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ANALYTICAL AND NUMERICAL ANALYSIS OF AXIAL STRESSES IN A HIGH EXPLOSIVE ROCKET ASSISTED PROJECTILE BODY DURING ITS LAUNCH

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Abstract: *The paper presents analytical and numerical analysis of axial stresses in a novel designed high explosive rocket assisted projectile body during its launch. Classical theoretical approach and finite element method (FEM) were used for this purpose. The novel projectile design is based on the M107 and M549 projectiles, enhancing range and withstanding the barrel pressure from the propellant charges used. The goal of the research is to present that the obtained stresses results, in characteristic cross-sections, founded by the classical theoretical and numerical methods, give good agreement. The obtained results are helpful in a preliminary stage for the design of extended range projectiles. The analysis of axial stresses enables the selection of the rocket motor case material and its mechanical and thermal processing.*

Keywords: *Stress analysis, Finite Element Method analysis, High Explosive Rocket Assisted Projectile*

1. INTRODUCTION

During the initial phases of projectile design, it is important to determine the state of stress in the projectile body. One of the major concerns is to ensure that projectile is capable of surviving gun launch conditions on the account of firing stresses [1,2].

The development of rocket assisted projectiles enabled to extend the range and improve the performance of traditional artillery projectiles. This research evaluates the axial stress conditions of projectile body and rocket motor case of the novel designed high explosive rocket-assisted (HERA) projectile using classical theoretical methods and finite element methods (FEM), aiming to provide a comprehensive and reliable analysis of the design's safety and performance.

The study's results offer valuable insights into the necessary mechanical and thermal processing treatments to ensure the projectile's durability and effectiveness.

2. ANALYTICAL STRESS ANALYSIS

Analytical stress analysis is a great tool for understanding projectile stress distribution, providing quick and exact solutions within the scope of its assumptions [3]. It serves as a critical step in the design and preliminary analysis of projectiles.

Until the appearance of modern computers, classical theoretical methods based on analytical calculation were the only way to determine the stress state of artillery projectile body. This paper deals with 155 mm novel designed rocket-assisted (HERA) projectile (shown in Fig.1).

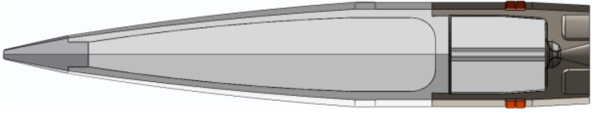

Figure 1. Newly designed 155mm HERA projectile

The projectile has the following characteristics: reference diameter (cal.) 155mm, total length ~ 5.61 cal., nose length ~ 3.37 cal., boat-tail length ~ 0.55 cal., center of gravity (CG) from nose ~ 3.53 cal., explosive

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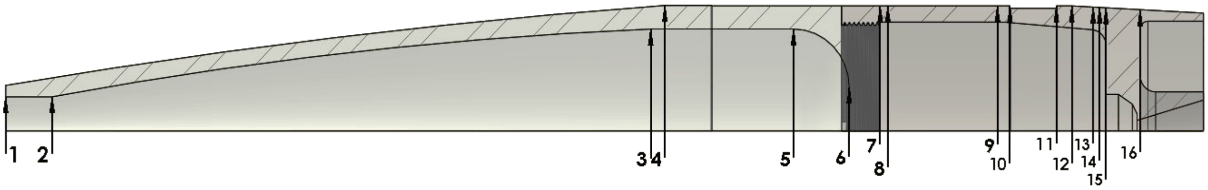

Figure 2. Cross-sections of the projectile body and rocket motor case

Table 1. Cross-sections characteristics

Location of **i**th section	Forward distance of **i**th section [mm]	Outer radius r_o [mm]	Inner radius r_i [mm]	Weight of parts forward of **i**th section m_A [kg] ***(e_c = 6mm)***	Weight of parts forward of **i**th section m_A [kg] ***(e_c = 10mm)***	Weight of parts forward of **i**th section m_A [kg] ***(e_c = 12mm)***
1	0	28	21	0.57		
2	30	32.75	21	1.16		
3	416.88	76.71	62.82	16.82		
4	426.05	77.37	62.82	17.45		
5	509.21	77.09	62.82	23.27		
6	545.21	77.09	26.83	26.36		
7	565.21	77.09	0	29.29		
8	570.21	77.09	71.09	29.5	29.57	29.6
9	641.11	77.09	71.09	32.66	33.7	34.19
10	649.05	77.09	70.77	33.02	34.16	34.7
10'	649.05	75.95	70.77	33.02	34.16	34.7
11	679.04	77.09	68.31	34.73	36.27	37.01
11'	679.04	75.95	68.31	34.73	36.27	37.01
12	689.05	77.09	67.49	35.26	36.94	37.73
13	702.95	76.36	66.35	36.02	37.87	38.75
14	706.95	76.15	64.69	36.23	38.12	39.05
15	711.21	75.93	22.5	36.49	38.44	39.37
16	733.21	74.78	7.05	39.41	41.37	42.29

