41st Danubia-Adria Symposium Advances in Experimental Mechanics
September 23-26, 2025, Kragujevac, Serbia

Original scientific paper

DOI: 10.46793/41DAS2025.067T

NUMERICAL ANALYSIS OF BARREL LOADS IN THE DESIGN PHASE OF AN ARTILLERY SYSTEM

Bogdan TODOROVIĆ[1], Aleksandra OBRADOVIĆ[2], Nebojša HRISTOV[3], Damir JERKOVIĆ[4]

[1.] 0009-0008-4572-1318, Matikon GmbH & Co. KG, Milana Mijalkovića 21, Jagodina, Serbia, E-mail: bogdanto2000@gmail.com;

[2.] 0000-0001-7973-8590, Military Technical Institute, Ratka Resanovića 1, Belgrade, Serbia, E-mail: aleksandrazivkovicbm@gmail.com;

[3.] 0000-0002-8163-2223, University of Defence in Belgrade, Military Academy, Veljka Lukića Kurjaka 33, Belgrade, Serbia, E-mail: nebojsahristov@gmail.com;

[4.] 0000-0001-5182-7057, University of Defence in Belgrade, Military Academy, Veljka Lukića Kurjaka 33, Belgrade, Serbia, E-mail: damir.jerkovic@va.mod.gov.rs.

1. Introduction

The production and design of artillery weapons is a complex and expensive process. Usually, the design of such systems is based on the experience of previous models or their modifications. The tendency is to unify most of the basic elements, which are also used in other weapon systems. Tactical requirements generally define initial and boundary conditions during project setup. The basic element of every classic artillery system is the barrel, which is the most complex to design and produce.

The purpose of the paper is to present the process of barrel redesign, specifically changing a caliber of an existing barrel to a new caliber, taking into account various methods in order to determine the optimal design that would ensure the longest possible service life of the weapon system. In addition to the barrel design, an optimization of the propellant charge was carried out, i.e., variation of the gunpowder characteristics that directly affect the internal ballistic processes occurring in the barrel during firing.

The barrel was redesigned based on known data from an existing system and results obtained from the optimal configuration of gunpowder characteristics. The practical application of such a barrel is uncertain, which is why a numerical simulation of the loading conditions during firing was conducted. Numerical analysis was conducted by applying static stress in the region experiencing the maximum loads, along with variable loading conditions in the same area, to evaluate the structural durability of the designed barrel.

2. Conceptual design of the projectile and powder charge

In its original configuration, the M65 howitzer uses a two-part round. The propellant charge is caseless. Since the howitzer undergoes changing of caliber from the original caliber of 155 mm, by machining the barrel, the caliber is increased to 160 mm, resulting in a smoothbore barrel. A smoothbore barrel requires a different round design. The projectile already designed for this purpose and of this caliber is the Soviet mortar projectile for the M1943 mortar, shown in Fig. 1.

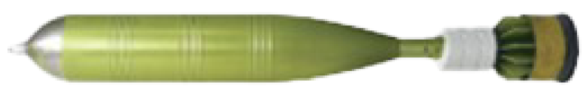

Fig. 1. Soviet mortar projectile 160 mm.

Its basic characteristics are presented in Table 1.

Table 1. Characteristics of the projectile's 160 mm

Characteristic	Value
Caliber	*160 mm*
Projectile length	*1350 mm*
Projectile weight	*42 kg*
Explosive charge weight	*30 kg*
Muzzle velocity	*343 m/s*
Range	*8200 m*

The smoothbore systems can also use projectiles with extendable stabilizers, as seen in the 2A46 tank gun used on T-72, T-80, T-90, and M-84 tanks. This type of projectile design allows for achieving higher muzzle velocities and greater maximum ranges, but it also results in significantly increased barrel wall loading. For the purposes of this study, a projectile concept based on this design approach has been proposed.

A conceptual design is shown in Figure 2.

Fig. 2. Conceptual design of a 160 mm projectile.

The basic characteristics of the conceptual projectile design are shown in Table 2.

Table 2. Characteristics of the conceptual projectile's design

Characteristic	Value
Caliber	*160 mm*
Mass	*42,264 kg*
Center of mass, distance from nose	*0,409 m*
Center of pressure, distance from nose	*0,416 m*
Axial (Mass) moment of inertia	*0,138 kg m^2*
Transverse moment of inertia	*1,78 kg m^2*

Initially, the original propellant charge for the M65 model was used, and after optimizing the characteristics of the propellant, an internal ballistic calculation was performed. The optimization was realized by varying the values of the ballistic characteristics by ±2.5%, which is technologically justified and possible to implement. The calculation diagram is shown in Figure 3.

