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STRUCTURAL STATIC ANALYSIS OF ACADEMIC ROCKET ENGINE USING 6061 ALUMINUM WITH AISI 1020 STEEL

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Abstract. The use of aluminum as material in rockets is favorable to weight reduction, which is an important factor in the aerospace area. However, the structural and thermal properties of aluminum leave something to be desired. Carbon steel, on the other hand, has a higher density and better structural and thermal properties. Numerical methods were used to perform the structural static analysis of an academic rocket engine called Poty G, designed for a 300 m apogee. The engine was dimensioned as having an aluminum envelope, with SAE 1020 steel nozzle. The maximum internal design pressure of 3 MPa was placed as the main contour condition, to a detailed analysis of the most critical region. von Mises stress, displacement and structural safety coefficient were analyzed using the Ansys AIM software. It was found that the displacement was negligible radially and of low value for the longitudinal direction, not representing a concern regarding the structural aspect. As expected, by means of static analysis using the von Mises criterion, it was possible to identify that the components had maximum stresses below the yield stress and the rupture stress of the respective materials, ensuring structural safety. It was possible to simulate an academic rocket engine, which uses different materials, managing to reduce the weight in relation to conventional ones, and still guarantee structural safety. Through the static analysis using the von Mises criterion, it was possible to identify that the components presented maximum stresses below the yield stress and rupture stress of the respective materials, guaranteeing structural security.

Keywords: structural analysis, rocket engine, aluminum, AISI 1020 steel, numerical simulation.

1. INTRODUCTION

In the history of humanity, the rocket was one of the greatest inventions. The first appearances of what is considered similar to a rocket occurred in the 13th century, when the Chinese created a device for military purposes using gunpowder.In the following centuries, other cultures perfected the device for the same purpose. After the Middle Ages, with the expansion of studies in the areas of Mathematics, Physics and Chemistry, the idea of traveling to space became something possible for some members of the scientific community (Carleial, 1999).

In the twentieth century, with the knowledge acquired, scientists began to think about rockets as the main way to reach space.During the Second World War, there was an increase in the development of the liquid propellant rocket by the Germans to (Galvão, 2018). However, it was only in the Space Age during the Cold War (1947-1991) that the rocket was designed for its intended purpose, as planned by scientists centuries ago. Both the United States and the Soviet Union strongly developed the aerospace industry, building satellites and rockets, which reached the Moon in the

late 1950s (Carleial, 1999). Nowadays, this sector plays an important role in the technological environment, contributing in several areas, such as military, scientific, education, security and meteorology.

To remain a reliable technology, a rocket requires heavy investments in research. However, it is possible to conduct research at a low cost through computers. In the present work, we consider the analysis of the structural behavior of an academic rocket engine. As a reservoir, the rocket engine is responsible for providing sufficient energy to the flight, efficiently and safely.

During the design of an engine, it is important to consider: the internal tensions and efforts. Then failure mechanism must be considered, especially the combination of all stress components present in the structural element (tension, compression, shear) which will cause the material to fail. For ductile materials, the Tresca and von Mises criteria are commonly used to identify the failure. (Rodrigues, 2018)

Still dealing with a project, aluminum materials have a lower density than steel, being a positive point of view for rocket engine designs, in addition, aluminum is easier to transport and assemble. From a financial point of view, aluminum is more expensive than carbon steel depending on the final function of the product, and can be between 10 to 15% more. When it comes to the quality of the material, carbon steel is superior, presenting a better mechanical resistance, which is fundamental when its resistance to fatigue is questioned, obtaining a better useful life of its material and therefore, a better safety.

The objective of this work is to use numerical computational methods to analyze the internal forces, the maximum stresses and the displacement in the combustion chamber of an academic rocket engine, of solid fuel, with maximum internal pressure of 3 MPa and thrust 197 N maximum, designed as a thin-walled cylindrical pressure vessel, using the engine envelope and aluminum BulkHead (BH), and SAE 1020 steel nozzle, to reduce total weight and improve structural safety. The project of the rocket "Poty G" was developed by the Potiguar Rocket Design team at the Federal University of Rio Grande do Norte, and was experimentally tested on a test bench.

