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# PVC Tube Bearing Tests for a Lab Scale Rocket Fuselage Design

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***Abstract.*** *In the aerospace industry, weight reduction is of fundamental importance. Thus, it is necessary to know precisely and thoroughly the characteristics of the materials being employed. Within this context, this paper aims to determine a PVC tube bearing stress resistance, that will be used in the design of a small scale rocket fuselage, to which a small rocket engine will be fixed by screws. Most of the stress the structure will be subjected to occurs during launch. For this reason, it is crucial for the design of the fuselage to know exactly how much bearing stress is necessary for the tube to suffer permanent strain. It is possible to know the amount of stress through cyclic and monotonic bearing tests. These tests consist on tractioning sideways an equivalent to the real situation screw fixed to the tube wall. It was possible to measure the PVC bearing allowable, confirming its fitness for this use. These experimental results were compared to computational models. From these data, it is possible to calibrate and validate the computational model for future applications and optimize the structures dimensions without compromising its reliability.*

***Keywords:*** *Bearing Test, PVC, Rocket, Finite Elements Analysis*

## 1. INTRODUCTION

Weight minimization is a fundamental directive in any aerospace project, bringing better results in terms of range, fuel consumption, speed and payload capacity. Therefore, it is imperative to know the properties of each material and part used.

During a rocket's flight, its engines produce thrust, which pushes the fuselage. In the case of the small scale rocket currently under development by the Topus Aerospace Research Group in the University of São Paulo, the engine is fixed to the fuselage by 12 screws, 6 in the upper assembly arrangement and 6 in the bottom arrangement, all equally spaced. In the critical case beign considered, only the upper 6 will receive the mentioned thrust load during the flight. This load leads to a crushing of the fuselage's regions next to the screws, creating what is known as bearing stress.

During this rocket's development, the limit or ultimate bearing stresses for the PVC, material employed in the fuselage, were not available. So, it was necessary to develop a method to evaluate this property of the PVC, allowing the fuselage thickness calculations.

## 2. LITERATURE REVIEW

The bearing stress has been considerably studied throughout the development of engineering. From bridges and buildings to the high-performance structures present in aircrafts and aerospace vehicles, however, much changes on the bearing problem (Camanho and Tong, 2011).

High-performance structures tend to be remarkably thin and slender, but also rigid and resistant. That certanly leads to a good global performance of the structure, but locally this combination can lead to some particular strucural phenomena (Vangrimde and Boukhili) and joints are even more susceptible to them. Joints must be verified for four types of local phenomena: rivet or bolt shearing, bearing, tear out, and net-section tension failure (Peery, 2011).

Even though the bearing problem is a clear and well-known phenomenon, it does not have a precise threshold as the other ones. All references quote a limit to the hole's diameter elongation under the bearing stress as a threshold, but a precise value is not indicated (Peery, 2011), and the indicated ones vary. A good motivation for this work is, then, the determination of this threshold to the structural problem at hand. However, it is worth it pointing out that the different references approach the bearing problem throught studying materials and structures different from the ones proposed here, consequently, their findings will not directly comparable.

Yeole's work (2000) studies the bearing phenomenon in composite laminates and uses a 2 per cent limit to the holes's diameter elongation under bearing stress. For composite characterization in general, a 4 per cent diameter elogation is suggested (Department of Defense, 2002). Menzemer et al (2002) study the bearing strength of alluminum alloys and proposes a 25 percent of diameter elongation as limit. As mentioned, none of these materials are compatible to the PVC which is much more flexible and less resistant than the others, but this work's bearing tests follow the same lead as all of them.

## 3. METHODS

### 3.1 Experimental

The bearing test consisted in restraining the specimen's lower extremity in the test machine, while in the highter claw was connected to a screw perpendicularly bolted to the PVC test specimen. The machine then pulled up the screw, with a speed of 0.5 mm/s, creating a stress that locally would crush the PVC.

In this study, twelve specimens were used. The specimens came from PVC tubes that had a 300 mm lenght, a 49 mm inner radius and 55 a mm outer radius. Each specimen was the result of the original tube division into six 60-degrees pieces (approximately resulting in a plain width of 50mm). Six of the specimens would be used to a M6-screw tests and the other six would be used to M8-screw tests. Holes with the respective dimensionswere made in each one of the specimens.

