Numerical modeling of the stress-strain behavior of a viscoelastic material in a 2D model by FEM

Modelagem numérica do comportamento tensão-deformação de um material viscoelástico num modelo 2D pela FEM

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ABSTRACT
Numerical modeling of behavior plays an important role in knowing the changes to be made and in optimizing simulation results. Currently, modeling occupies a very necessary place in modern industry for the life study of any problem. This paper deals numerically with the variation and relationship between stress and strain for a model of tensile behavior. In addition, the study is based on the one hand on the number of holes in a plate, and on the other hand by the increase in the tensile load 10, 20 and 30N. The FEM finite element method was used. Additionally, the viscoelastic material was applied. In addition, the parametric mesh has square elements of type (CPS4) bilinear plane stress quadrilaterals, with 4 nodes were used. However, can contribute to a better understanding of the problem of guiding by different numbers of holes concerning viscoelastic behavior for an epoxy material. In addition, this study allows us to know which model is the most resistant
during tightening. The results of the final element method (FEM) numerical model were compared, after application of different loadings, to determine the deformation and stress resulting from these loadings, particularly at the holes. On the other hand, the study showed that there is a relationship between viscosity and stress, and a relationship between deformation and stress according to Hooke's law. The variation and the relationship between the stress-strain is then modeled using the finite element calculation code ABAQUS. In addition, the results obtained concerning the numerical simulation were compared and discussed between the different case studies. A good correspondence was obtained between the different comparison results in all the modeling cases of our work.

**Keywords:** strain, stress, viscoelastic, hole, FEM, CPS4.

**RESUMO**

A modelagem numérica do comportamento desempenha um papel importante no conhecimento das mudanças a serem feitas e na otimização dos resultados da simulação. Atualmente, a modelagem ocupa um lugar muito necessário na indústria moderna para o estudo da vida útil de qualquer problema. Este artigo trata numericamente da variação e da relação entre tensão e deformação para um modelo de comportamento de tração. Além disso, o estudo se baseia, por um lado, no número de furos em uma placa e, por outro, no aumento da carga de tração de 10, 20 e 30N. Foi usado o método de elementos finitos FEM. Além disso, foi aplicado o material viscoelástico. Além disso, a malha paramétrica tem elementos quadrados do tipo (CPS4) quadriláteros de tensão plana bilinear, com 4 nós. No entanto, pode contribuir para uma melhor compreensão do problema de orientação por diferentes números de orifícios em relação ao comportamento viscoelástico de um material epóxi. Além disso, esse estudo nos permite saber qual modelo é o mais resistente durante o aperto. Os resultados do modelo numérico do método do elemento final (FEM) foram comparados, após a aplicação de diferentes cargas, para determinar a deformação e a tensão resultantes dessas cargas, especialmente nos furos. Por outro lado, o estudo mostrou que há uma relação entre a viscosidade e a tensão, e uma relação entre a deformação e a tensão de acordo com a lei de Hooke. A variação e a relação entre a tensão-deformação são então modeladas usando o código de cálculo de elementos finitos ABAQUS. Além disso, os resultados obtidos com relação à simulação numérica foram comparados e discutidos entre os diferentes estudos de caso. Foi obtida uma boa correspondência entre os diferentes resultados de comparação em todos os casos de modelagem de nosso trabalho.

**Palavras-chave:** deformação, estresse, viscoelástico, furo, FEM, CPS4.

**1 INTRODUCTION**

Nowadays, materials occupy a very necessary part in modern industry for the study of the lifespan of all structures. In this context, we can cite some research carried out within the framework of the studies, (Huang et al., 2019) used an improved morphological multi-scale algorithm, to segment the images of adhesive
coarse aggregates of an FE model based on the Embedded image, with damage-coupled viscoelastic asphalt mastic phase and elastic aggregates, using Abaqus simulation software. On the other hand, (Gbadam and Frimpong, 2017) developed a two-dimensional discrete element method (DEM) to model the viscoelastic response of an oil sands formation. In addition, they constructed a digital sample of the oil sand with different particle shapes and sizes by the PFC2D discrete element software. (Warnez and Johnsen, 2015) have developed a comprehensive numerical framework for the dynamics of spherical bubbles in isotropic media, obeying a wide range of viscoelastic constitutive relationships.