2. PROCEDURES

For the simulation methodology, an analysis of the model was made, which was done through the Solid Works Software, then the considerations, boundary conditions, creation of the mesh were placed and, finally, the structural static simulation was performed.

2.1 Analysis model

The design of the rocket engine for this mission was developed based on the theory of solid propellant rocket engines proposed by Sutton (2017) and on the Solid Rocket Motor (SRM) spreadsheet Nakka (2014), the design of the rocket engine for this mission was developed. Thus, initial parameters were defined, such as: internal diameter of the engine, length of the combustion chamber, external and internal diameter of the propellant, number of fuel cell segments, type of propellant used and internal pressure of the rocket engine. With these data, the corresponding values of: impulse, force, burning time and nozzle dimensions (conical top with convergent and divergent nozzle, which provides gas acceleration) were calculated.

For the structural design of the rocket engine, the thin-walled pressure vessel equations were used, with the engine envelope being considered a cylindrical tube, the BulkHead (BH) as being a cylindrical top, and the nozzle being a top conical, where the coupling of these components was made with alloy steel screw.

The thin-walled pressure vessel calculations are demonstrated by Eq. (1, 2), (Hibbeler, 2010).

$$\sigma_c = \frac{Pr}{t} \tag{1}$$

$$\sigma_l = \frac{Pr}{2t} \tag{2}$$

Where P represents the internal design pressure, the internal radius of this wall thickness for the pressure vessel. With the design pressure being 3 MPa, the internal radius equal to 17.5 mm, and the thickness equal to 3.5 mm. The model of the academic rocket engine used for computational analysis is shown in Fig. 1
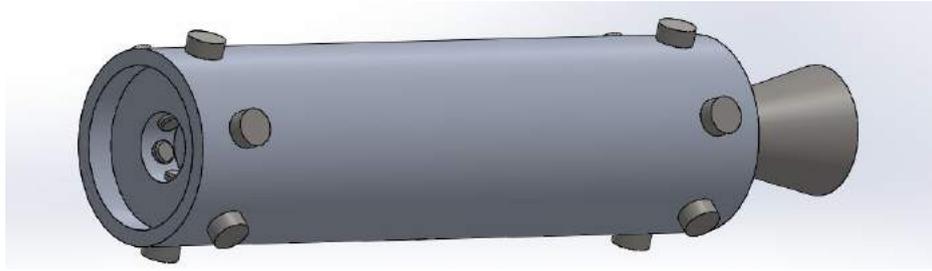
Figure 1. Model used for simulation of the assembled Poty G Motor.

The envelope and BH were made of 6061 aluminum, the SAE 1020 Steel nozzle, and the alloy steel screws.
For the analysis, the following data on the dimensions of the engine were considered, as shown in Fig. 2, with dimensions in millimeters.
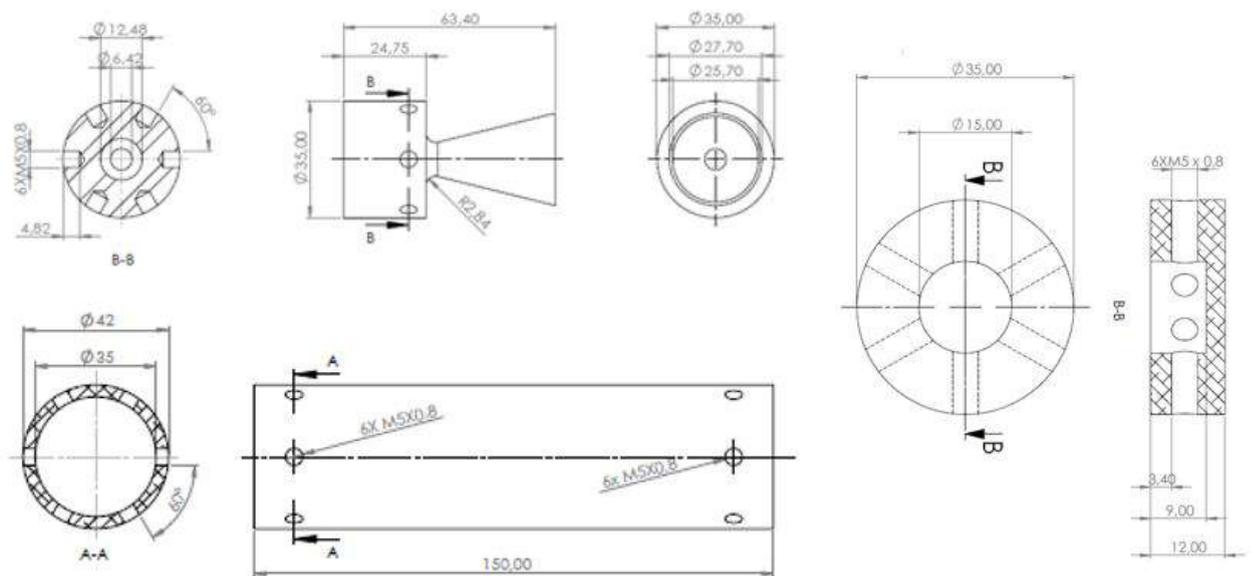