Once the specimens are originally from tubes, they were not plane, making impossible to attach them directly into the classic claw of the test machine. In order to adapt the claws to this use, a special mounting was developed, with the purpose of creating the plane surface necessary to attach the specimens to the equipment.

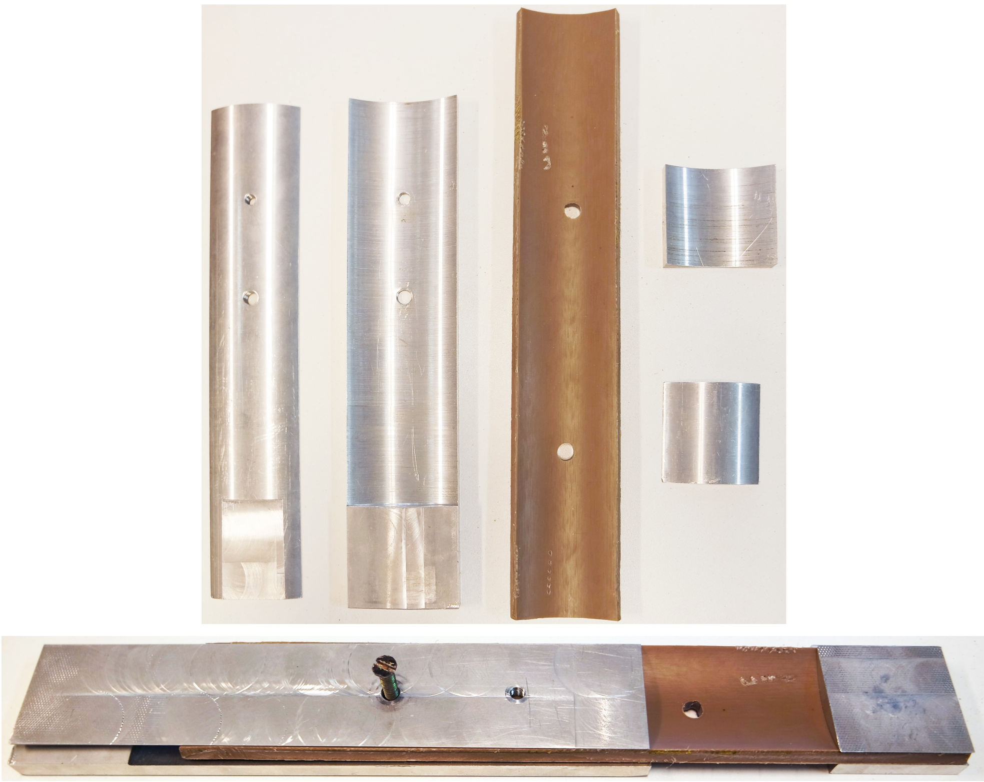

Figure 1. (a) Specimen and support parts (b) Assembly for testing

It is important to remark that the thread influences the test results. It reduces the contact area between the screw and the specimen, accelerating the occurrence of bearing.

Initially, a monotonic test was done and the specimen was tensioned beyond its elastic range. This way, the PVC behaviour could be estimated for the cyclic tests, in which cycling loads were applied to the specimens, better signalizing in which point permanent deformation has happened and thus where is the begining of the bearing phenomenon.

In order to determine the allowable bearing stress, the load necessary to cause plastic deformation in each one of the specimens was defined and the arithmetic mean of the loads was calculated. Then, this load was be divided by the contact area between the screw and the specimen.

Figure 2. Thread marks in specimen 2 (M6) after testing

### 3.2 Computational

A finite element computational analysis was also performed using the Dassault Abaqus™ software. Both the specimen and the screw were modeled. Boundary conditions were used to model all other parts.

The specimen is modeled with the 6 mm hole 100 mm from the top. A non-displacement boundary condition is placed at its base and the top is only allowed to move in the force's direction.

The screw was modeled as a steel cylinder and its diameter was defined as the screw's working diameter, 4.7 mm. The thread was not included because it would require a much finer and more complex mesh, increasing the computational cost beyond the scope of this work. A linearly increasing displacement was used as boundary condition for this part.