A mathematical model of modulus relaxation and its numerical solution has been proposed by (Xu and Engquist, 2018) to develop a finite element (FE). Moreover, they proposed a robust numerical algorithm to simulate responses, under static and dynamic loadings and to find the relationship between stress and strain. (Shen et al., 2019) presented a computational formulation to describe the transient behavior of the viscoelasticity of polymer networks. (Courtois et al., 2019) presented a viscoelastic constitutive model depending on the temperature, and the degree of cure for an epoxy resin, to perform multi-temperature relaxation tests on rectangular epoxy samples. (Marotzke and Feldmann, 2015) have defined epoxy resins as a composite material reinforced with fibers and exhibit a very complex mechanical behavior. (Nosrati et al., 2022) compared the stress dependence of viscoelastic creep behavior for glass/epoxy composite and neat epoxy near the glass transition temperature and room temperature. Moreover, (Saseendran et al., 2016) developed a methodology by two different experimental approaches to analyze the influence and hardening history on the viscoelastic storage modulus. (Younes and Abdel Rahman, 2016) evaluated the tensile relaxation behavior of fiberglass fabric/epoxy composite to study the effects of stress relaxation temperature with respect to ambient temperature.

(Masoud Yekani et al., 2012) developed a piecewise linear parametric uniaxial stress-strain model with a simplified post-peak response to obtain the nonlinear load deflection response of epoxy resin materials.

(Papanicolaou et al., 2016) studied the quasi-static mechanical properties of nano composites, and microcomposites of reinforced epoxy resin composite material, with different weight fractions of a tensile test. On the other hand, (Felipe
et al., 2018) used the different weight fractions of Curaua fiber of an epoxy material, to observe the quasi-static mechanical properties and its physical properties, due to the temperature variation by the method of dynamic mechanical analysis (DMA).

(Asimina Manta et al., 2020) experimentally studied the behavior of a model, in tension and in bending, of a polymer material reinforced with grapheme Nano platelets, to study the average mechanical characteristics of the statistical samples, and the macroscopic stress-strain data. (Müller et al., 2018) presented a new approach that combines elastic and plastic domains. (Tao and Xia, 2007) investigated the effects of average stress and strain on the fatigue life of an epoxy system; furthermore they evolved the stress range and strain energy density.

The purpose of this study is to model the effect, of the load and the number of holes of a tensile behavior model, on the variation of the stress and the deformation of a viscoelastic material, two different cases have been studied. Firstly the change in the load of P= 10, 20 and 30 N and the other case the change in the number of holes on the model studied which equals 0, 1, 2, 3 and 9 holes.

2 ELEMENT MODELING

The elements used in modeling to evaluate the constraint and the deformation, of a Viscoelastic material, in 2D are simple elements (CPS4) quadrilaterals of bilinear plane constraint with 4 nodes.

![Elements (CPS4) 4-node bilinear plane stress quadrilaterals](Source: Authors, Bartosz and Jerzy 2017).

3 MODEL OF MATERIAL

The epoxy matrix is considered a viscoelastic material. Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. (Brinson and Brinson, 2015) defined that viscoelastic materials show both stress relaxation and creep deformation. Additionally, the behavior of this material is strain rate dependent, and the loading history affects
the material's response to current loading. The modulus \( G(t) \) is used to define the stress relaxation is defined by an extension of the Prony series as:

\[
G(t) = G_0 \left(1 - \sum_{i=1}^{n} g_i \left(1 - e^{-\frac{t}{\tau_i}}\right)\right)
\]  

(1)

Where:

\( G_0 \): Instantaneous shear modulus  
\( \tau_i \): Time of relaxation  
\( g_i \): Modulus de relaxation  
\( g_i \) and \( \tau_i \) are material constants defined in table 1.

4 MATERIAL PROPERTIES (EPOXY)

4.1 PRONY SERIES PARAMETERS

Prony series parameters of the material are presented in the table 1.

<table>
<thead>
<tr>
<th>( g_i )</th>
<th>( \tau_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0738</td>
<td>463.4</td>
</tr>
<tr>
<td>0.1470</td>
<td>0.06407</td>
</tr>
<tr>
<td>0.3134</td>
<td>0.0001163</td>
</tr>
<tr>
<td>0.3786</td>
<td>( 7.321 \times 10^{-7} )</td>
</tr>
</tbody>
</table>

Source: Authors, (Liu et al., 2013).

4.2 INSTANT ELASTIC PROPERTIES

The instantaneous elastic properties of the material are presented in the following table.

| \( G_0 \) | 1481.8MPa |
| \( E \) Module de Young | 4060.1MPa |
| \( V_0 \) Coefficient Poisson | 0.37 |
| \( \rho \) | \( 1.18 \times 10^9 \) tonne/mm\(^3\) |

Source: Authors, (Shank et al., 2018)

5 VISCOUS MODEL

The relationship between stress and viscosity is given by:
\[ \sigma = \eta \frac{d\varepsilon}{dt} \] \hspace{1cm} (2)

Where:

\( \sigma \): is the stress  
\( \eta \): is the viscosity of the material  
\( \frac{d\varepsilon}{dt} \): is the time derivative of the strain.