Figure 2. Dimensions of the rocket engine in mm.

2.2   Materials and their properties

Table 1 shows the mechanical properties (SAE 1020 steel and 6061 aluminum) of the materials used for the present study.

Table 1. Physical and mechanical properties of the materials used.
Taken from: Norton L. R Machine Designs and SolidWorks 2020 Library.

Property	AISI 1020 steel	Aluminum 6061
Yield Stress (MPa)	250-310	55-110
Elasticity Module (GPa)	200-206.8	69-71
Poisson's ratio	0.28	0.33
Breaking stress (MPa)	350-393	124

Throughout this work, the most critical situation for the data highlighted above was considered, obtaining a more reliable result with this.

2.3 Software and considerations

The software used to substantiate the work was Ansys AIM. Unlike other programs created by Ansys, this version allows the creation of intelligent meshes that improve the optimization of simulation processes and provide agility in navigation.

The work was restricted to the use of structural static analysis, where the thermal effect in the structural analysis was disregarded because it involves a very fast fuel burn (in the order of 2 s).

For simplification of the real model, the hexagon head screws were considered to be cylindrical, and for the purposes of calculations as being made of carbon steel instead of alloy steel.

2.4 Boundary conditions

For the analysis, some considerations were adopted in the boundary conditions:

- The engine was considered fixed (Fig. 3) in the region of contact with the load cell, equipment responsible for acquiring the data related to the engine thrust, to have a consistent reading of the damage, since the load cell needs to be pressed by the engine and do not allow it to "escape".
- The maximum design pressure of 3 MPa was considered, as it is the most critical situation for structural analysis.
- The contact between the envelope and the nozzle (Fig. 4a), as well as the envelope and the BH (Fig. 4b), are considered to be of the No separation type, because they allow longitudinal sliding due to the action of force.
- The contact of the screws with the nozzle and with the BH were considered Bonded type, as it is a coupling made by the screw threads.

Figure 3. (a) Fixation of the real motor, (b) Fixation as support.
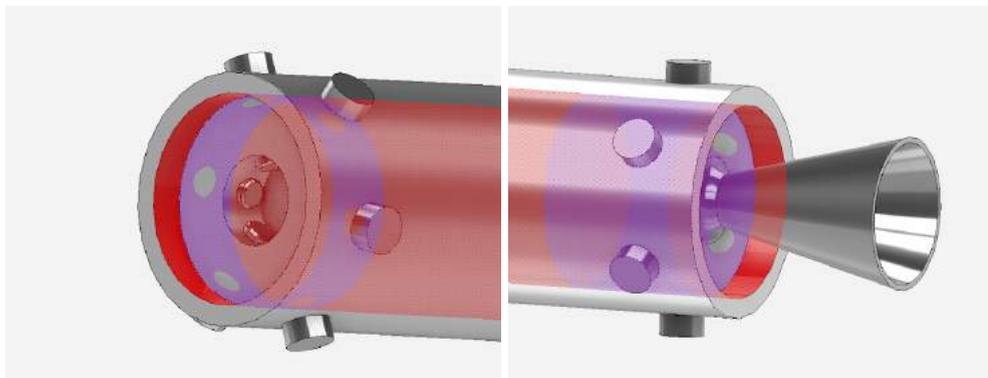