charge mass ~ 7 kg, rocket motor propellant mass ~ 3 kg.

Changes in geometry can notably affect the stress distribution, making it required to analyze these points with higher precision. To calculate the stress state in a projectile body it is necessary to split the projectile body into cross-sections [4], as shown Fig.2. and summarized in Table 1. When calculating the stress of the rocket motor (RM), different casing wall thicknesses (***e_c***) were taken into consideration as follows: 6, 10 and 12 mm, as well as two types of gun propellant charge with 9 kg (Zone 8) and 13 kg of propellant (Zone 9). This allows to consider different firing scenarios by combining the chosen thicknesses (***e_c***) with the two types of gun propellant charge.

Based on knowledge of principal stresses and von Mises failure criteria, one can determine the equivalent stress [5]. The axial stresses $(\sigma_P)_{i\text{-}i}$ in the zones of different cross-sections were calculated using different equations [4,6,7], as follows:

- Cross sections 1-10, the zone in front of driving band:

$$\left(\sigma_P\right)_{i\text{-}i} = \frac{m_A}{S_{i\text{-}i}} a_{\max} \tag{1}$$

- Cross sections 11-12, the zone behind of driving band, in front of rear cone:

$$\left(\sigma_P\right)_{i\text{-}i} = \frac{1}{S_{i\text{-}i}}\left(m_A a_{\max} + nF_{na}\right) \tag{2}$$

- Cross sections 13-16, the zone of rear cone:

$$\left(\sigma_P\right)_{i\text{-}i} = \frac{1}{S_{i\text{-}i}}\left[m_A a_{\max} + nF_{na} - P_{pr}(s_c - r_o^2\pi)\right] \tag{3}$$

Where are:

$$a_{\max} = \frac{P_{pr} s_c}{m} \tag{4}$$

$$F_{na} = N(\sin\varphi + f\cos\varphi) \tag{5}$$

$$N = \frac{I_x}{n}\frac{4}{d^2}\frac{\tan\varphi}{\cos\varphi}\frac{P_{pr}}{m}s_c \tag{6}$$

$$s_c = \frac{d^2\pi}{4} + \frac{en}{2}\left(d_0 - d\right) \tag{7}$$

When designing a new projectile, the stress calculation is performed with a pressure P_{pr} [MPa] that is higher than the maximum pressure P_m [MPa] of the powder gases in the gun barrel under normal conditions:

$$P_{pr} = kP_m \tag{8}$$

The parameters in equations (1-8) are defined as follows: a_{max} [g] maximum acceleration in the barrel during launch, m_A [kg] mass of projectile's part left from cross section *i-i* (including mass of fuse, explosive charge filling and rocket motor propellant), m [kg] projectile total mass, s_c [mm^2] bore area, F_{na} [N] axial force on one tooth of driving band, N [N] normal force on active surface of driving band's tooth, I_x [kg·mm^2] axial moment inertia of projectile, n [/] number of grooves, d_o [mm] outer diameter, d [mm] inner diameter, φ [°] angle of groove's twisting, f [/] friction coefficient (steel – cooper), k [/] safety factor, e [mm] groove's width. $S_{i\text{-}i}$ [mm^2] represents area of projectile body in cross-section *i-i* which can be calculating using equation:

$$S_{i\text{-}i} = \pi(r_o^2 - r_i^2) \tag{9}$$

Input data for analytical calculation of the axial stresses for the 155mm newly designed HERA projectile are given in Table 2.

