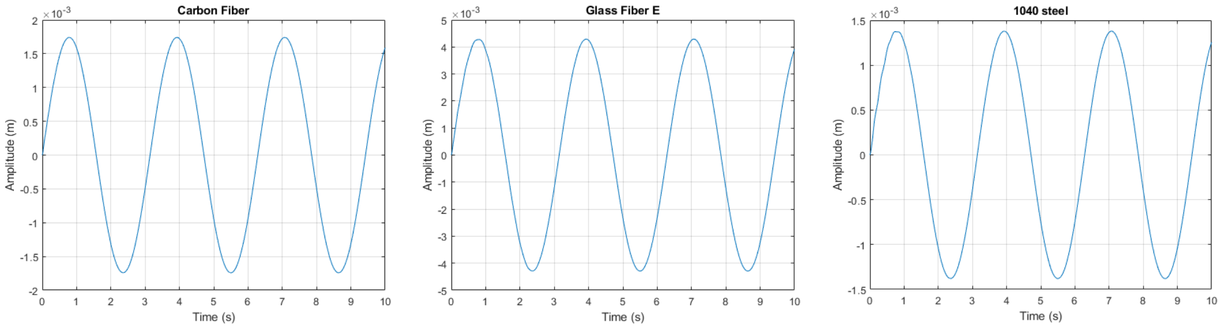

Figure 3. Responses over time for all materials.

Analyzing the time responses obtained for the three vehicular platforms composed of different materials, it is noticed that in the three cases the oscillation amplitudes were relatively low. This can be explained in view of the values of the parameters used, both in relation to the sizing of the plates and the module of the unbalance force of the system. Comparing the time responses obtained for the three vehicular platforms, it can be observed that the structure consisting of the composite material formed by Epoxy Resin and Glass Fiber - E presents the highest oscillation amplitudes (greater than twice as compared to the others), indicating that the parameters used may not be very suitable to simulate the structure made from this material.

In addition, a comparison was also made between the three materials from an initial condition in the structure. For this, an initial (impact) force with a magnitude of 35 N was used. Figure 4 presents the results obtained for the three materials.

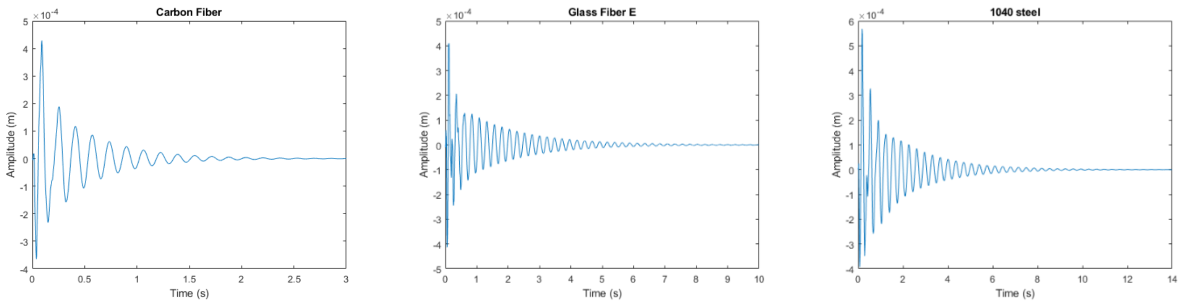

Figure 4. Time response due to initial impact for all materials.

Analyzing the results obtained in general, it is noted that the behavior found is consistent with what was expected, since the energy of the system is being dissipated by the spring-mass system, in order to reduce the amplitude of motion at each time interval. This occurs because there is only an initial influence on the system, in this case, an impact force.

Comparing the responses for each of the materials, it can be observed that the plate made of the composite material formed by the Epoxy Resin and the Carbon Fiber presented a shorter total time to return to the equilibrium situation, in approximately 3 seconds. Therefore, it can be said that this structure is more stable. The suggestion to explain this phenomenon is related to the properties of this composite material made from Carbon Fiber, which combines a high modulus of elasticity with a low density when compared to the other two materials analyzed.

From a general analysis of the results obtained with the simulations, the vehicle platform made of composite material from Carbon Fiber tends to be a more adequate choice. However, in engineering projects, analyzing the cost of manufacturing equipment used in mechanical systems is also of great importance, a point that was not analyzed in this work. Therefore, in addition to the dynamic behavior, the choice of the best material must take into account the costs associated with each one of them. In addition, it is worth mentioning that the parameters and dimensions used in the calculations performed for each structure probably do not converge with those of real cars. However, aiming at a more practical and complete application in a project in the automotive sector, the necessary adaptations can be made.

4 Conclusions

The application of the Finite Element Method proved to be quite adequate to facilitate the study of complex systems, which is the case of a vehicle. By dividing the total system into lower parts, called finite elements, the complexity of the structure is reduced. In this work, using this method, a vehicle platform could be divided into 12 finite elements of Kirchhoff Plates, which made the study less complex and facilitated its understanding.

The study developed in this work also showed the importance of knowing the characteristics, behavior, dynamics and performance of mechanical systems even before their construction. For example, the analysis of the natural frequencies obtained for the materials studied is important so that they do not coincide with the excitation frequencies, that is, with the rotation ranges of the system, in order to avoid the phenomenon of resonance.

Regarding composite materials, the plate made from Carbon Fiber presented higher natural frequencies in relation to E-Glass Fiber, a fact that can be explained in view of its high modulus of elasticity. Furthermore, analyzing the responses over time, it was possible to notice that the Carbon Fiber makes the structure more stable, considering that it returns to its equilibrium position in a shorter time when compared to the other materials studied. However, it is worth mentioning that, in design matters, it is also necessary to evaluate the relative costs for each material, since the value of Carbon Fiber is 5 times the value of Glass Fiber-E.

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References

[1] Callister, W. “Ciência e Engenharia de Materiais: uma introdução”. Rio de Janeiro: Technical and Scientific Books S.A, 2002.
[2] Tita, V. “Análise diâmica teórica e experimental de vigas fabricadas a partir de materiais compósitos poliméricos reforçados”. 1999. Dissertation (Master in Computer Science) - Federal University of São Carlos, São Carlos.
[3] Campbell, F. C. “Structural Composite Materials”. Ohio: ASM International, 2010.
[4] Vinson, J. R.; Sierakowski, R. L. “The Behaviour os Structures Composed of Composite Materials”. New York: Kluwer Academic Publishers, 1996.
[5] Chung, D. D. L. “Composite Materials: science and applications”. New York: Springer, 2009.
[6] Dawe, D. J., “Matrix and finite element displacement analysis of structures”. Oxford: Clarendon, 1984.
[7] Hull, D.; Clyne, T. W. “An Introduction to Composite Materials”. Cambridge: Cambridge University Press, 1996.