A NUMERICAL ANALYSIS ABOUT THE BEHAVIOR OF A RESIN EPOXY BASED COMPOSITE SUBJECTED TO MECHANICAL SHOCKS

Iago Pereira Lemos
Tobias Souza Morais
Federal University of Uberlândia - Faculty of Mechanical Engineering
João Naves de Ávela Avenue - 2121, Uberlândia, Minas Gerais, Brazil
lemosiago123@gmail.com
tobias.morais@gmail.com

Abstract. The objective of this work is to numerically study the behaviour of a composite material subjected to mechanical shocks. Where analyzed structure is a system with composed by an aluminium beam and an epoxy resin used to glue the beams. The goal here is to evaluate the stress propagation in the region where the glue is located when subjected to mechanical waves generated by the collision of an object at one end of the structure. The direction of the collision is considered longitudinal, therefore this type of waves are in center of the presented analysis. Thus, in this study is evaluated the effect of the mechanical properties changes of the glue by mixing it with an inert compound aiming to reduce the effects caused by the acoustic impedance differences between the materials. To perform this study, the softwares SolidWorks 2018® and Ansys Workbench 17.0® with the Explicit Dynamics package are used. The first one to create a 3D model, and the second one to perform the explicit simulations. From the obtained results, it is determined a maximum percentage of improvement in comparison to the decreased main stresses in the analysis for different mixtures.

Keywords: Mechanical Waves, Epoxy Resin, Numerical Analyses, Acoustic Impedance and Explicit Dynamics.

1. INTRODUCTION

The aeronautical and aerospace sectors are constantly evolving. Every day new technologies emerge in order to find solutions and meet the demands of the industry. In these areas, for instance, the request to reduce the final product weight ensuring an improvement in transportation load and efficiency is one of the biggest challenges faced by the aircraft manufacturers.

In this scenario, we have as main alternative the composite materials. According to Rezende and Botelho (2000), since the 1960s, composite materials were introduced in the aerospace industry and the use of these materials is growing every year due to its excellent mechanical properties that, in contrast to any metallic component, have good advantages when the cost or the weight over the resistance ratio of the material takes important place to the designed structure.

In this way, it is possible to observe that the substitution of aluminium by structural polymeric composites, for example, which allows a weight reduction of 20 to 30%, besides 25% in reducing the final cost of the obtaining parts. This category of materials has numerous applications within the aerospace and aeronautics fields. The polymer matrices of the reinforcements are, in general, 40% of the epoxy type (Rezende and Botelho, 2000). In this way, it can be considered that epoxy type resins are strongly present in aircraft and aerospace structures.

Entering in the world of epoxy resins and their presence in the aerospace and aeronautical products, their applications are extensive used as polymer matrices, as well as adhesives for bonding metallic components, motor cases and hardware compounds. According to Neto (2016) epoxy resins are widely used in the aerospace and aeronautic industries as adhesive to unite components, promoting a weight reductionof the overall component, which results in a decreased fuel consumption and greater technical and financial feasibility of aircraft projects. Also, the author affirms that the bonding made by this material presents great resistance to compressive stresses and hardly they fail due to that. The same thing does not occur in tensile stresses, whose glues present less resistance, 56% when compared to the previous situation.

Aeronautical structures are always subjected to aerodynamic loads, which generates tensions in these structures. In this context, we have come to the greatest obstacle in the use of these materials in these sectors: Security. With our current technology it is complex to predict, with the level of security required, when an union by a polymeric adhesive will fail. These aerodynamic loads induce the propagation of different type of stresses in the aircraft's structures, which propagate through it by the mechanical waves form to the energy transfer. When passing from a material to another, the acoustic impedance difference makes a certain amount of the incident energy to be transferred and another quantity reflected (Kinsler *et al.*, 2000). Thus, in the analysis scope, the mechanical stress waves meet different means exactly in the union of the metallic components, which makes the study of the behaviour of this union extremely necessary, with the

aim of improving the applications and reducing the risks of failure.

