COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-2048
STRUCTURAL PERFORMANCE ANALYSIS OF A THREAD IN AN ACADEMIC ROCKET MOTOR

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Abstract. *Considering the great importance of operating a rocket engine, the engine design must be very well thought out. It will be responsible for all the propulsion of the set, lifting it in the air. Calculations related to structural safety are parameters that must be performed with caution, considering above all a safety factor that promotes its guarantee. The main objective of this work is to structurally analyze a screw profile chosen for an academic internal combustion rocket engine with a solid propellant. The chosen profile is trapezoidal with coarse settings. The engine is designed as a thin-walled pressure vessel, internal pressure of 4 MPa, solid fuel composed of potassium nitrate and sucrose, maximum thrust of 1491 N, thrust of 1998 Ns and 1.474 s of burn, validated for 1500 missions feet tall. The structural analysis was carried out, considering the action of pressure on the thread, by the von Mises criterion, evaluated through simulation with the finite element method. In addition, a thread fatigue analysis was performed. The analytical results were consistent with the numerical ones, corroborating the veracity of the equations used in the model. As expected through the analysis, it was possible to identify that the components presented maximum stresses below the yield and final strength. The analysis also proved that the strengths above the thread are structurally safe, resulting in a safety factor greater than 2. In addition, the fatigue analysis proved to be safe. It was possible to verify that an academic rocket engine, using trapezoidal threads, does not present structural problems.*

Keywords: *Structural analysis, thick trapezoidal thread, solid rocket motor, simulation.*

1. INTRODUCTION

Rockets are launch vehicles, which have well-defined objectives. For example, carrying a payload to a certain place in space, or even under the Earth's atmosphere. This purpose must be done with reasonable structural safety margins, always taking into account operational simplicity and safety costs (Carande, 2011).

The application of simulation with motor structures is already increasing, with regard to the application of safety factors for the walls and tops used, considering the need for safety, whether at a professional level, or even in university competences. However, there are few studies aimed at an analysis of threads, which are used in sets and couplings.

Triangular and trapezoidal profiles have good application qualities for rocket engine models due to the need for internal pressure containment, fixing the union of the components. (Gordo and Ferreira, 2001).

This is due to the need for a resistant profile, which can occur on all imposed loads and, at the same time, is responsible for correcting the union between the top and the body's components. Another important factor of choice is made taking into account the possibility of leakage, since the profile needs to reduce the chances of leakage (Queiroz, et al., 2021).

There are many errors and problems involved in practical situations that cannot be discovered through theoretical calculations. Therefore, numerical simulation is interesting, being able to predict factors observed in assemblies and operational tests. Therefore, given the possibility of replacing conventional academic rocket coupling models that use screw fixation, it is necessary to use simulation, as a step prior to manufacturing, eliminating possible errors. Since the use of screws in rocket engines often results in fuel leaks, material brittleness, assembly and sequencing errors.

Thus, the present study aims to structurally analyze the trapezoidal type coarse thread wires of an academic rocket engine, surveying the von Mises tension criteria and the safety coefficients, presenting themselves as a substitute for conventional screw models, or other types of thread.

According to the American Society of Mechanical Engineers (1989), the use of thick wires is more applicable in materials with lower resistance to flow. This is because coarse threads have greater resistance to loads, including cyclic loads. As a result, they are more efficient in situations that have greater internal pressure than fine wires.

According to Kyle W.D. and NIcholas J.H. (2015) "Thick wires have larger tension areas, which is good for carrying in tension", this may indicate that thick wires are more likely to be used in rockets. As rockets are designed to be as lightweight as possible, using thin wires can have its benefits. However, due to the high pressure inside the engine, as mentioned earlier, coarse threads are more useful and have more uses.

According to Budynas and Nisbett (2011), the increase in area due to the angulation of the fillets causes additional friction that makes trapezoidal and triangular screws more used as fasteners. Therefore, the project included a threaded motor model with thick wires, with a trapezoidal profile.

2. METHODOLOGY

The methodology was centered on the 2D static structural simulation of the trapezoidal coarse screw threads of an academic rocket engine, with the steps prior to this realization being demonstrated.

