Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 6	Month	: December
p-ISSN	: 1693-5462	Volume	: 21	Year	: 2023

Article Processing Dates: Received on 2023-08-04, Reviewed on 2023-08-26, Revised on 2023-08-27, Accepted on 2023-11-03 and Available online on 2023-12-30

Weight optimization of 200 mm diameter rocket motor tube using finite element method

Lasinta Ari Nendra Wibawa[1*], **Alit Daryana**[2], **Parid Saparudin**[2], **Wan Dedy Fitrah Indrayana**[2], **Handriyana**[2], **Asep Diana**[2], **TorisSobirin**[2]

[1]Directorate of Laboratory Management, Research Facilities, and Science and Technology Park, National Research and Innovation Agency (BRIN), Garut, 44175, Indonesia

[2]Technology Centre for Rocket, Research Organization for Aeronautics and Space, National Research and Innovation Agency (BRIN), Bogor, 16350, Indonesia

*Corresponding author: lasinta.ari.nendra.wibawa@brin.go.id

Abstract

The lightweight design of the rocket motor tube is a critical requirement for enhancing the rocket's flight performance. This study assesses the impact of wall thickness, cap thickness, and fillet radius on structural strength and the optimization of rocket motor tube weight using the finite element method with the assistance of Ansys software. A total of 12 finite element model variations, utilizing Aluminium 6061-T6, were developed and subjected to a uniform internal operating pressure load of 10 MPa. The design includes wall thickness variations of 8 mm and 10 mm, cap thickness options of 25 mm and 30 mm, and fillet radius dimensions of 20 mm, 25 mm, and 30 mm, allowing for a comprehensive comparison to achieve the required minimum safety factor while minimizing structural weight. The research concludes that increasing the fillet radius is a more recommended approach compared to increasing wall thickness and cap thickness. The results indicate that Model 9, with wall thickness, cap thickness, and fillet radius dimensions of 10 mm, 25 mm, and 30 mm, respectively, is the optimal choice due to its lightweight construction.

Keywords:
Finite element method, rocket motor tube, stress analysis, thin and thick-walled cylinder, weight optimization.

1 Introduction

The rocket motor is an essential element of a rocket. Rocket engines often function in situations characterized by elevated levels of pressure and temperature. The rocket motor comprises tube components, propellant, an igniter, an insulator, a cap, a liner, and a nozzle [1], [2]. Out of all these components, the rocket tube has the greatest dimensions. The weight of the rocket tube is a crucial factor in determining the range of the rocket.

The design of the rocket motor tube is generally determined by the internal pressure and the material employed. Rocket motor tubes with high internal pressure use thick-walled cylinders, and those with low internal pressure use thin-walled cylinders. Thin-walled cylinders are often used in materials with high yield strength, whereas thick-walled cylinders are required in materials with low yield strength.

Assuming that the rocket motor tube's insulator system performs properly and does not fail, the major need for the rocket motor tube is to endure the internal pressure it encounters. As a result, the choice of rocket motor tube material, even one with a low melting point, such as an aluminum alloy, is unimportant. The material utilized for this study was Aluminium 6061-T6, and it.

The research looks into the design of rocket tubes with different cap thicknesses, tube thicknesses, and fillet radiuses. As in previous experiments, increasing the cap thickness, tube thickness, and fillet radius reduces the maximum von Mises stress and increases the safety factor [3], [4]. However, each increment in cap thickness, tube thickness, and fillet radius results in an increase in the weight of the rocket tube. This study aims to determine the optimal configuration that results in the lightest rocket tube while ensuring an acceptable safety factor, with a minimum threshold of 2, as a requirement for rocket flight testing, similar to prior research [3]–[10]. This value surpasses the safety factor required for rocket static tests, which is 1.5 [11].

Previous research determined the suitable design for rocket motor tubes with a 550 mm diameter; however, analogous studies for rockets with a 200 mm diameter have not been undertaken [3], [4]. In fact, the design of the rocket motor tube varies with different rocket diameters. Each rocket diameter serves a distinct purpose, with varying missions and range requirements. The 200 mm diameter rocket in question was designed for trajectory correction purposes.