2. METHODOLOGY

Based on the above, a 3D structure composed by aluminum and epoxy material is modeled in the commercial software SolidWorks 2018®.

In order to evaluate the propagation behavior due to the material impedance change, the resin epoxy is mixed with different concentrations of graphite. In place to propitiate the propagation of three-dimensional mechanical waves in the longitudinal direction an impact in this direction is performed by a sphere at free end of the component. The solution of the differential equation that governs the wave propagation stress is performed by an explicit dynamic analysis using the software Ansys Workbench 17.0®, where it is possible to observe the stress fields concentrated by the acoustic impedance difference in the glue region for each composition of the tested glue.

The next subsections present the geometry modeling and the model validation used in this work. Also, it is presented a description of the different concentration of graphite adopted with the epoxy resin and the methodology used implement the explicit dynamics model

2.1 Geometry Modeling

It consists of two identical aluminum beams united by an epoxy resin. In one extremity of one beam, a steel massive sphere is located which, it is responsible for the collision. Considering the centroidal axis of the sphere coincides with the geometric center of the beam extreme face, and the impact direction occurring in the longitudinal direction, the main propagation stress direction is considered on the same longitudinal direction of the component.

The aluminum beams and the glue have the same transversal section, a square of $(10x10) \times 10^{-3}$ m. The aluminum beam length is, 50×10^{-3} m, and the glue length is 1×10^{-3} m. The diameter of the sphere is 0.005 m. In the Fig.1, it is possible to see a renderization of the modeled structure in an isometric view.
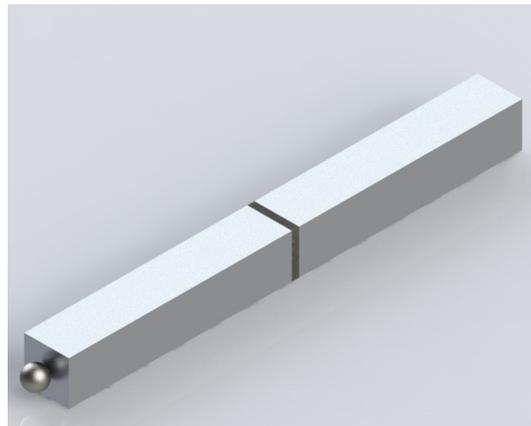

Figure 1: The idealized structure renderization in an isometric view.

It was considered five cells to model the whole structure. As the periodic properties of the structure related to the propagation or attenuation bands are not herein investigated, the number of cells were adopted without any pre-analysis. The divisions are shown in the Fig.2.
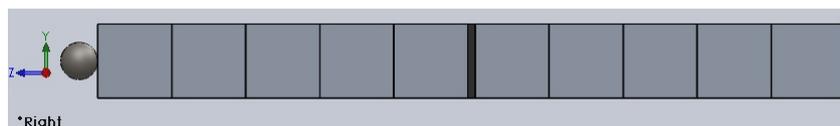

Figure 2: Divisions in the beams in order to facilitate the next analyses. The image was captured in the SolidWorks 2018® software.

2.2 Model Validation

Before starting any numerical analysis utilizing the glue, it is necessary to determine, initially, the mesh size of the model that will be applied to the posterior analyses. For this, it is utilized the propagation velocity of the sound in aluminum medium as a control parameter, just the aluminum material was employed in order to keep the same material impedance on the system and due to its higher velocity compared to the glue wave propagation velocity, which give the lower mesh size. To conduct the comparison of the model wave velocity against the theoretical wave velocity, it is

necessary to obtain the theoretical value for this parameter. The wave propagation velocity in an isotropic solid in which the dimensions are larger than the wave length is obtained by the Eq. (1) (Kinsler *et al.*, 2000). This way, an analysis was carried out in order to determine the mesh size until the control parameter reached an acceptable value. To perform this analysis, an initial velocity in the longitudinal direction of the structure is applied on the sphere creating a collision between the sphere and the extreme face of the beam. With this, it was determined the mesh parameters of the posterior simulations. The initial velocity applied at the sphere was 10 m/s, and for this first analysis, attempting to determine a representative mesh size.