2.1 Utilized software and materials

For the 3D modeling, as well as the technical drawings of the rocket engine, the Solidworks software was used. For the simulations, ANSYS Workbench software was used, from finite element concepts, identifying the loads imposed on it, to analyze the reliability of the project and its limitations

The engine was designed in SAE 1020 steel, with the properties shown in Table 1 below.

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Table 1. SAE 1020 Properties.

Properties	Value
Density, kg/m³	7850
Young's Modulus	200
Poisson's Coefficient, GPa	0.2
Yield Stress, MPa	352
Temperature °C	32

2.2 Thread Models

In order to study the thick line applied to a rocket engine, its structure must be calculated to prevent further wear. Therefore, the table below describes the dimensions used to define the thread, with trapezoidal shapes.

Table 2. Coarse Thread Configurations

Item	Trapezoidal
Nominal Diameter [mm]	61.9
Root Diameter [mm]	55.9
Fillet Angle [mm]	30.0
Superior side [mm]	2035.0

These settings will be used in a CAD software, considering a step of 5.5 mm, to carry out other simulations in order to determine the drive stresses and consequently the structural safety.

2.3 Project analysis and conditions

The rocket engine design for this mission was developed based on solid propellant rocket theory. Engines proposed by Sutton (2017) and in the Solid Rocket Motor (SRM) Nakka (2014) spreadsheet. This model was designed with SAE 1020 steel and has an envelope whose length corresponds to 500 mm, with 59.9 mm outside diameter and 2 mm thick cylindrical shell. The cylindrical top of the bulkhead and nozzle shell have thicknesses equivalent to 2 mm each, all to withstand an internal pressure of 4 MPa with a burn time of 1.474 s.

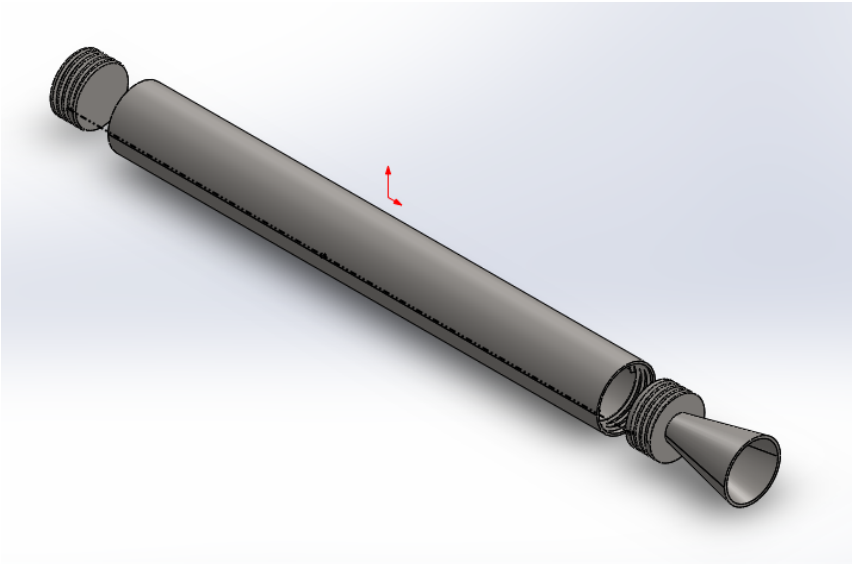

Figure 1. 3D threaded motor in exploded view

The force acting on the lids is calculated by the distribution pressure, according to Eq. (1), with the area corresponding to the section of the lids.

$$F_i = P * A \tag{1}$$

According to Budynas and Nisbett (2011), 81% of the load applied to a screw will be on the first three threads, while 38% of this load is directed to the first. Thus, when there are only three fillets, 100% of the load will be applied on them, which by proportion has:

$$c = 0.38/0.81 = 0.47 \tag{2}$$

Where "c" determines the new portion of load applied on the first fillet, in a screw with three fillets. The result was 0.47, which means 47% of the load just on the first fillet.

The most critical situation is in the first fillet, so that for this, "Fp" represents the percentage of charge, which will be calculated by Eq. (3),

$$F_p = F_i * c \tag{3}$$

Also, as the trapezoidal thread has inclination, the new force calculation will be interpreted as in Figure 2.