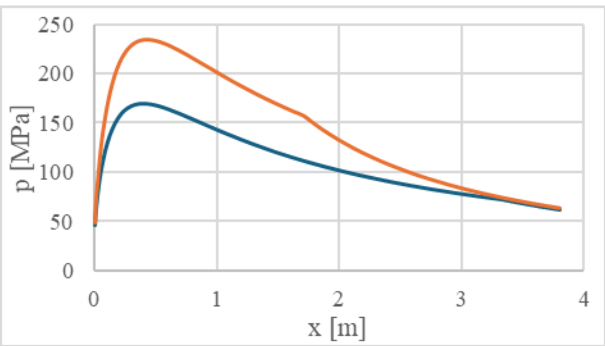

Fig. 3. Pressure changes as a function of projectile path (orange is optimal, blue is initial).

Based on the ballistic calculation using optimal parameters, the muzzle velocity of the projectile is 698.95 m/s, and with an elevation angle of 50°, the calculated range is approximately 11,5 km.

3. Barrel Dimensioning

The barrel was dimensioned according to the Huber-Mises-Hencky theory, i.e., the distortion energy criterion [3]. Based on Hooke's law, the specific strain energy can be represented as the sum of the specific volumetric deformation energy and the specific distortion energy [3].

$$(\sigma_t-\sigma_r)^2+(\sigma_r-\sigma_z)^2+(\sigma_z-\sigma_t)^2=2\sigma_e^2 \qquad (1)$$

After simplification, the following is obtained:

$$p_{1gr}^{IV}=\sigma_e\frac{a_{21}^2-1}{\sqrt{3a_{21}^4+1}}. \qquad (2)$$

The ratio of the barrel's outer diameter to its inner diameter is given by:

$$a_{21}=\frac{r_2}{r_1}. \qquad (3)$$

After inputting the data for the internal bore profile of the barrel, the external barrel profile is calculated using the equation derived from equations (2) and (3):

$$r_2=\frac{\sqrt{\sigma_e^2+\sqrt{4\sigma_e^2\cdot p^2-3p^4}}}{\sigma_e^2-3p^2}r_1. \qquad (4)$$

The diagram of the elements of the longitudinal barrel cross-section, after calculation using equation (4), is shown in Figure 4.

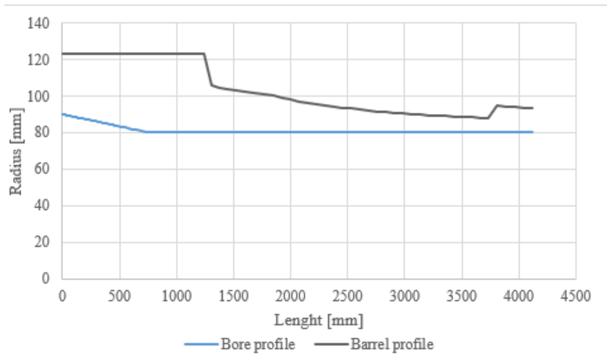

Fig. 4. Elements of the Longitudinal Barrel Cross-Section.

The CAD model of the barrel, with a total length of 3800 mm, dimensioned according to the aforementioned theory and using the properties of structural steel intended for barrel manufacturing, is shown in Figure 5.

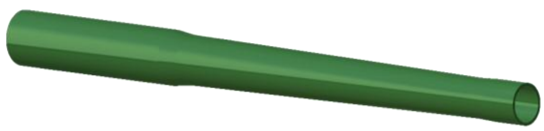

Fig.5. CAD model of the barrel.

4. Numerical Stress Analysis of the Barrel During Firing

The numerical stress analysis of the barrel was performed using the FEMAP software package. The most heavily stressed part of the barrel, located in the projectile seating area, is at 439 mm from the start of the bore, as shown in Figure 6.