The rocket tubes in this study feature variations in tube thickness, with options of 8 mm and 10 mm, cap thickness, with options of 25 mm and 30 mm, and fillet radius, which can be 20 mm, 25 mm, or 30 mm. The selection of fillet radius changes is more important, since past research has shown that increasing the fillet radius is preferable than increasing wall thickness and cap thickness [3], [4].

The stress within the rocket motor tube is simulated using Ansys software to determine the optimal weight for the rocket motor tube while ensuring adequate safety factors. To date, Ansys software has demonstrated its capability in analyzing rocket motor tubes made from various materials, including composites and metals [12]–[14].

2 Materials and Methods

The rocket motor tube utilized in this investigation was fabricated from Al 6061-T6, selected for its benefits which include moderate tensile strength, resistance to corrosion, and lightweight characteristics. The mechanical characteristics of Al 6061-T6, obtained from material engineering data in the Ansys software, are displayed in Table 1.

Table 1. Mechanical properties of Aluminium 6061-T6.

Material	Density (g/cm³)	Yield strength (MPa)	Tensile strength (MPa)	Young modulus (GPa)
Al 6061-T6	2.71	259.2	313.1	69.04

The rocket motor functions on the principle of the pressure vessel design, which involves the storage of propellant fuels [1]. Pressure vessels are classified as either thin-walled or thick-walled depending on their dimensions. A thin-walled cylinder is characterized by a wall thickness that is smaller than 1/20 of the inner diameter (Di), whereas a thick-walled cylinder has a wall thickness that is larger than 1/20 of the inner diameter (Di).

This study used wall thicknesses measuring 8 mm and 10 mm. The cylinder is classified as a thin-walled cylinder due to its 8 mm wall thickness, which is less than 1/20 of its internal diameter. On the other hand, when the wall thickness is 10 mm, the cylinder is considered to be thick-walled because the thickness of the wall is greater than 1/20 of its internal diameter.

Thin-walled cylinders experience stress in three directions: hoop (circumferential), longitudinal (axial), and radial. The stress equations for thin-walled cylinders in the hoop, longitudinal, and radial directions are given by Eq. 1 – Eq. 3.

$$(\sigma_h)_{max} = \left(\frac{P_iD_i}{2t}\right) \quad (1)$$

$$(\sigma_l)_{max} = \left(\frac{P_iD_i}{4t}\right) \quad (2)$$

$$(\sigma_r)_{max} = -\,p_i \quad (3)$$

The maximum stress equation for thick-walled cylinders in the hoop, axial, and radial directions are Eq. 4 – Eq. 6.

$$(\sigma_h)_{max} = p_i\left(\frac{r_o^2 + r_i^2}{r_o^2 - r_i^2}\right) \quad (4)$$

$$(\sigma_l)_{max} = p_i\left(\frac{r_i^2}{r_o^2 - r_i^2}\right) \quad (5)$$

$$(\sigma_r)_{max} = -\,p_i \quad (6)$$

where:

$(\sigma_h)_{max}$= maximum hoop stress (MPa)
$(\sigma_l)_{max}$ = maximum longitudinal stress (MPa)
$(\sigma_r)_{max}$= maximum radial stress (MPa)
p_i = internal pressure (MPa)
D_i = inner diameter of cylinder (mm)
r_i = inner radius of cylinder (mm)
r_o = outer radius of cylinder (mm)
t = wall thickness of cylinder (mm)

The von Mises stress analysis of the rocket motor tube was conducted using the finite element method with the assistance of Ansys software. Ansys is among the most widely used software for finite element analysis [15], [16]. It is also extensively employed for assessing stress concentration in both thick-walled and thin-walled cylinders [17]–[20].

The reference model utilized in this investigation is a rocket motor tube, which may be classified as both a slender-walled and stout-walled cylinder, with an external diameter of 200 mm. The length of the cylinder in this model is 500 mm, and the wall thickness can range from 8 mm to 10 mm. The cap thickness can vary between 25 mm and 30 mm, while the fillet radius can be modified to either 20 mm, 25 mm, or 30 mm.

The geometric arrangement of the thin-walled cylinder, referred to as 'Model 1', is depicted in Fig. 1. The simulation employed in this work utilizes a 90-degree section of the solid cylinder model. The several configurations of the rocket motor tube's shape are outlined in Table 2. Table 3 presents the quantities of nodes and elements for different models.