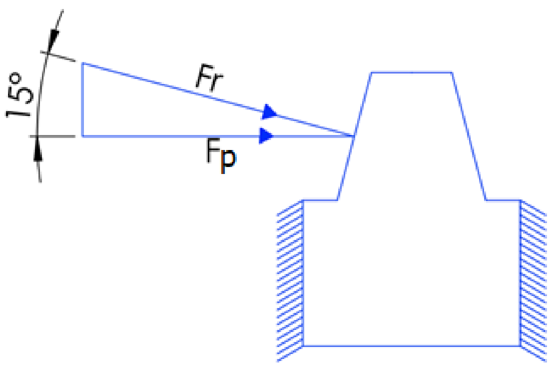

Figure 2. Applied forces on thread fillet.

The final force (Fr) was calculated from Eq. (4), converting to the existing angulation.

$$F_r = \frac{F_p}{cos(15º)} \tag{4}$$

In possession of the final acting force, the pressure distributed along an edge in the fillet profile was calculated (P), as follows:

$$P = \frac{F_r}{La * 1} \tag{5}$$

Considering that the edge has an area with the length equal to the length of the edge itself, and thickness equal to "1mm".

2.4 Definition of mesh and convergence

As a static structural simulation it was done in 2D, considering the thread profile and the wall thickness where it is present. After this consideration, the thread profile was divided into two parts, the central one, in blue, which is not as relevant and the two on the sides, in red, that were very influential in the study and, therefore, they will be more refined. The profile and its divisions can be seen in Figure 3.

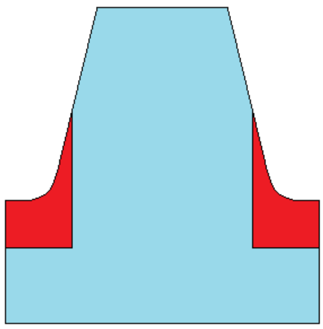

Figure 3. Thread profile divided between lateral and central parts.

The sides received further refinement, since they were in a critical situation, that is, most of the load. The central part, on the other hand, is responsible for providing a fixed support to the thread, resisting the load applied to it, which is why so much refinement in the mesh was not required.

The mesh elements were solved using the "Quadrilateral Dominant" method with a "Quad/Tri" type face. Due to the 2D analysis geometry, the types of elements used were surf153 and plane183. This method provides a mesh capable of adapting to complex geometries with greater ease, as according to Canann et al. (1998), he creates quadrilateral elements that, when necessary, can be distorted into a more triangular profile according to the concepts of Lee and Lo (1994). In Figure 4 it is possible to see the mesh model used for a trapezoidal thread that illustrates this concept.

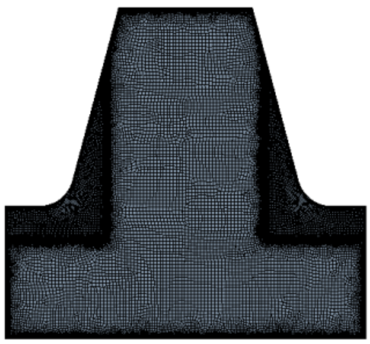

Figure 4. thread profile with refined meshes.

Each mesh element will define its equations according to interpolation functions in the form of Lagrange polynomials, using Eq. 6.

$$N_i(x) = \prod_{j=1, j\neq i}^{n} \frac{(x - x_i)}{(x_i - x_j)} \quad (6)$$

Once the mesh was defined as previously mentioned, the step was repeated, due to the performance of the mesh convergence test. The test consisted on analysing the maximum load, as a function of the number of elements, being considered convergent when the variation stabilizes, resembling a constant line (Bezerra, et al., 2020).

2.5 Structural analysis

Defining the mesh on the threads, the pressure on the thread edge, calculated by Eq. (5), the main conditions were set. In addition to the load considerations, a fixed edge was also considered, in order to be the support point for the thread to resist the load. Thus, the lateral edges of the thickness of the wall where the thread is present were defined as fixed, as can be seen in Figure 2.