Figure 4. (a) BuckHead-Envelope contact, (b) Envelope-Nozzle contact.

2.5   Mesh structure

To generate structural results in the engine, a mesh was created using the finite element method in all engine components (Fig. 5). For studies in the whole regions of the envelope, bulkhead and nozzle, the curvature mesh was used, which is based on the configuration of adjacent triangles, in the geometries of all components, with a minimum size of 0.095710 mm and a maximum size of the faces 4.8757 mm. In addition, the resulting mesh generated 94948 nodes and 55608 elements, a determining factor in obtaining the results.
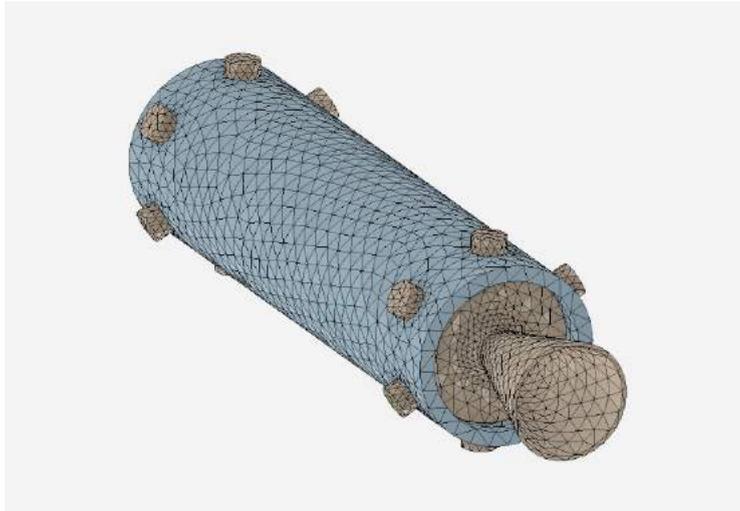

Figure 5. Mesh under motor used for the analysis.

It is important to have numbers of elements and larger nodes, this indicates that the adjacent triangles that are used in the mesh are smaller, with a better convergence of the simulation results and all the engine components (Siqueira, 2009).

2.6   Convergence test

To determine the number of minimum elements necessary to obtain reliable results, a convergence test was carried out, which consisted of the variation of the maximum voltage obtained in the entire body of the engine according to the number of elements.

The criterion for the mesh convergence was the analysis of the variation of the results of maximum tension in the whole body, being considered converged, when the variation is stabilized resembling a constant line.

2.7   Analytical and numerical analysis

The Finite Element Method (FEM) was used in the simulations, which was an alternative model that can be applied to any situation, regardless of its complexity, providing results with acceptable deviations for engineering (IECKER, 2014).

According to von Mises theory (maximum distortion energy criterion), flow in a ductile material occurs when the distortion energy per unit volume of the material is equal to or exceeds the distortion energy per unit volume of the same material when subjected flow in a simple tensile test (Hibbeler, 2010).

The maximum von Mises stress criterion is based on von Mises Hencky's theory, also known as shear energy theory or maximum distortion energy theory. So that considering (radial tension) we have: $\sigma_2 = 0$

$$\sigma' = \sqrt{(\sigma_1^2 - \sigma_1\sigma_3 + \sigma_3^2)} \tag{3}$$

Where it represents the circumferential tension and the longitudinal tension, both obtained through Eq. (1,2) σ_1 and σ_3.