A contact condition was also placed between the screw's outside surface the the hole's inside surface.

The mesh consists in just over 22000 Hex elements, more refined closer to the hole and coarser away from it.

Fig. 3 illustrates the model and its boundary conditions.

Linear mechanical behavior was considered for the materials for both parts. The PVC's elastic modulus is set at 2.84 GPa and the steel's modulus at 203 GPa. Both Poisson ratios are 0.3. The PVC's plastic behavior was extracted from (Ognedal, 2012) and simplified; it was assumed the plastic range starts at 50 MPa tension and that at 60 MPa the plastic deformation is 200%.

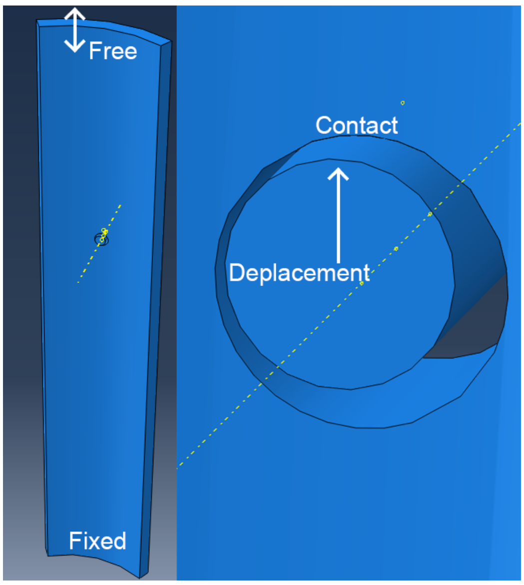


Figure 3. Finite element model and boundary conditions, detail to the screw position

## 4. RESULTS

### 4.1 Experimental

Fig. 4 shows the force and displacement for each of the test runs.