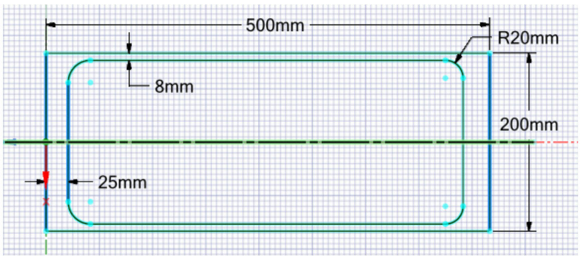

Fig. 1. Design geometry of thin-walled cylinder (Model 1) with 8 mm wall thickness, 25 mm cap thickness, and 20 mm fillet radius.

Table 2. Rocket motor tube design geometry variation

Parameters	Value
Length of cylinder (*L*)	500 mm
Outer diameter of cylinder (*D_O*)	200 mm
Wall thickness (*t_w*)	8 mm and 10 mm
Cap thickness (*tc*)	25 mm and 30 mm
Fillet radius (*R*)	20 mm, 25 mm, 30 mm
Internal pressure (*P*)	10 MPa
Mesh size	3 mm

Table 3. The number of nodes and number of elements for various models.

Model	t_w (mm)	*tc* (mm)	R (mm)	Number of nodes	Number of elements
1	8	25	20	74680	42320
2	8	25	25	73479	41547
3	8	25	30	73008	41354
4	8	30	20	74577	42458
5	8	30	25	72686	41067
6	8	30	30	74960	42662
7	10	25	20	76354	43771
8	10	25	25	76621	43911
9	10	25	30	76192	43662
10	10	30	20	76608	43954
11	10	30	25	75348	43186
12	10	30	30	75355	43178

Fig. 2 depicts the boundary conditions for the finite element simulation of rocket motor tubes using Ansys software, including the loading condition (above) and frictionless support (below).

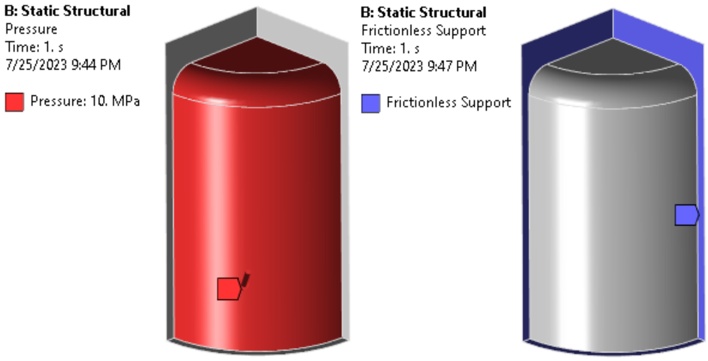

Fig. 2. Boundary conditions for finite element simulation of rocket motor tubes using Ansys software: loading condition (above) and frictionless support (below).

3 Results and Discussion

The static stress analysis is crucial for the first and thorough evaluation of the performance of the rocket motor tube design. This chapter showcases the outcomes of finite element simulations, which are used to evaluate and compare the structural integrity and safety considerations of various parameters under investigation.

Fig. 3 illustrates the highest von Mises stress (above) and the design factor of safety (below) for Model 1. This model has an 8 mm wall thickness, 20 mm cap thickness, and 25 mm fillet radius. Table 4 provides a summary of the influence of wall thickness, cap thickness, and fillet radius on the maximum von Mises stress for all 12 models that were studied.

Increasing the wall thickness, cap thickness, and fillet radius reduces the maximum von Mises stress. However, these three variations also result in an overall increase in the weight of the rocket tube (see Fig. 4). It's worth noting that all maximum von Mises stress values remain below the yield strength of Al 6061-T6 material, which is 259.2 MPa. This implies that the rocket motor tube is considered safe for all variations, as yielding is one of the failure criteria the rocket industry recognises, in addition to potential cracking issues [21].