From the equivalent von Mises tension, the value of the coefficient of safety by von Mises can be found. σ'

$$N_{VON\ MISES} = \frac{S_y}{\sigma'} \tag{4}$$

The criterion of maximum distortion energy (von Mises) indicates that the structural element will be in safe conditions from the consideration of the safety coefficient above 1 (BARRA, 2018).

Considering the steps previously described, the structural static analysis of the rocket engine designed as a pressure vessel was carried out, using the von Mises criterion and later compared with the analytical calculations.

Subsequently, the analysis of the displacement of the engine using the different materials was carried out, being likewise, first analytically, and then the computer simulation, making the comparison between both above all.

It is possible to develop an equation that can be used to determine the elastic deformation of an element subjected to axial loads. Using the definitions of stress and strain described by Eq. (5 and 6) respectively. (Hibbeler, 2010).

$$\sigma = \frac{P}{A} \tag{5}$$

$$\varepsilon = \frac{\Delta L}{Lo} = \frac{\delta}{L} \tag{6}$$

As long as the amounts of stress and deformation do not exceed the proportionality limit and if the body is homogeneous and both the load and the cross-sectional area are constant, one can relate the Eq (5 and 6) using Hooke's law Eq (7), to obtain the expression for the displacement Eq (8) (Hibbeler, 2010).

$$\sigma = \varepsilon E \tag{7}$$

$$\delta = \frac{PL}{EA} \tag{8}$$

3. RESULTS AND DISCUSSION

3.1 Convergence test

Fig. 6 shows the results of convergence through of the graph in which, as essential parameters, it is maximum tension and the number of mesh elements to arrive at a better precision.
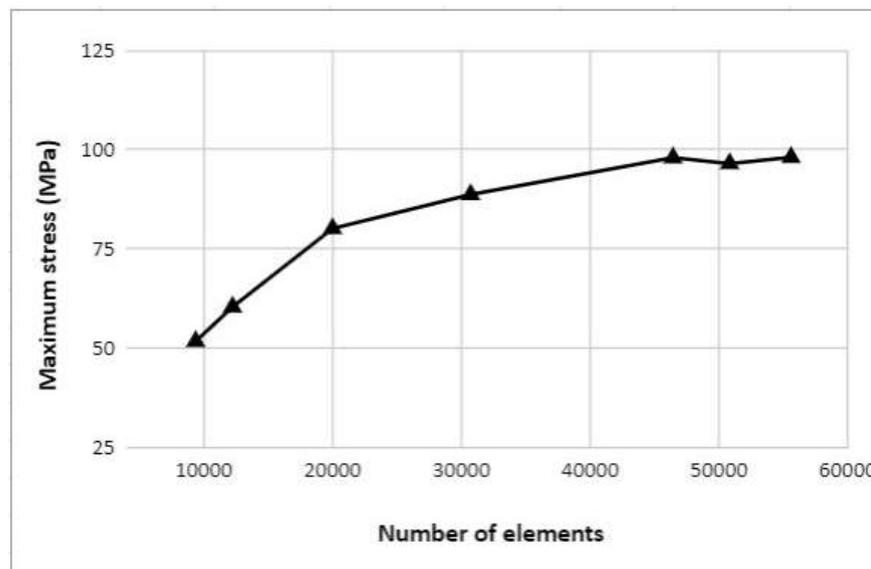

Figure 6. Convergence test.

An initial abrupt growth is observed, starting at 50 MPa, until a certain decrease in growth is reached, approximately 100 MPa.

After that, the graph stabilizes and remains in the range of its rising (100 MPa). This growth will also occur as the numbers of the elements increase, since it is necessary to have a good convergence of its results.

3.2   Structural analysis by von Mises

For ductile materials, the Tresca and von Mises criteria are commonly used. Being chosen in the present work, the von Mises criterion for numerical and analytical analysis.