$$c^2 = \frac{K + \frac{4}{3}G}{\rho} \qquad (1)$$

Where K is the Bulk Modulus, G is the Shear Modulus and ρ is the material density.
Bower (2009) affirms that K and G may be rewritten as the Eq.(2) and Eq.(3).

$$K = \frac{E}{3(1 - 2\upsilon)} \qquad (2)$$

$$G = \frac{E}{2(1 + \upsilon)} \qquad (3)$$

Where E is the Young's Modulus and υ is the Poisson's Ratio.
With the Eq.(1), Eq.(2) and Eq.(3) it is possible to define a single expression for the wave propagation velocity in an isotropic solid in function of the Young's Modulus, material density and the Poisson's Ratio, which is given by the Eq.(4).

$$c^2 = \frac{E(1 - \upsilon)}{\rho(1 - 2\upsilon)(1 + \upsilon)} \qquad (4)$$

By means of the Ansys Workbench 17.0® material library and the Eq.(4), it was possible to obtain the theoretical wave propagation velocity in the aluminum. The theoretical wave propagation velocity obtained is $c \approx 6163\ m/s$.
The respective properties values are in the Table 1.

Table 1: Properties values for the aluminum alloy utilized to determine the theoretical wave propagation velocity

Aluminun Alloy Properties	
Density (kg/m^3)	2770
Young's Modulus (Pa)	7.1E+10
Poisson's Ratio	0.33

In order to compute the wave propagation velocity on the model, it was set up three $Probes$ in different faces of the subdivided beam. By setting the $Probes$ in the geometric centers of each face, it is possible to obtain the time when the maximum stress happens. Utilizing the length of each block, it is easy to determine the medium velocity of the wave by determine the time when the maximum stress happens and the distance from one probe to another.
Various simulations were done and the main parameters that presented the best results are in the Table 2. The rigid contact of each block was set as $Bonded$ and the extreme face against the shock face was fixed as an boundary condition.

Table 2: Main parameters determined to perform the simulations and the model validation.

Simulation Parameters	
Beam Element Size (mm)	0.225
Sphere Element Size (mm)	3
End Time (s)	0.000021
Result of Points	400
Mesh Method	Sweep

The Fig.3 shows the position of each $Probe$ on the face where it is located. The maximum stress and the corresponding time of the $Probe\ 1$, $Probe\ 2$ and $Probe\ 3$ were determined. By knowing the distance between each probe, it is possible to calculate the wave stress velocity. The medium velocities of the wave propagation is shown in the Table 4. The mean velocity value of the medium is $V_{mean} = 6237.67\ m/s$. The percentual error in relation to the theoretical velocity value is 1.22 %.
The time of the maximum stress in each probe is shown in the Table 3

Table 3: Time corresponding to each maximum stress found in each Probe.

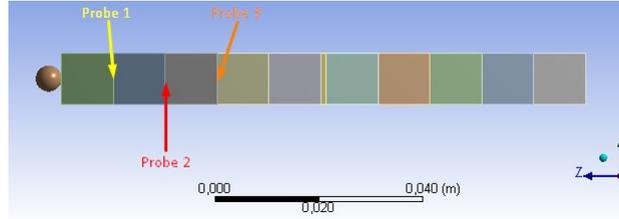| Probe	Time (s)
$Probe1$	0.000016763
$Probe2$	0.000018395
$Probe3$	0.000019970

Figure 3: Positions of each $Probe$ employed in the analysis. The image was captured in the Ansys Workbench 17.0® software.

The medium velocities of the wave propagation is shown in the Table 4.

Table 4: Medium Velocity obtained for each distance.

Distance	Medium Velocity (m/s)
$Probe_{1-2}$	6127.45
$Probe_{1-3}$	6236.35
$Probe_{2-3}$	6349.00

Considering that the percent error is acceptable, the mesh parameters in the Table 2 were fixed for the next analyses.