Fig. 4 provides a complete presentation of how the design safety factor and structural weight are affected by the wall thickness, cap thickness, and fillet radius. An increase in wall thickness, cap thickness, and fillet radius results in a corresponding increase in the design safety factor. Nevertheless, this augmentation is not inherently beneficial, as it results in an elevated mass for the rocket motor tube. Only three variations of the rocket model match the minimum safety factor criterion of 2 for the rocket tube design. The lightest form of the rocket tube has a wall thickness of 10 mm, a cap thickness of 25 mm, and a fillet radius of 30 mm. It weighs 12.10 kg. The rocket tube with the second lowest weight has a mass of 12.63 kg. This weight is obtained by using specific dimensions, including a wall thickness of 10 mm, a cap thickness of 30 mm, and a fillet radius of 25 mm. The third rocket tube, which is the heaviest among the lightest ones, has a weight of 12.79 kg. It has a wall thickness of 10 mm, a cap thickness of 30 mm, and a fillet radius of 30 mm.

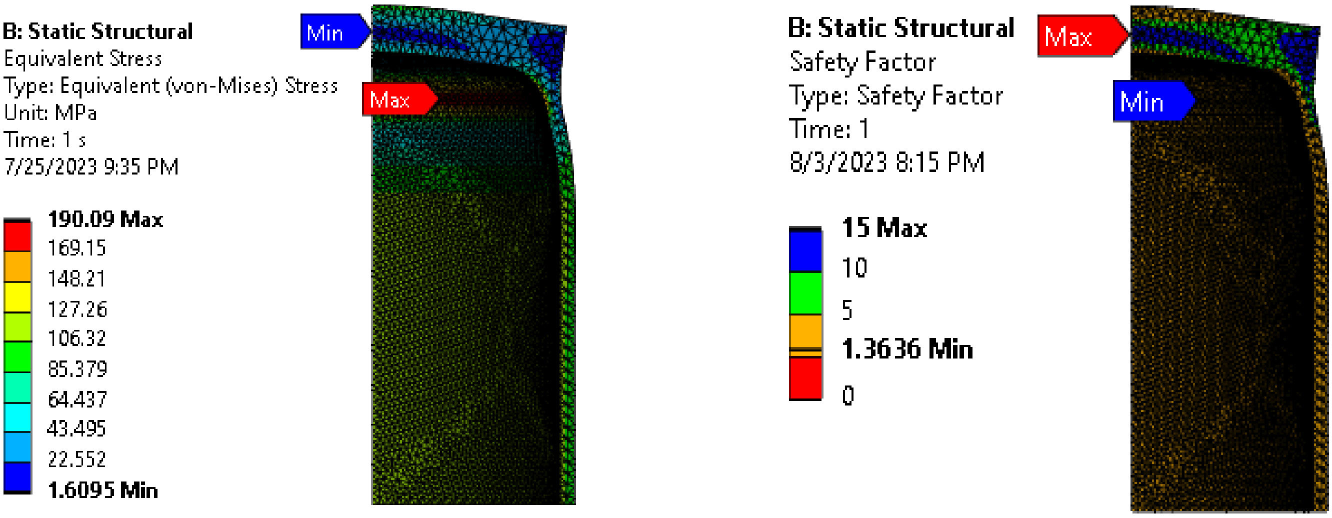

Fig. 3. Maximum von Mises stress (above) and safety factor (below) of a rocket motor tube with 8 mm wall thickness, 25 mm cap thickness, and 20 mm fillet radius.

It can be concluded that none of the models using the smallest wall thickness of 8 mm met the requirements (failed) because the safety factor obtained did not exceed the value 2. Only three models, namely Model 9, Model 11, and Model 12, met the criteria. From this data, it is evident that increasing the fillet radius is more effective than increasing wall thickness and cap thickness. This study aligns with previous research results [3], [22].

A change in geometric shape introduces additional stresses, known as stress concentrations, which go beyond the calculated stresses. The larger the fillet radius, the less impact stress concentration has on the critical stress area. In a closed cylindrical fluid container, the exerted pressure is distributed uniformly in all directions. Stress concentration can be mitigated in spherical pressure vessels due to the absence of sudden geometric changes. In theory, a spherical pressure vessel exhibits superior strength compared to a cylindrical pressure vessel with the same wall thickness and is an ideal shape for withstanding internal pressure. However, this doesn't hold for cylindrical pressure vessels, both thin-walled and thick-walled cylinders. In cylindrical pressure vessels, geometric variations in the fillet radius result in uneven stress distribution along the tube's wall. Consequently, if the fillet radius is small, deformation occurs more abruptly, limiting the capacity for even redistribution of internal pressure. As a result, actual stress exceeds theoretical stress at the bottom of the fillet on the narrower side.