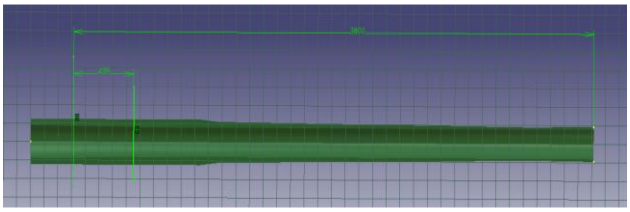

Fig. 6. Area of maximum stress in the barrel

During firing, the barrel walls are subjected to high stress levels, so the most critically loaded section was examined. The barrel was modeled as an axisymmetric 3D element, and only one quarter of the geometry was used for analysis, Figure 7. For discretization (meshing), a 3D tetrahedral finite element (four-node) with midside nodes was used. Boundary conditions were applied such that the front face is constrained from movement along the longitudinal z-axis. In the z-x plane, movement of all points along the y-axis is restricted, while in the z-y plane, movement of all points along the z-axis is constrained.

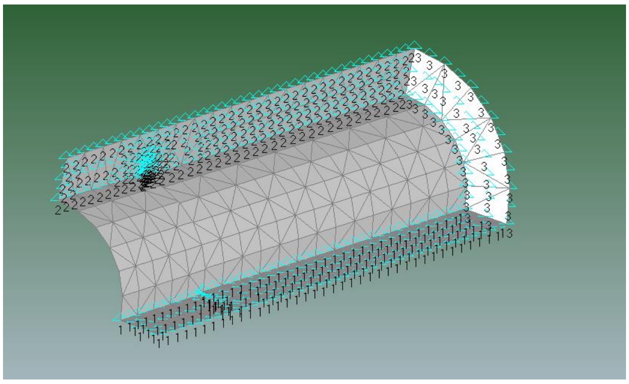

Fig. 7. Constraints on the Most Heavily Loaded Section of the Barrel.

The stress analysis was conducted under both static and dynamic loading conditions.

4.1 Static Stress Analysis

The load was applied normal to the inner surface, with maximum pressure intensity as shown in Figure 8.

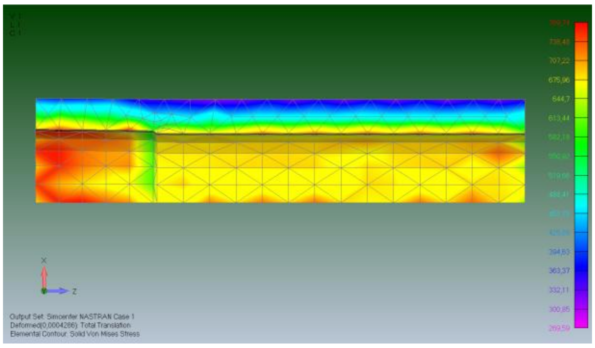

Fig. 8. Stress of the Critical Part of the Barrel in the Longitudinal Section.

The figure 9 shows the loading of the rear cross-section of the barrel, which corresponds to the area of highest stress.

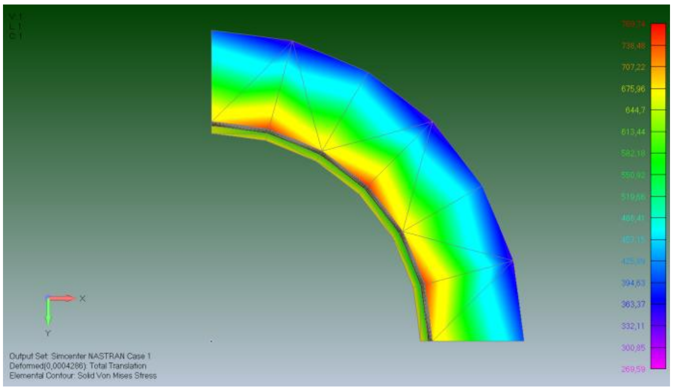

Fig. 9. Cross-section of the barrel at maximum stress

The scale indicates a maximum stress value of 769.74 MPa, which is below the yield strength of 800 MPa, meaning that the deformation occurs within the elastic range.

4.2 Dynamic Stress Analysis

For the calculation of the barrel's dynamic loading, a subroutine in the FEMAP software called NX Nastran with the Transient Dynamic / Time History function was used. During the numerical calculation of the dynamic pressure load, the boundary conditions were set the same as in the static loading case. The load was applied as pressure acting on the internal walls, similarly to the static test, but with a pressure variation law defined over time. In order for the software to compute the barrel loading over time intervals, it was necessary to specify the pressure values at moments defined by equal time steps Δt. The total time for the projectile to travel through the barrel is

0.01086 s, so the time step was set to Δt = 0.000128 s, and the calculation was performed in 81 steps.