2.3 Matrix Composite Modeling

The first analysis is made using only the epoxy resin properties as the glue, which is presented in the Ansys Workbench 17.0® library. For the new composite, it is considered to insert a dispersed phase of graphite particles in the glue, because this material presents a good Young's Modulus and an easy insertion in the matrix. The insertion is done by adding different concentrations of graphite powder in the glue. It was considered 2, 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50% of graphite.

For each different epoxy and graphite concentration a new isotropic material is crated, it is necessary to insert only three properties: Young's modulus, the Poisson's Ratio and the density. For each mixture it is possible to calculate the required properties by means of the Eq.(5), Eq.(6) and, Eq.(7) bu considering the matrix (epoxy resin) and dispersed phase volume fractions of graphite (Gay, 2015):

$$E_{composite} = E_{matrix}V_{matrix} + E_{reinforce}V_{reinforce} \qquad (5)$$

$$v_{composite} = v_{matrix}V_{matrix} + v_{reinforce}V_{reinforce} \qquad (6)$$

$$\rho_{composite} = \rho_{matrix}V_{matrix} + \rho_{reinforce}V_{reinforce} \qquad (7)$$

Where E_{matrix} is the Young's modulus of the matrix, v_{matrix} is the Poisson's Ratio of the matrix, ρ_{matrix} is the density of the matrix, $E_{reinforce}$ is the Young's modulus of the reinforce, $v_{reinforce}$ is the Poisson's Ratio of the reinforce and $\rho_{reinforce}$ is the density of the reinforce. Also, the volumetric fraction can be obtained by:

$$V_{matrix} = \frac{volume_{matrix}}{volume_{total}} \qquad (8)$$

$$V_{reinforce} = \frac{volume_{reinforce}}{volume_{total}} \qquad (9)$$

The matrix properties (epoxy resin) was obtained in the finite element's software library and these properties are shown in the Table 5

The graphite (reinforce) density and Young's Modulus theoretical values are obtained from Poco Graphite (2015) and the Poisson's Ratio was obtained from Politano and Chiarello (2015). The reinforce properties values are shown in the Table 6.

Table 5: Matrix (Epoxy Resin) properties obtained in the Ansys Workbench 17.0® material library.

Property	Value
E_{matrix} (Pa)	3.78E+9
v_{matrix}	0.35
ρ_{matrix} (kg/m^3)	1160

Table 6: Reinforce (Graphite Powder) properties utilized for the composite modeling.

Property	Value
$E_{reinforce}$ (Pa)	1.1031E+10
$v_{reinforce}$	0.19
$\rho_{reinforce}$ (kg/m^3)	2226

With these values, and using the Eq.(5), Eq.(6) and Eq.(7), the properties necessary create the new glue mechanical characteristics were calculated and parameterized in the software. Here is important to observe the new material is an idealized material where just the volumetric fractions of each component governs its mechanical properties.

2.4 The Explicit Dynamics Model

Three principal stresses were analyzed, the stress at the geometric center of the faces of the beams in contact with the glue, the stress at the center of the glue and the maximum tensile stress at the interface of the beam in contact with glue. The Fig.4. shows, respectively, the three regions of analysis..

Table 7: Parameters utilized in the numerical analysis.

Parameter	Value
Sphere Initial Velocity (m/s)	10
End Time (s)	0.000035
Result Number of Points	700
Bem and Glue Element Size (mm)	0.225
Sphere Element Size (mm)	3
Mesh Method	Sweep

Three principal stresses were analyzed, the stress at the geometric center of the faces of the beams in contact with the glue, the stress at the center of the glue and the maximum tensile stress at the interface of the beam in contact with glue. The Fig.4. shows, respectively, the three regions of analysis.
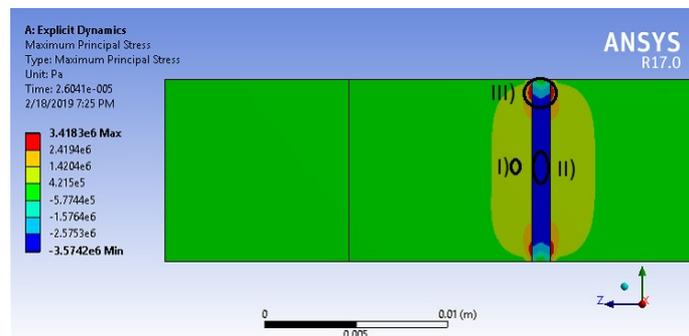

Figure 4: Exemple of the three stress regions analyzed for each composition of the glue.