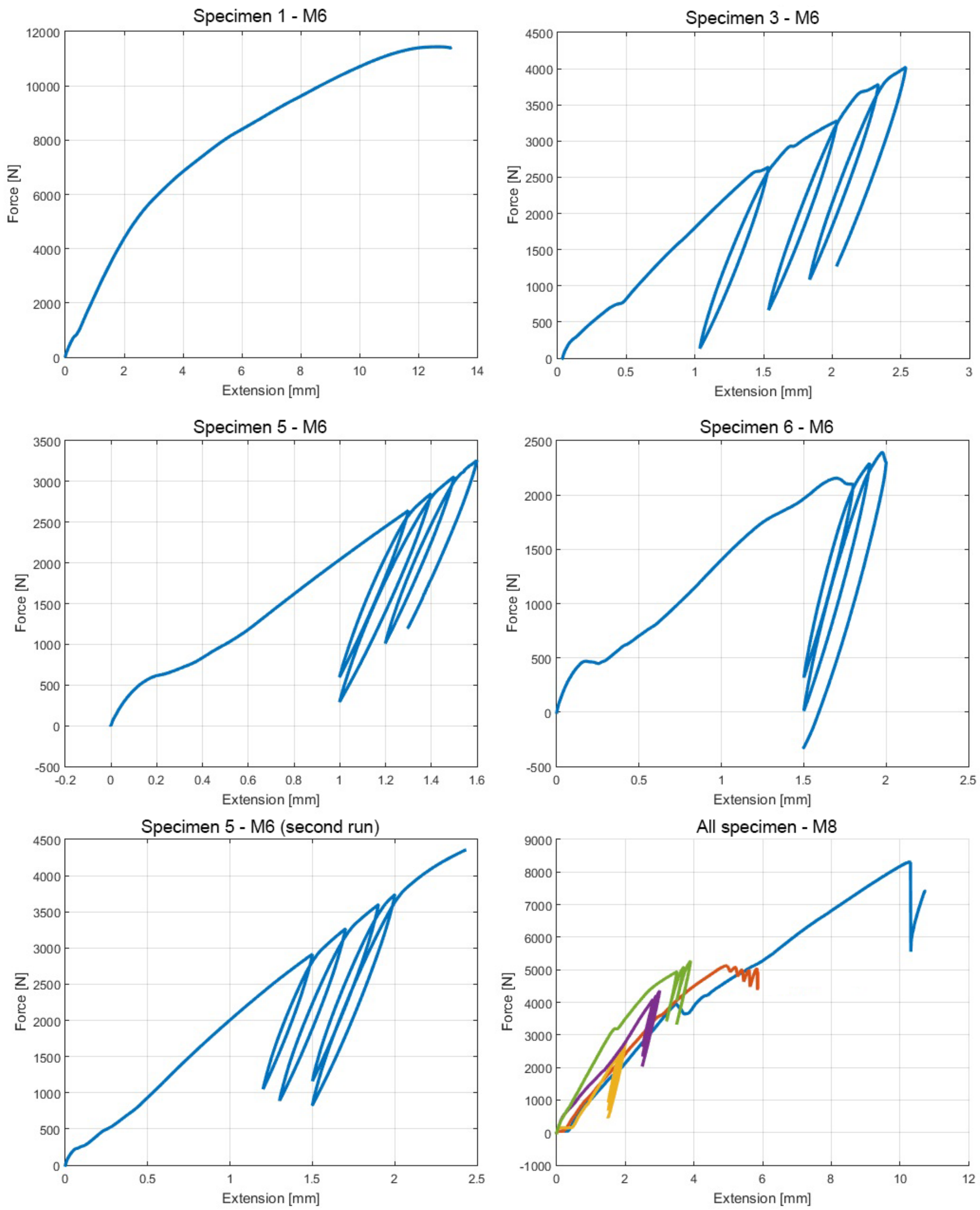


Figure 4. Extension vs force for all specimens

A static load test was used in the M6 specimen 1 and a cyclic test for the others. M6 specimen 5 was tested twice as the first run resulted in no visible damage. The tests with M8 screw generated inconsistent results, and were not used.

### 4.2 Computational

The finite element model was run with screw displacements of up to 1 mm. This is enough to observe the beginning of the plastic deformation.

Fig. 5 depicts the Von-Mises tension at 1 mm displacement and the resulting plastic strain. Plastic deformation starts to happen around 0.3 mm displacement,

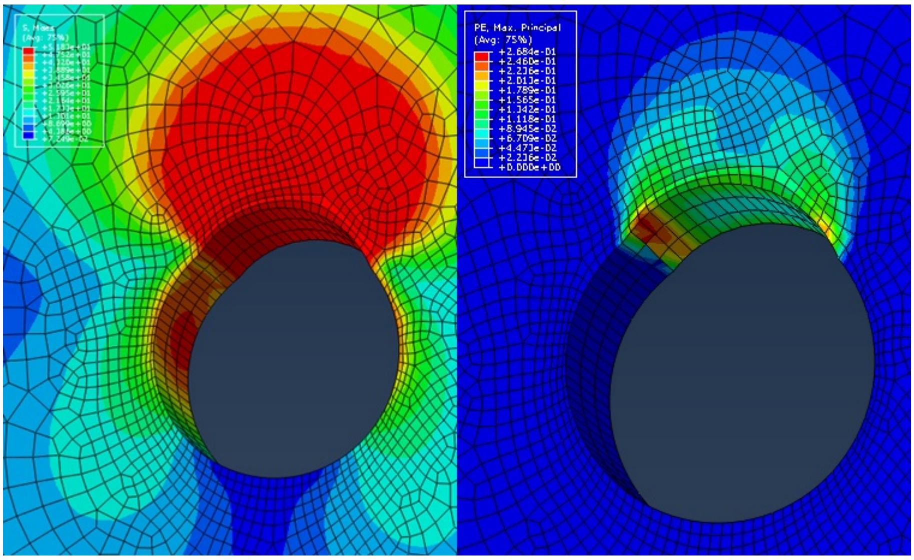


Figure 5. (a) Von Mises tension field (b) Plastic strain

At higher deformations, plastic strain is also expected to happen at the sides of the hole as can be observed experimentally. Note the red areas in this region in Fig 5(a), this tension is already very close to the plastic range.

### 4.3 Comparison between experimental and computational data

Fig. 6 shows the force applied at the screw for each displacement for both experimental and computational runs.