From the point of view of analytical analysis, by Eq. (1, 2) the main stresses were 15 Mpa and 7.5 Mpa respectively, with these values, through Eq. (3), an average tension was reached von Mises of 13 MPa, a value well below the yield stresses of the material, described in Table 1. Consequently, the safety coefficient using the von Mises criterion, as in Eq. (4) and the yield stress value, for the aluminum alloy highlighted in Table 1, will be determined:

$$N_{VON\ MISES} = \frac{55\ Mpa}{13\ Mpa} = 4,2 \tag{9}$$

In turn, as the safety coefficient resulted in a value above 1, it is understood that the structural design, as a thin-walled pressure vessel, using the von Mises criterion, is analytically safe.

By numerical analysis, placing all the conditions previously highlighted, using the structural simulation by von Mises, Fig. 7 was obtained.
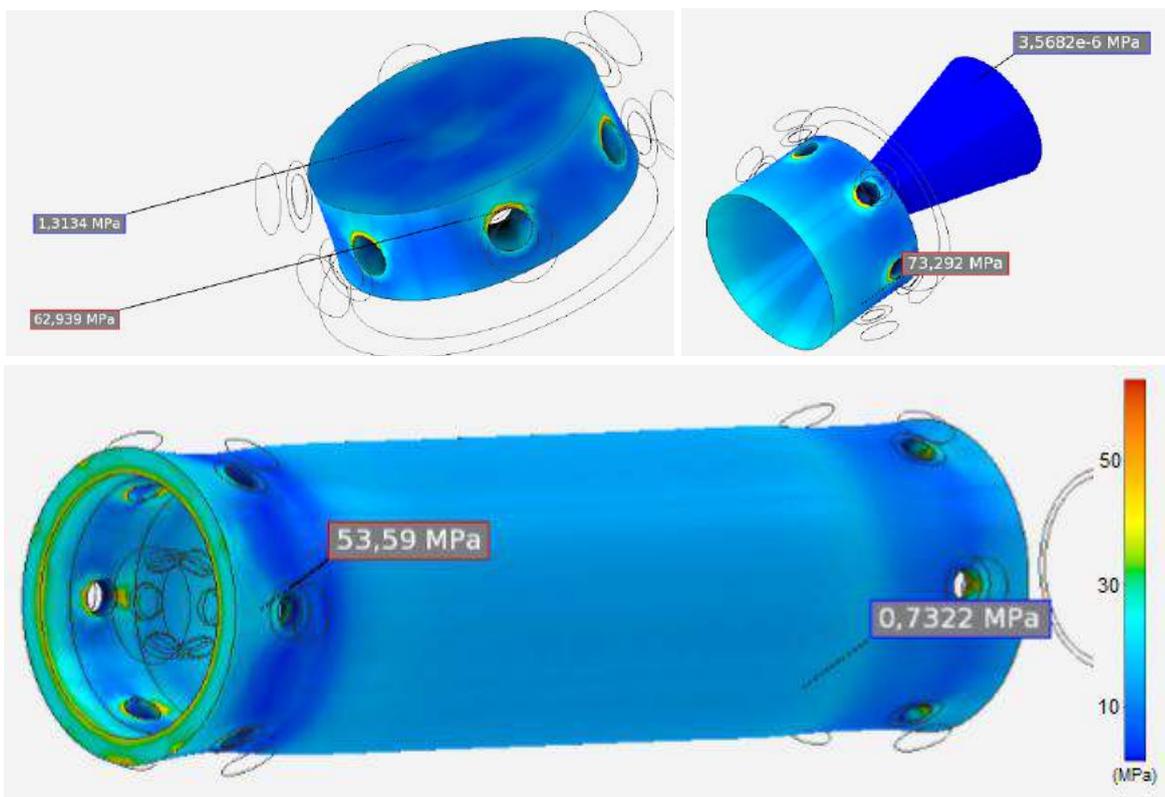

Figure 7. Analysis by the finite element method, using the von Mises criterion: (a) for the Bulck Head, (b) for the nozzle, (c) for the envelope.

Through the numerical results using the von Mises method, it is possible to identify the resulting stresses at different points in the material. Figure 7, can represent this very well, where the blue color represents voltages up to 30 Mpa and the yellow colors up to approximately 70 Mpa.