**6 STRESS-STRAINS RELATIONSHIP**

**6.1 HOOKE’S LAW**

The linear relationship between stress and strain, for a bar in simple tension or compression is expressed by the following equation:

\[ \sigma = E \varepsilon \] \hspace{1cm} (3)

Where:

\( \varepsilon \): is the deformation of an elastic problem  
\( \sigma \): is the stress of an elastic problem

**7 RESULTS AND DISCUSSIONS**

A tensile behavior model was modeled in our work, the model considered has a length \( L = 50 \) mm and a height \( h = 10 \) mm, in the case where the structure without holes the mesh is structured and composed of 500 square elements of plane stress with four nodes of the type (CPS4) and 561 nodes. The properties of the Epoxy material are illustrated in the tables above. Prony series parameters see (Table 1) and instantaneous elastic property see (Table 2). The analysis is done by the finite element code ABAQUS. The boundary conditions of the simulation to evaluate the stress and the deformation are the following: the embedding was applied on the right part of the structure \( (U_1 = U_2 = U_3 = UR_1 = UR_2 = UR_3 = 0) \), and the part left is subjected to a tensile stress \( P = 10, 20 \) and \( 30 \) N see figure 3(a), the hole diameter \( d = 3 \) mm for the different examples of 1, 2, 3 and 9 holes, except the first model which does not contain a hole.
7.1 CASE OF A MODEL WITHOUT A HOLE

Figure 4(a) presents the model of a tensile behavior, concerning the studied viscoplastic material, this figure presents the model in the case without hole with a structured mesh.
Figure 5. The variation of stress and strain with actual distance along the path: a) stress11, b) stress22, c) strain 11, d) strain 22, and e) stress versus strain for a model with no holes

Source: Authors.

Figure 5 shows the evolution of the stress and strain in the three cases of the load of $p=10$, 20 and 30N, concerning the behavior of the viscoelastic material in tension, note that the increase in the load causes an increase in stress and deformation. Indeed, from this illustration, we can notice that the elastic part is always linear. Figure 5(e) shows the relationship between stress and strain of the tensile behavior model in the no-hole case. On the other hand, the results obtained are proportional in the three cases of the load. Thus, it is shown that the values of the constraint is much higher than that of the deformation, for the modeling of the problems in viscoplastic.

7.2 CASE OF A SINGLE HOLE PATTERN

We consider the proposed model consists of 690 elements and 765 nodes, of a viscoelastic material Epoxy, in the case of a single hole.
The variation of stress and strain as a function of the real distance along the path, for the studied model is presented in Fig. 7. The different tensile loads \( P = 10, 20 \) and \( 30N \) have been applied. In effect, we notice that the increase in the load causes an increase in the stress and strain, and the increase in the values of the real distance along the path causes an increase in the strain and stress. Moreover,
there is also another analysis regarding figure 7(e) based on the variation of stress as a function of strain, the increase in strain causes an increase in stress, a linear part is called the elastic part of the material viscoelastic starts from point 1 to point 2 of all the graphs of the model, but from the fourth point we can notice that there is a constant state. These forms of the results were obtained by (Volgers and Anders, 2017) in the case of the stress-strain curves of the treatment of multilayered plastic materials, nominal stress - nominal strain.

7.3 CASE OF A TWO-HOLE MODEL

We propose in this part a modeling model of a viscoelastic material (Epoxy) presented on figure 8(a), to evaluate the stress and the deformation. The model consists of 777 elements and 866 nodes in the case of two holes with a diameter of 3 mm.

Figure 8. Finite element model of tensile behavior: a) two-hole mesh, b) S11, c) S22, d) E11 et e) E22

Source: Authors.
Figure 9 shows the different stress values and the strain, as a function of the actual distance along the path of the behavior model, in tension which contains two holes of a viscoelastic material (Epoxy). However, an increase in the stress-strain, except figure 9(e) which presents the variation of stress according to strain, there is a stability of the results from the fifth point.

7.4 CASE OF A THREE-HOLE MODEL

We present in this example, the model of a behavior in tension concerning the material of my choice which is viscoplastic. The number of elements is 866 and the number of nodes is 969, the three-hole pattern with the same diameter of 3mm. Figure 10(a) below explains this problem.
Figure 10. Finite element model of tensile behavior: a) three-hole mesh, b) S11, c) S22, d) E11, and e) E22

Source: Authors.

Figure 11. The variation of stress and strain with actual distance along the path: a) stress11, b) stress22, c) strain 11, d) strain 22, and e) stress versus strain regarding a model that contains three holes

Source: Authors.