Taking into account the two considerations of load and fixed edge, the von Mises stress was calculated using finite methods in computer simulations, in order to obtain the stress points, and their numerical values, for subsequent calculation of the safety factor.

To calculate the stresses applied to the fillet, the von Mises maximum stress criterion was used, also known as shear energy theory or maximum distortion energy theory, according to Eq. (7), considering only the stress longitudinal and circumferential, according to the cylindrical model, $\sigma_2 = 0$.

$$\sigma' = \sqrt{(\sigma^2{}_1 - \sigma_1\sigma_3 + \sigma^2{}_3)} \quad (7)$$

For the safety coefficient, if it is greater than or equal to "1", it guarantees that the thread can support the load without plastically deforming, as described by Norton (2013), this coefficient is obtained by the relationship between the limit stress and the stress imposed, as can be seen in Eq. (8).

$$N = \frac{S_y}{\sigma'} \geq 1 \quad (8)$$

The von Mises stress is calculated by the software taking into account load and fixed edge considerations to support the flow and applied pressures.

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3. RESULTS AND DISCUSSIONS

From the considerations and conditions imposed, the structural analysis of this screw model was obtained, the results being demonstrated and discussed in this section.

3.1 Convergence Test

In order to guarantee that the obtained results were coherent, the convergence test was made and got the following charts as its results.

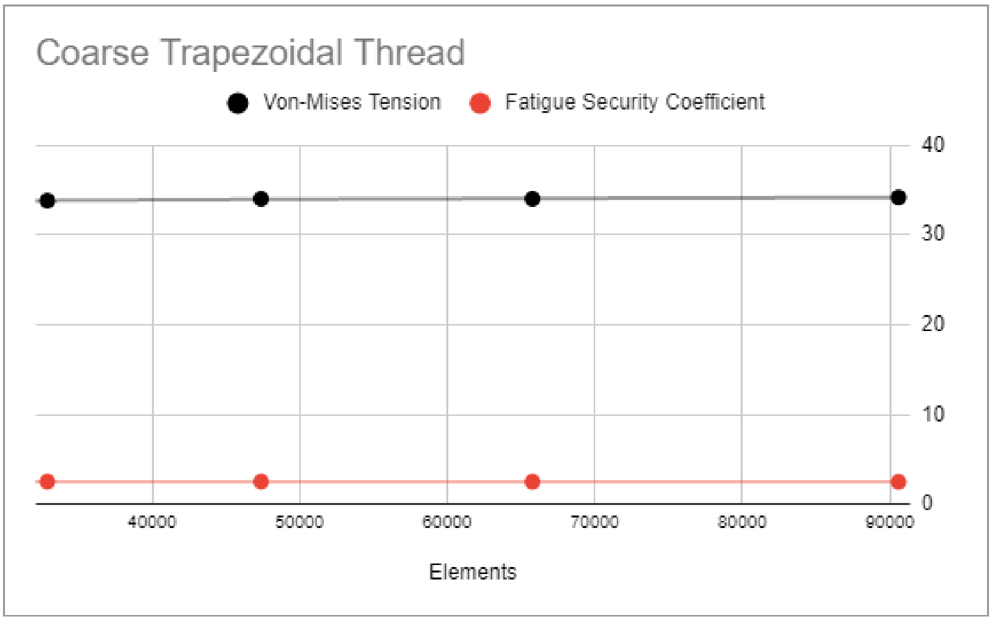

Figure 5. Convergence Test Results.

Utilizing the results shown on Figure 5 it is possible to determine that both von Mises Tension and the Fatigue Security Coefficient were converging to a constant value. This means that the results are consistent, even when increasing the amount of elements. This test guaranteed that all the results were coherent and could be used to further conclusions.

3.2 Von Mises Tension

The force applied to the fillet, called preload force, was calculated by Eq. (1), where the internal pressure of 4 MPa and the cross-sectional area of the engine cylinder of 0.0025 was used as a parameter. m^2, as it corresponds to the internal area of the cylindrical top, which will sustain a pressure of 4 MPa, so that this will influence the thread, resulting in a force of 9816.88 N.