In the tops represented by Fig. 7 (a and b), it is possible to identify more accentuated stresses as predicted, in the contact region between the screws and the members, represented by the yellow color. This is due to the containment of the longitudinal pressure, resulting in a possible tearing and crushing effect of the screws. The maximum stresses were 62.93 Mpa and 73.292 Mpa in BH and nozzle respectively.

Another interesting point to be analyzed, is the entrance region of the converging section of the nozzle and the strangulation region, as an increase in pressure is expected, due to the direction of the gases and tension concentrator, despite that, the tensions were still lower than 30 Mpa, which is not such a critical point of analysis. A possible explanation for this, is the fact that the structural analysis takes into account the boundary conditions previously

informed, not considering the action of directing the gases, being necessary a more elaborate analysis in Computational Fluids Dynamics (CFD).

In the case of the motor envelope, the highest voltage recorded was 53.59 Mpa, also located in the screw region, corroborating the effects on the other components. In addition, a marked effect on contact with the BH and the nozzle was also observed, and is also shown in yellow. However, the stresses were shown to be lower than the rupture and flow stresses of aluminum, which confirms the possibility of using this material for this rocket engine project.

The stresses on the aluminum motor envelope were more balanced and constant, and were even close to what was predicted mathematically in this project by Eq. (3), either due to the average von Mises stress, but also to the circumferential stresses for vessel pressure.

3.3   Displacement analysis

The Figure 8 shows the analysis of the displacement made in a rocket engine using the Ansys AIM software, more specifically in its bulkhead, body (envelope) and nozzle. These displacements occur for several reasons, but are mainly subjected to the pressure made in the flow of the nozzle, and also by the increase in temperature caused by the transfer of heat from the flow to the structure, thus being able to generate its displacement (Pedroni, 2016).
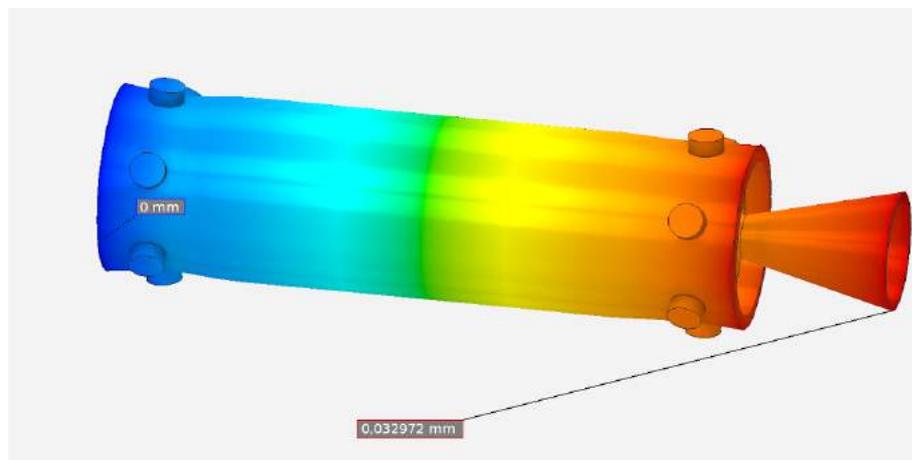

Figure 8. Rocket engine displacement graph.

According to Fig. 8, the critical points of displacement stress can be highlighted. The transition from dark blue to light, obtains a deformation of 0.01 mm, in the most yellowish part until the bulkhead, there is a deformation of 0.02 mm, and finally, the red part has a displacement of approximately 0,033 mm . The precision of these displacements occurs according to Eq. (5 and 6), due to the elastic deformation of axial loads of the material, which, also, in the case of a homogeneous body, and which is within the limit of proportionality of the material, is made the use of Eq. (7 and 8) is necessary.

The region with the highest tension is the nozzle convergence part, considering that the engine is fixed on the test bench in the BulkHead region, as well as being predominantly wear stress points, which indicate the largest total displacement in other engine components. These results are consistent with logical thinking, since the greatest deformations occur where the load is highest. Therefore, fig. 8 shows that the horizontal deformation (X-axis) directly interferes with the total displacement.