Figure 11 shows the evolution of stress and strain as a function of actual distance along the path. It can be noted that the results obtained in the three cases of comparison give proportional results. Figure 11(e) shows the relationship
between stress and strain regarding the different load values of P=10, 20 and 30N, always the load value plays a very important role between the stress-strain relationship. Indeed, we note that the increase in the real distance along the path, causes an increase in stress and strain. Moreover, from figure 11(e) it can be noticed that the values of strain and stress, become almost constant from the sixth points.

7.5 CASE OF A NINE-HOLE MODEL

We propose to model the model of a tensile behavior concerning the studied viscoplastic material, the model in this case, consisting of nine holes. The mesh is composed of 1998 elements and 2185 nodes see Fig. 12(a) below.

Figure 12. Finite element model of tensile behavior; a) model of the mesh with nine holes of diameter 3 mm, b) stress S11, c) stress S22, d) strain E11 and e) strain E22
Figure 13. The variation of stress and strain with actual distance along the path: a) stress11, b) stress22, c) strain 11, d) strain 22, and e) stress versus strain for a model that contains nine holes

Figure 13 presents the model of the tensile behavior of the model studied to have the distribution of the stresses and the deformation along the length of the model and in the vicinity of the holes, indeed the distribution is real. In addition, the elastic zone always keeps its shape, ie even for the nine holes, and the results obtained almost keep the general shape of the stress-strain diagram. Thus, there are similar results were obtained by (Imandoust et al., 2015) of a true stress-true strain curve, for compression tests with the strain rate for a steel material with induced plasticity, and the Technical stress-strain curve shape of LDPE and UHMWPE presented by (Xu et al., 2016) regarding the work of static and dynamic properties of polyethylene. The results obtained are; S11 varies between -0.44MPa, 26.38MPa and S22 varies between -6.88MPa, 4.70MPa the strain; E11 varies between 0.00%, 0.7% and E22 varies between -0.03%, 0.00%.
Figure 14 shows the evolution of strain energy and strain, as a function of time respectively, for different patterns of 0, 1, 2, 3 and 9 holes, it can be seen that the rate of strain increase as a function of time Figure 14(b) is small compared to the energy versus time strain of Figure 14(a). However, these forms of results were obtained by (Volgers and Anders, 2017) precisely the standard stress-strain curve relating to engineering polymer analysis work. Indeed, Figure 14(b) the results
obtained show a good correlation between them. That is to say that the chosen model describes a good state at the level of the deformation as a function of time, figure 15 explains the variation of stress and max stress, according to deformation and number of holes respectively, the results obtained show a good correlation between them in the case of holes, but the model without holes the results obtained with the others are proportional. These forms of results were obtained by (Lahtela et al., 2020) in the case of stress-strain processing of multi-layered plastic materials. The increase in the holes causes a decrease in max stress, except the first part of the elastic zone between the model without a hole and the model with a hole, but the stress S22, is increased by a small slight between the different holes of the model. Figure 16 shows the evolution of displacement as a function of time for the different holes. However, we can notice that the more the number of holes increases, the more the deformation of the model increases.

8 CONCLUSION

This article proposes, a finite element modeling method to quantify and evaluate different mechanical stresses and deformations, at the level of holes resulting from the assembly of structures together. On the other hand, deformations at holes during assembly are one of the most common deformations during the assembly, of structures in mechanical and civil engineering.

However, the method used here helps us to know what is the value, of the normal load that the holes, of the structures can support and what is the number, of holes necessary for these structures to function normally and better during assembly and resist types resulting shocks, various stresses and deformations. Furthermore, the proposed method could be the beginning, of an effective research approach for academics and researchers in the field of mechanical engineering, particularly researchers in the field of assemblies, stresses, deformations and contacts resulting from the connecting element, on the one hand and the glued element. On the other hand, elements that have the ability to resist materials have a major role in maintaining the life of structures, regardless of the material from which they are made. Five modeling models were studied of a viscoelastic material, behavior in tension. On the one hand, the FEM model of our work contains several numbers of elements and number of different nodes.
Elements of CPS4 types were used to model the different models.

The results obtained in this study justified, that the increase increase in the load always causes the increase of the stress - deformation, moreover the increase in the number of the holes causes a reduction of S11.

There is proportionality between all the results obtained from our work, especially the results found in Figure 14(b) the case of the deformation as a function of time and show a good correlation between them.

Finally, this work must be taken advantage of from a technical standpoint, understanding how structures are used during assembly, and the extent to which the effects of stress and deformation are understood, especially at the level of holes. This helps us maintain the life of the structures while taking into account the financial and economic aspects. Future work should also focus on modeling the structure by friction and contact with other structures, allowing for further expansion and understanding of the topic in several types of materials, especially composite materials.
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