Furthermore, this preload force acts on the coupling assembly, so that it will be divided and distributed to all threads. As three threads were used, considering what was exposed by Budynas and Nisbett (2011), a correction coefficient was calculated, as shown in Eq. (2).

Thus, it is necessary to make a correction, for the analysis of only the first thread, considering that it is in the most critical situation, resulting in a force of 4613.93 N.

As the trapezoidal fillet has a 15° angulation, as shown in Figure 2, Eq. (4) was used to determine the resulting final force, after angulation adaptation, resulting in 6073.45 N of final applied force.

With the values of "Fr" defined, the edge size (La) was calculated from the dimensions described in Tab. 1, with this, the resulting pressure value was defined, corresponding to 8.31 MPa.

The edge of the fillet was considered fixed, since it was the support dot of the base of the fillet, not interfering with the analysis of the result, but resembling real situations.

The calculated pressure of 8.31 MPa was placed as a boundary condition, acting on a single thread. This consideration is interesting, as it is superior to real conditions, meaning that the application of this pressure to the von Mises simulation is artificially imposed by another security.

Thus, placing the lateral fixation and defining the acting pressure, the graphic result obtained through the simulation by von Mises, is represented in Figure 6.

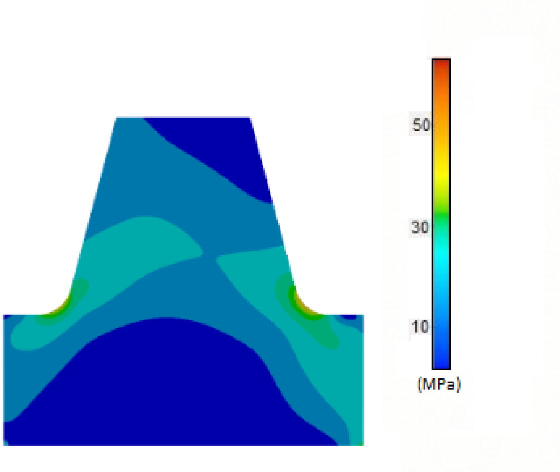

Figura 6. Representation of the tension by Von Mises.

Through Figure 4, it is possible to see the action of the stresses on the 2D surface of the trapezoidal thread, where in blue are the lowest stresses, and in yellow the highest. The highest tension was 34.152 MPa, being located just at the base of thread division, both on one side and on the other side of the thread.

The highest stress was located at the base, as expected, due to a stress concentration, however, it did not present itself as a point of concern, as it was a low stress when compared to the breaking strength.

The results show that this trapezoidal type thread design, for the application of this motor, proved to be safer, with lower loads than on the first thread. Even so, the use of at least 3 threads is recommended, as a precaution, Budynas and Nisbett (2011).

3.3 Safety coefficient analysis

With the values expressed by the structural simulation, according to von Mises' criteria, the structural safety coefficient by the fatigue criterion by Goodman, were stipulated via simulation the most critical value, that is, the lowest value. This is because higher values mean even more security.

The value corresponding to the fatigue safety coefficient by Goodman was 2.542, which means that the threads are dimensioned almost 2.6 times safer, when the material's resistance to flow is taken as a parameter.

Therefore, it can be stated that for Goodman's fatigue criterion, the threads used in this project were shown to be safe, even allowing them to be used for other tests.

4. CONCLUSIONS

Thus, the objectives of the work were achieved, with a static structural analysis being carried out, through computational simulation, for the wires of an academic rocket engine.

Regarding the simulation steps, the mesh was defined by the "Dominant Quadrangle" method and has a face defined by the "Quad / Tri" type, being more explored in the external and lateral regions, which generated good results.

In the von Mises analysis, the highest load was 34,152 MPa, which would be slightly below the elastic limit, not representing a danger, but showing that a coupling was well accepted. Likewise, the safety factor reported that the system is approximately 2.6 times more secure, already taking into account the most critical point.

Therefore, it is possible to conclude that the coarse trapezoidal threads showed structural static efficiency, both of support and stresses, configuring a high safety coefficient.

As a future activity, the aim is the fluid-structure simulation of the entire set, also taking into account the threaded coupling, implemented in the structure, to reduce weight.

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6. RESPONSIBILITY NOTICE

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