Table 4. Effect of wall thickness, cap thickness, and fillet radius on the maximum von Mises stress.

Model	t_w (mm)	*tc* (mm)	R (mm)	Maximum von Mises stress (MPa)
1	8	25	20	190.09
2	8	25	25	162.69
3	8	25	30	141.83
4	8	30	20	167.58
5	8	30	25	147.08
6	8	30	30	129.81
7	10	25	20	156.67
8	10	25	25	135.32
9	10	25	30	117.72
10	10	30	20	138.51
11	10	30	25	120.80
12	10	30	30	107.24

Fig. 4.The chart of influence of different rocket motor tube models on safety factors and design weight (model failure criteria: safety factor < 2).

Hoop stress is consistently tensile, and the maximum hoop stress always occurs at either the inner or outer radius depending on the direction of the pressure gradient [23]. In this study, the cylinder was subjected only to internal pressure, resulting in the maximum hoop stress occurring at the inner radius ($r = r_i$).

Fig. 5 illustrates the maximum hoop stress (above) and longitudinal stress (below) for Model 1, which features a wall thickness of 8 mm, cap thickness of 20 mm, and a fillet radius of 25 mm. The maximum stress values for hoop and longitudinal stress are 120.22 MPa and 55.09 MPa, respectively, with the highest stress occurring at node 355.

Validation of the results was conducted by comparing the outcomes of the finite element simulation with the analytical calculations for the maximum hoop and longitudinal stresses, while considering fixed boundary conditions. Table 5 presents the comparison between analytical calculations and the simulation of maximum hoop stress, while Table 6 displays the comparison between analytical calculations and the simulation of maximum longitudinal stress. The findings indicate that the percentage discrepancy for the maximum hoop stress in thin-walled cylinders, spanning from Model 1 to Model 6, is below 5 percent. The percentage error for the maximum longitudinal stress in thick-walled cylinders, when comparing Model 7 to Model 12, is below 0.5 percent.

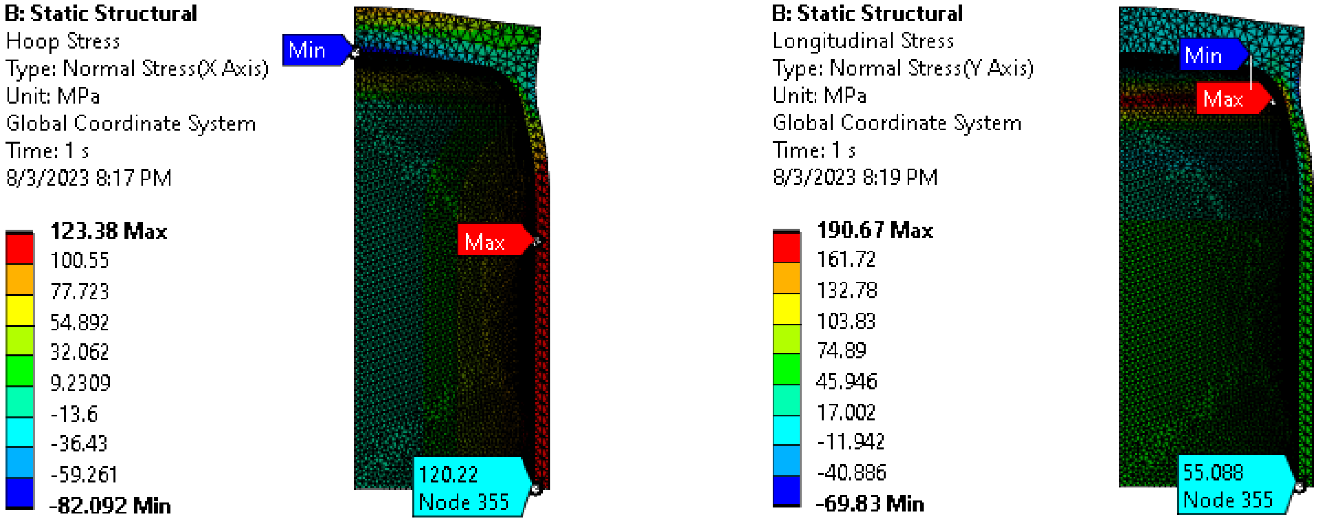

Figure 5. The maximum hoop stress (above) and longitudinal stress (below) of cylinder model 1 with 8 mm wall thickness, 20 mm cap thickness, and 25 mm fillet radius.