Table 2. Input data for calculation

Input data	Unit	Value
Number of grooves n	[/]	48
Inner diameter d	[mm]	155
Outer diameter d_o	[mm]	156.56
Groove's width e	[mm]	5.071
Angle of groove's twisting φ	[°]	8.9
Friction coefficient f	[/]	0.2
Safety factor k	[/]	1.3
Projectile total mass for each e_c case (m_1, m_2, m_3)	[kg]	(40.72, 42.67, 43.6)
Axial moment inertia of projectile for each e_c case (I_{x1}, I_{x2}, I_{x3})	[kg.m^2]	(0.13, 0.14, 0.15)
Maximum pressure for each e_c case (P_{m1}, P_{m2}, P_{m2}) when using 9kg of propellant charge)	[MPa]	(160, 166, 169)
Maximum acceleration for each e_c case (a_{max1}, a_{max1}, a_{max1}) when using 9kg of propellant charge)	[·10^{3}g]	(9. 92, 9. 82, 9. 79)
Maximum pressure for each e_c case (P_{m4}, P_{m5}, P_{m6}) when using 13kg of propellant charge	[MPa]	(258, 270, 275)
Maximum acceleration for each e_c case (a_{max1}, a_{max1}, a_{max1}) when using 9kg of propellant charge)	[·10^3 g]	(16. 02, 15. 98, 15. 93)

In this study, the projectile rotation was not taken into account (generally, axial stresses are dominant during the launch phase of projectiles [6]). Additionally, the influence of other parts of the projectile, including high explosive charge, rocket motor propellant charge as well as stresses in all components of the projectile were not included in the analysis also.

Graphic results with values of stresses in characteristic cross sections calculated by analytical method are shown in Figs.3 and 4, for each of the three casing wall thicknesses cases and for the two types of propellant charge.

The obtained values were compared with the material limits of the projectile components as it is high-fragmentation steel (HF-1) for the high explosive warhead and high-strength steel (AISI 4340) for the rocket motor case. The critical axial stress for these materials is 750 MPa [8] and 1500 MPa [9], respectively. Based on the analysis results, the rocket motor case wall thickness was decided to be 10 mm.

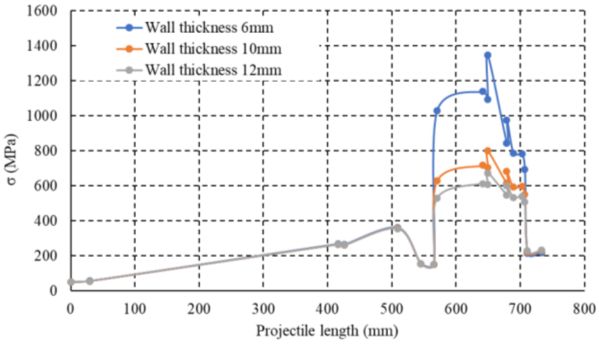

Figure 3. Values of stresses in characteristic cross-sections for 9 kg gun propellant charge

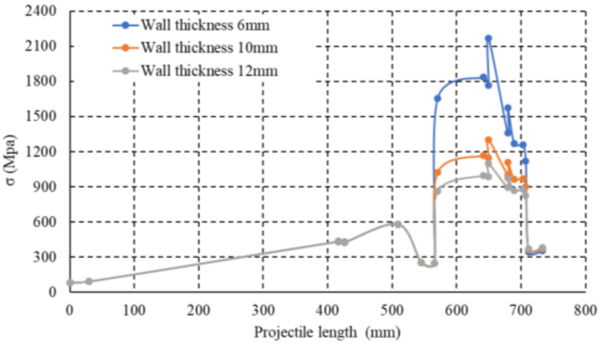

Figure 4. Values of stresses in characteristic cross-sections for 13 kg gun propellant charge

3. FINITE ELEMENT METHOD AND COMPARATIVE ANALYSIS

Finite Element Method (FEM) analysis involves a series of steps to model, simulate, and analyze the physical behavior of components and assemblies under various conditions [10]. Also, it includes defining loads and boundary conditions [10] (shown in Fig.5), which divides the model into smaller and simpler elements.