3.4   Comparison of results

It is very important to design an engine that is structurally safe, but the reduction in total weight, linked to this safety, is an enriching objective for the projects.

Through the calculations highlighted above, the best material option for the envelope would be aluminum, as the stresses under it are less than the yield and rupture stresses, and can even be used in more than one test, also providing a decrease in weight due to its low density, faster manufacturing, easier purchase of aluminum tubes.

In the case of BH and Tubeira, the use of carbon steel is recommended, as the maximum stresses recorded on them are higher than the yield stresses, so that the material would not fail, but it would not be recommended to reuse it, due to the flow of material.

The results obtained using different materials can be compared, based on parameters related to their weight, safety, quality, time and financial viability.

It is also important to note that, using the same structural calculations applying to carbon steel, the thickness of the engine envelope would be corresponding to 0.7 mm, the thickness of the pipe would be 0.91 mm and the thickness of the BulkHead 5.75 mm, which would consequently result in a lighter and safer design for the rocket engine. However, these dimensions are outside the reality of the team, in view of the requirement for high technical knowledge to carry out this very detailed manufacturing. Therefore, the minimum values used and recommended by the team are 1.0 mm thick, which in this way would be an alternative to the structural design with aluminum, because despite containing greater thickness, it has less density and in the total set it would result in lower weight if these minimum thickness conditions were observed.

Table 2. Comparative values between projects.

Parameters	Carbon steel design	Aluminum project with carbon steel
Safety Coefficient	3	3
Wall thickness	1.0 mm	3.5 mm
Weight	381.41 g	355.67 g

4. CONCLUSION

Therefore, the objectives of this work were achieved, being a structural static analysis was carried out through computer simulation, for an academic rocket engine, which uses different materials, managing to reduce the weight in relation to conventional ones, and still guarantee structural safety. .

Regarding the simulation results, the mesh constructed by adjacent triangles for this simulation generated good results, showing that the rocket engine can be designed with the envelope made of 6061 aluminum, which guarantees safety and less weight, compared to an envelope made 1020 steel.

Through the analysis carried out, at first it can be observed that the maximum pressure of the project is around 100 MPa, being lower than the flow limit of carbon steel, but higher than the aluminum alloy. That is, the material would not flow, if an alternative use of both materials was used.

There was a significant increase in pressure in the region of the screws, which can cause crushing and tearing of the screws. On the other hand, higher pressure values were expected at the point of convergence of the nozzle, due to the gas flow direction and for being a tension concentrator. However, surprisingly, there was a reduction in pressure, compared to other points, requiring a more elaborate analysis to better understand this factor.

When analyzing the displacement of the engine, a higher elongation was found in the nozzle region, which was reduced along the body towards the bulkhead. Corresponding to the predicted, since the displacement occurs mainly due to the temperature and pressure performed in the flow. For this reason, it is necessary to use a material with superior properties, since a deformation, however small, at the point of convergence of the nozzle can cause a catastrophic failure in the entire project. Thus, we can conclude that the use of aluminum alloys as a constituent material of the combustion chamber of the engine analyzed in this work is valid.

It is recommended to use more resistant materials in the nozzle and bulkhead, such as SAE 1020 steel. The results of this work enable a reduction in costs and, mainly, weight for the engine in question. Once you reduce both, you can invest more in the project and further increase its associated income, proving the importance of selecting materials for making any project. For bulkhead and nozzle it is recommended to use carbon steel due to the critical stresses observed in the simulation.

The results of this work may assist future work related to the optimization of a rocket engine and structural simulation, taking into account physical aspects, such as mechanical strength, as well as the material to be adopted.

Moreover, it is recommended that the comparison with the real situation be used in future work, with the rocket engine being placed in static tests and analyzing the conditions submitted.

As future suggestions, a fluid dynamic analysis is recommended to understand other factors; thermal simulation associated with structural simulation in transient regime; It is also recommended that the same methodological procedure is always performed when each and every engine is designed, being a crucial step before sending it for manufacturing.

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