Table 5. Comparative analysis of analytical calculations and maximum hoop stress simulation.

Model	Hoop stress-analytic (MPa)	Hoop stress-FEA (MPa)	Error (%)
1	115.00	120.22	4.54
2	115.00	120.22	4.54
3	115.00	120.21	4.53
4	115.00	120.22	4.54
5	115.00	120.22	4.54
6	115.00	120.21	4.53
7	95.26	95.26	0.00
8	95.26	95.26	0.00
9	95.26	95.26	0.00
10	95.26	95.25	0.01
11	95.26	95.25	0.01
12	95.26	95.23	0.03

Table 6. Comparative analysis of analytical calculations and maximum longitudinal stress simulation.

Model	Long. stress-analytic (MPa)	Long. stress-FEA (MPa)	Error (%)
1	57.50	55.09	4.19
2	57.50	55.09	4.19
3	57.50	55.08	4.30
4	57.50	55.09	4.19
5	57.50	55.08	4.30
6	57.50	55.08	4.30
7	42.63	42.58	0.12
8	42.63	42.58	0.12
9	42.63	42.58	0.12
10	42.63	42.58	0.12
11	42.63	42.60	0.07
12	42.63	42.56	0.16

4 Conclusion

The research has examined the impact of wall thickness, cap thickness, and fillet radius on the structural strength and weight optimization of rocket motor tubes through the utilization of Ansys software. A total of 12 models were subjected to simulation using Ansys. The results of the finite element simulations indicate that increasing the fillet radius is more effective than increasing the wall thickness and cap thickness. The lightest rocket model was achieved with wall thickness, cap thickness, and fillet radius dimensions of 10 mm, 25 mm, and 30 mm, respectively, denoted as "Model 9".

References

[1] L. A. N. Wibawa, K. Diharjo, W. W. Raharjo, and B. H. Jihad, “Stress Analysis of Thick-Walled Cylinder for Rocket Motor Case under Internal Pressure,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 70, no. 2, pp. 106–115, 2020.

[2] F. H. Reema *et al.*, “Theoretical Aspects on Design and Performance Characteristics for Solid Rocket Motor,” *Int. J. All Res. Educ. Sci. Methods*, vol. 10, no. 2, pp. 2455–6211, 2022.

[3] L. A. N. Wibawa and Tuswan, “Lightweight optimization design of thin-walled cylindrical rocket motor tube using FEA,” *AIP Conf. Proc.*, vol. 2590, no. May, 2023.

[4] L. A. N. Wibawa and Tuswan, “Effect of cylinder length on the ratio of safety factor and weight of rocket motor tube using thin-walled cylinder,” *AIP Conf. Proc.*, vol. 2590, no. May, 2023.

[5] S. Setiadi, B. Wicaksono, K. Kurdianto, and B. H. Jihad, “The Data Acquisition Role on Static Test for Validation of RX 320 Rocket Motor Design,” *Spektra J. Fis. dan Apl.*, vol. 6, no. 1, pp. 9–18, 2021.

[6] K. F. Foster *et al.*, “Design and integration of a high-powered model rocket – I,” *AIAA Scitech 2020 Forum*, vol. 1 PartF, no. January, pp. 1–11, 2020.

[7] V. Sella *et al.*, “Development of a nytrox-paraffin hybrid rocket engine,” *AIAA Propuls. Energy 2020 Forum*, pp. 1–29, 2020.

[8] J. Lee, T. S. Roh, H. Huh, and H. J. Lee, “Performance Analysis and Mass Estimation of a Small-Sized Liquid Rocket Engine with Electric-Pump Cycle,” *Int. J. Aeronaut. Sp. Sci.*, vol. 22, no. 1, pp. 94–107, 2021.