3. RESULTS AND DISCUSSIONS

The results present the stress propagation through the structure. In Fig.5 it is possible to verify the stress concentrating at the glue region. It happens because, while the wave propagates in the glue region, there is a stress concentration due to the reflections inside the glue. In Fig. 5, it is possible to analyze the stress propagating during the impact. It is observed the positive stresses at the faces of the glue region.

(a) Compressional wave in the beginning of the structure.

(b) The wave starts to find the glue

(c) A little percent of the wave goes to the other beam.

(d) The result tensile and compression stress get the maximum value.
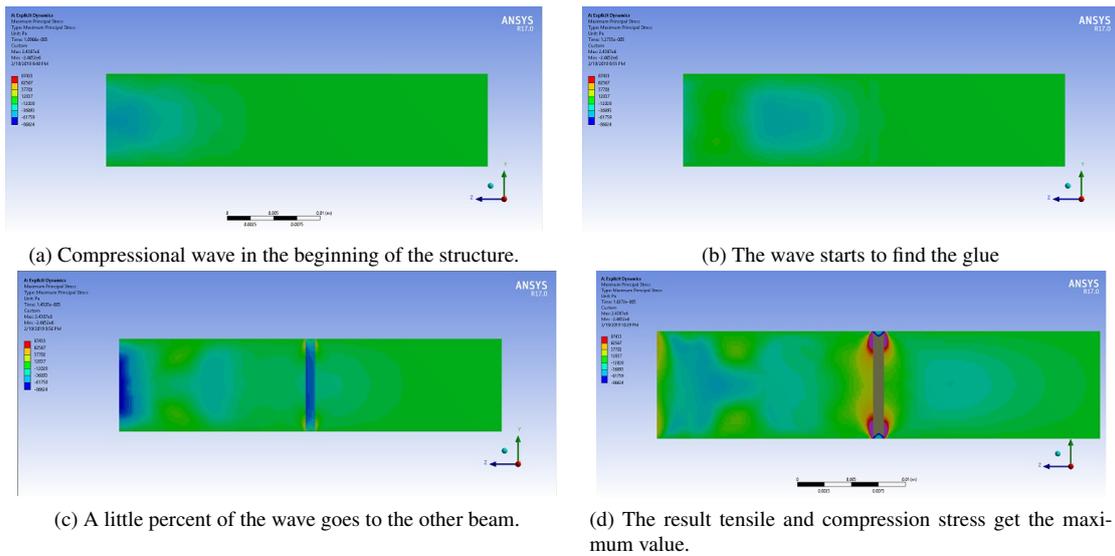
Figure 5: Wave propagation in a structure in which the glue has 45% of its composition of graphite.

Table 8 shows the results after all simulations are done.

Table 8: Simulation results in the three regions of analyses

Compositions	Maximum Stress in the geometric center of the interface (Pa)	Maximum Stress in the geometric center of the glue (Pa)	Maximum Tensiles (Pa)
100% Epoxy Resin	1479100	-4035300	3684900
2% Gr	1420400	-3574200	3418300
5% Gr	1394500	-3493300	3349600
10% Gr	1349000	-3358400	3233000
15% Gr	1303700	-3224700	3115000
20% Gr	1260100	-3092400	3001100
25% Gr	1215800	-2962400	2887100
30% Gr	1171300	-2834500	2773600
35% Gr	1126500	-2708900	2660700
40% Gr	1092000	-2585700	2549000
45% Gr	1037600	-2465200	2438700
50% Gr	993390	-2347000	2329600

Observing the results presented in Table 8, it is possible to see that as the concentration of graphite increases in the glue, the tensile stress decreases. The same happens with the compressive stress in the center of the glue. It happens because the acoustic impedance of the glue increases together with the increasing of graphite in the concentration, proving that the higher Young's modulus of the graphite in relation of the Young's modulus of the epoxy resin helps in the wave propagation and decreases the resulting tensile stress in glue region, thus, turning less critical the difference of acoustic impedance effects.