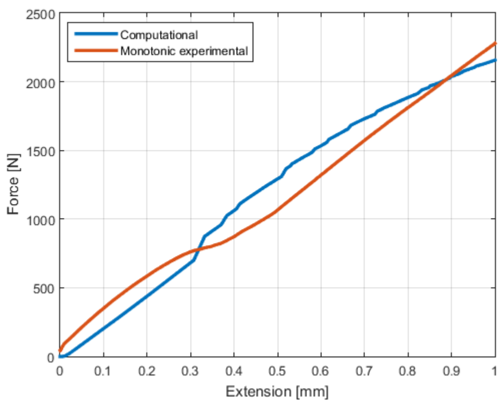


Figure 6. Force and extension plot for the simulation compared to the experiment

Both curves present a similar slope. The computational model reaches the plastic range earlier, this is most likely caused by the values used for the PVC non-linear modeling, which may differ from the PVC used in the tests. Note the change in slope just after 0.3 mm displacement, when plastic strain starts to happen, the computational model increased the stiffness while the experiment shows a reduced stiffness, this can also be explained by differences in the non-linear modeling and by possible inaccuracy of the test machine.

### 4.4 Fuselage thickness calculation

With the allowable bearing stress it is possible to define the minimum thickness for the fuselage in order to make it not suffer permanent damage.

Using the maximum thrust generated by the engine, the resultant force in each screw, in the worst case scenario, only 6 screws of the top of the fuselage, is as follows:

$$F_s = \frac{T_{max}}{6} \tag{1}$$

Where $F_s$ is the force each screw applies to the fuselage and $T_{max}$ is the maximum thrust of the engine.
The maximum stress to the fuselage is then:

$$\sigma = \frac{F_s}{A_c} \tag{2}$$

$A_c$ is the screw and fuselage contact area, approximated by a projected rectangle and defined as:

$$A_c = d \times t = 6mm \times 4.7mm = 28.2mm^2 \tag{3}$$

Where $d$ is the screw's working diameter and $t$ is the fuselage's thickness.
The ratio between $\sigma_{adm}$ and $\sigma$ must be greater than the desired safety factor, $1.5$ in this case. Therefore, the minimum fuselage thickness can be defined as:

$$\frac{\sigma_{adm}}{\frac{F_s}{t \times d}} \geq 1.5 \qquad t \geq \frac{1.5F_s}{d \times \sigma_{adm}} \tag{4}$$

$\sigma_{adm}$ is the bearing admissible strength, defined as:

$$\sigma_{adm} = \frac{F}{A_c} \tag{5}$$

$F$ is the average of the forces applied to the screws that was enough to cause plastic deformation in each specimen. A difference in slope of 2.5% from one cycle to the next was convetioned to indicate the occurrence of plastic deformation. These forces are shown in the following table.

| | |
|---|---|
| Specimen 2 | [Discarded results] |
| Specimen 3 | $2550.4N$ |
| Specimen 4 | $1465.5N$ |
| Specimen 5 | $2057.7N$ |
| Specimen 6 | $3436.3N$ |

This way:

$$F = \frac{(F_3 + F_4 + F_5 + F_6)}{4} \qquad F = 2377.5N \tag{6}$$

Finally: $\sigma_{adm} = 84.3MPa$
The maximum thrust estimated for this motor is 2050 N. Resulting in 342 N of force in each screw. Considering a desired safety factor of 1.5, the fuselage thickness should be at least 1.0 mm (from a bearing failure point of view), much thinner and lighter than the current fuselage with the typical PVC tube commercial thickness: 4.7mm

## 5. CONCLUSION

By having the allowable bearing stress, it was possible to reduce the thickness of the fuselage to a satisfactory and safe level, lowering its weight and increasing the rocket's performance.

It is worth noting that other failure modes should be investigated before actually reducing the fuselage thickness, as other failure modes may also happen, especially buckling.

The computational model will be calibrated using the experimental results, making easier to extend this results to other projects with this material.

This work has increased the technical and practical knowledge of the group and has had a very large didactic value to all involved. It will, certainly, have a great value to future the groups researches.

## 6. ACKNOWLEDGEMENTS

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## 8. RESPONSIBILITY NOTICE

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