[9] Z.-B. Shen, L. Zhang, and Y.-F. Li, “Structural integrity analysis and experimental investigation for solid rocket motor grain subjected to low temperature ignition,” *MATEC Web Conf.*, vol. 293, no. 201 9, p. 04005, 2019.

[10] J. J. Hansen *et al.*, “Student design of a bipropellant liquid rocket engine and associated infrastructure,” *AIAA Propuls. Energy 2020 Forum*, pp. 1–36, 2020.

[11] Setiadi, B. Wicaksono, A. Riyadl, B. H. Jihad, and A. Apriyanto, *Analytical Calculation, Numerical and Hydrostatic Test as a Validation of Material Strength of the New RX-450 Rocket Motor Tube*. Springer Singapore, 2020.

[12] V. Ramanjaneyulu, V. Balakrishna Murthy, R. Chandra Mohan, and C. Naga Raju, “Analysis of Composite Rocket

Motor Case using Finite Element Method," *Mater. Today Proc.*, vol. 5, no. 2, pp. 4920–4929, 2018.

[13] B. Niharika and B. B. Varma, "Design and Analysis of Composite Rocket Motor Casing," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 455, no. 1, 2018.

[14] M. A. Muhammad, Z. Salleh, A. H. Abdul Hamid, M. J. Sujana, and K. Kamaludin, "Finite Element Analysis for Rocket Motor Case Under Internal Pressure and Thermal Loads," *J. Appl. Eng. Des. Simul.*, vol. 2, no. 2, pp. 11–21, 2022.

[15] L. A. N. Wibawa, "Effect of Fillet Radius of UAV Main Landing Gear on Static Stress and Fatigue Life using Finite Element Method," *J. Phys. Conf. Ser.*, vol. 1811, no. 1, 2021.

[16] L. A. N. Wibawa, "Effect of Bolt Hole Size on Static Stress and Fatigue Life of UAV Main Landing Gear Using Numerical Simulation," *J. Phys. Conf. Ser.*, vol. 1811, no. 1, 2021.

[17] A. F. Mohamed, "Finite Element Analysis for Stresses in Thin-Walled Pressurized Steel Cylinders," *Int. J. Sci. Eng. Res.*, vol. 9, no. 3, pp. 201–204, 2018.

[18] L. A. N. Wibawa, "Numerical Study of The Effect of Wall Thickness and Internal Pressure on Von Mises Stress and Safety Factor of Thin-Walled Cylinder for Rocket Motor Case," *JST (Jurnal Sains dan Teknol.*, vol. 9, no. 1, pp. 30–38, 2020.

[19] L. A. N. Wibawa, K. Diharjo, W. W. Raharjo, and B. H. Jihad, "Pengaruh Ketebalan Cap dan Tekanan Internal terhadap Tegangan Von Mises Silinder Berdinding Tebal untuk Tabung Motor Roket," *Teknik*, vol. 41, no. 2, pp. 111–118, 2020.

[20] P. Sai Teja, B. Sudhakar, A. D. Dhass, R. Krishna, and M. Sreenivasan, "Numerical and experimental analysis of hydroxyl-terminated poly-butadiene solid rocket motor by using ANSYS," *Mater. Today Proc.*, vol. 33, pp. 308–314, 2020.

[21] W. M. W. Mohamed, Z. Salleh, A. H. A. Hamid, M. A. Muhammad, and N. A. Salleh, "Thermal Analysis on Solid Rocket Motor Casing," *Int. Trans. J. Eng. Manag. Appl. Sci. Technol.*, vol. 12, no. 9, pp. 1–13, 2021.

[22] L. A. N. Wibawa, K. Diharjo, W. Raharjo, and B. H. Jihad, "The Effect of Fillet Radius and Length of The Thick-Walled Cylinder on Von Mises Stress and Safety Factor for Rocket Motor Case," *AIP Conf. Proc.*, vol. 2296, no. 1, 2020.

[23] L. Skinner, "Snubbing Theory and Calculations," in *Hydraulic Rig Technology and Operations*, Gulf Professional Publishing, 2018, pp. 189–275.