The projectile body model retains the same material and geometric properties in all cross sections along the longitudinal axis of symmetry, the fuze is not modelled

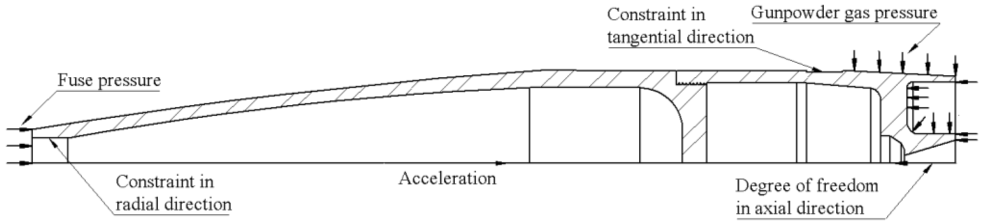

Figure 5. Loads and boundary conditions

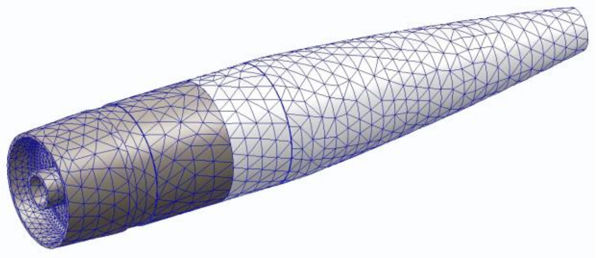

Figure 6. Numerical mesh for projectile model

Figure 7. Stress condition for a model with 9 kg propellant charge

Figure 8. Stress condition for a model with 13 kg propellant charge

[4]. The influence of fuze (weight 0.86 kg) is replaced by an equivalent pressure acting on the front area of the projectile body.

The structure is modelled with 19536 elements and 34402 nodes. Max size of element is about 22 mm and minimal size is about 4 mm. Numerical mesh for the given projectile model is shown in Fig.6.

The stress conditions based on the model with 10 mm of casing wall thickness are shown in Figs.7 and 8 for the both gun propellant charges with 9 kg. and 13 kg.

The maximum value of the stress in projectile body occurs at the place of the rocket motor, for the 9 kg propellant charge maximum value of the stress is 799,7 MPa, and for 13 kg propellant charge is 1249,2 MPa.

Stress distribution obtained using analytical and numerical methods are shown in Fig.9 for propellant charge with 9 kg and in Fig.10 for 13 kg.

It has been shown that the difference between results obtained using analytical and numerical methods is higher in the case with 9 kg of gun propellant charge. In both cases, the highest difference is observed for the maximum value of the stress. The general difference doesn't impact the choice of the material of the rocket motor body.

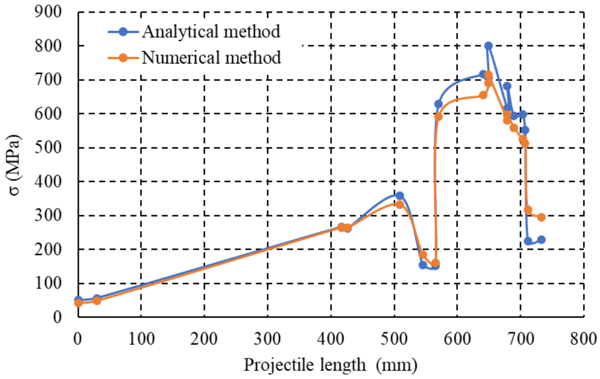

Figure 9. Stress distribution obtained using analytical and numerical methods with 9 kg propellant charge

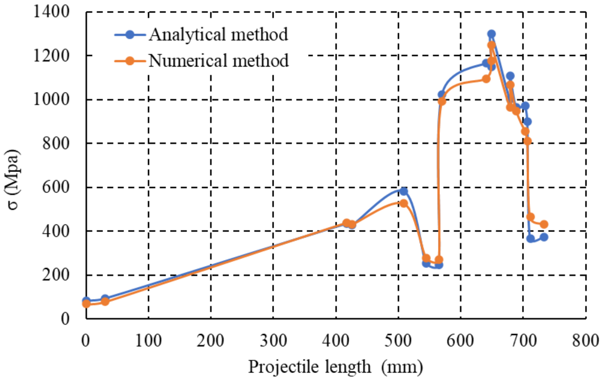

Figure 10. Stress distribution obtained using analytical and numerical methods with 13 kg propellant charge

4. CONCLUSION

The primary objective of this paper is to present that stress analysis enables the selection of the rocket motor case material for the newly designed rocket assisted projectile.

The general difference between results obtained using analytical and numerical methods shows that choice of method is not crucial for the choice of body materials of both the rocket motor and the high explosive warhead.

Compared to the analytical method, the numerical method provides visual distribution of projectile stress. Finally, this paper presents methodologies that helps in design of HERA projectiles or similar artillery shells.

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