In this context, for comparison purposes, it was computed the acoustic impedance for each glue compositions by Eq. (10) (Kinsler *et al.*, 2000).

$$z = \rho \times c \tag{10}$$

Where ρ is the material density and c is the wave propagation speed in the material.

Using the aluminum density found in the Table 1 and the velocity computed in Eq. (**??**), it is possible to compute the theoretical impedance for the aluminum given by: $z_{aluminum} = 17070402 \ (kg/s \times m^2)$

Using Eq. (7) and Eq. (4), it was possible to define the acoustic impedance for each glue composition. The Table 9 shows the results.

It is possible, in fact, to say that as the percent of graphite powder increases, the mixture acoustic impedance increases and, this is the main reason that the tensile stress field decreases. This happens because more the mixture acoustic impedance increases, the closer it is to the aluminum one.

Table 9: Acoustic impedance value for each glue composition.

Composition	$z \, (kg/s \times m^2)$
100%Epoxy Resin	2548866.075
2%Gr	2607914.427
5%Gr	2695456.817
10%Gr	2838906.792
15%Gr	2979695.180
20%Gr	3118213.166
25%Gr	3254785.203
30%Gr	3389684.109
35%Gr	3523142.041
40%Gr	3655358.648
45%Gr	3786507.248
50%Gr	3916739.581

Thus, it is determined a maximum percent of improvement in relation to the first and the last analyses, in other words, the analysis with the glue only based in epoxy resin and the analysis made with the glue counting with 50% of graphite. The percentage is approximately 37% of improvement.

Also, it is possible to say that the behavior of the composite after inserting graphite as reinforce is practically linear. For each 5% of graphite that is inserted in the composition of the glue, the maximum tensile decreases approximately 4%.

4. CONCLUSIONS

Based on the theory exposed and using the finite elements software it is possible to conduct a study about how three-dimensional compressional waves propagate in a structure with different materials.

It is proved that the difference of acoustic impedance creates a resulting tensile stress in the interfaces of the glue with the beams. It is possible to confirm that as the concentration of the reinforcer particle increases, smaller are the effects caused by the difference of acoustic impedance, because the acoustic impedance of the glue, obviously, approximates to the aluminum one.

From the obtained results, the maximum percentage of improvement is determined in relation to the first and the last analyses, besides determining an average value that represents the percentage of the decreasing stress for each 5% of inserting graphite in the glue composition. During this analysis, just the properties of the glue which influences directly in wave propagation effect were considered.

5. REFERENCES

Bower, A.F., 2009. *Applied Mechanics of Solids*. CRC Press, 1st edition.

Gay, D., 2015. *Composite Materials Design and Applications*. CRC Press, Boca Raton, 3rd edition.

Kinsler, L.E., Frey, A.R., Coppens, A.B. and Sanders, J.V., 2000. *Fundamentals of Acoustics*. John Wiley & Sons, INC, New York, 4th edition.

Neto, A.S., 2016. *Estudo de tensões e modos de falha no desenvolvimento de adesivos nanomodificados e juntas coladas*. Ph.D. thesis, Universidade Federal de Minas Gerais, Belo Horizonte, Brasil.

Poco Graphite, 2015. "Properties and characteristics of graphite". <http://poco.com/Portals/0/Literature/Semiconductor/IND-109441-0115.pdf>.

Politano, A. and Chiarello, G., 2015. "Probing the young's modulus and poisson's ratio in graphene/metal interfaces and graphite: A comparative study". *DOI 10.1007/s12274-014-0691-9*.

Rezende, M.C. and Botelho, A.C., 2000. "O uso de compósitos estruturais na indústria aeroespacial". *Polímeros vol.10 n.2*.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.