The data on the pressure variation of the propellant gases inside the barrel at equal time intervals were generated for the numerical analysis according to the time-domain function, as shown in Figure 10.

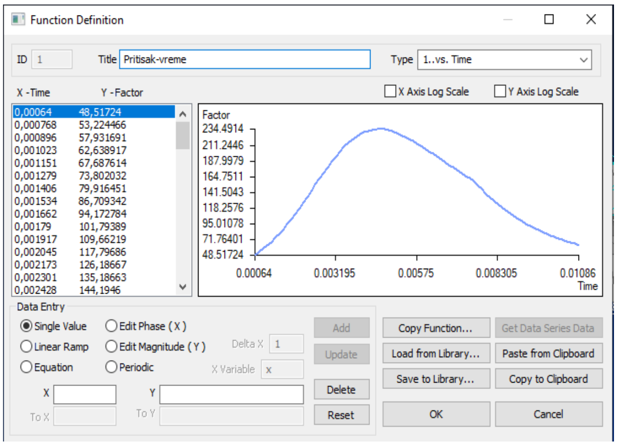

Fig. 10. Pressure variation function of propellant gases at the critical barrel cross-section.

Variation of maximum stress at the critical cross-section as a function of time is shown in Figure 11. The maximum stresses, as in the static analysis, occur on the inner part of the barrel, as shown in Figure 9. The stress value at any given time remains below 600 MPa, which is lower compared to the maximum values observed in the static stress analysis.

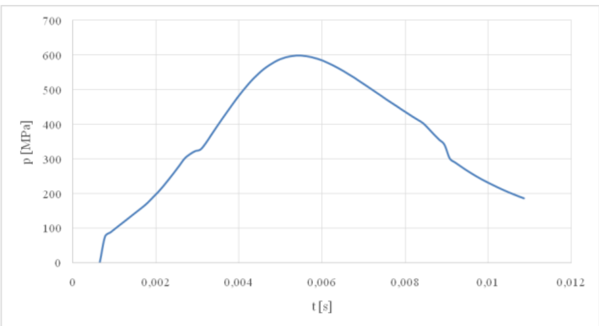

Fig. 11. Variation of maximum stress at the critical cross-section as a function of time.

5. Conclusions

The paper presents a methodology for the numerical calculation of barrel stress during firing in the design phase. The starting point is the improvement of the existing M65 howitzer system through recalibration to a smoothbore system of 160 mm caliber. Initial values for the projectile mass and propellant charge were taken from the mentioned system. An conceptual projectile design solution is provided, and an optimization of the propellant charge was performed. The results of the ballistic calculations demonstrate significant improvements compared to existing systems of the same caliber.

The crucial part of the work is the analysis of the barrel wall loading, aimed at assessing functionality and safe operation. The analysis was performed by numerical calculation of the part of the barrel subjected to the highest stresses, under both static and dynamic conditions. The stress value at any given moment remains below 800 MPa, which corresponds to the yield strength, so the entire deformation occurring during firing remains within the elastic domain. According to the obtained numerical results, it is evident that the barrel loading under dynamic conditions is of lower intensity, confirming that the design is well-conceived.

The next step in the design process is experimental validation. It is necessary to experimentally determine the characteristics of the weapon barrel material, measure the pressure intensity of the propellant gases, and determine the characteristics of the projectile contact surfaces. This approach would improve numerical analyses of fast processes for future research.

Acknowledgments

The paper is a part of the research done within the project of the University of Defence in Belgrade, No. VA-TT/1/24-26.

References

[1] Bogdanov J. *Osnovi konstrukcije ubojnih sredstava*; Medija centar „Odbrana“: Belgrade, 2020.

[2] Tančić LJ. *Klasična unutrašnja balistika*; VIZ (Vojnoizdavačni zavod): Belgrade, 2006.

[3] Ristić Z. *Mehanika artiljerijskih oruđa*; VIZ (Vojnoizdavački zavod): Belgrade, 2010.

[4] Tančić LJ. *Unutrašnjebalističko projektovanje*; Medija centar „Odbrana“: Belgrade, 2014.

[5] Kojić M. Slavković R, Živković M, Grujović N. *Metod konačnih elemenata I*; Mašinski fakultet u Kragujevcu: Kragujevac, 2010.

[6] Živković M.. *Nelinearna analiza konstrukcija*; Mašinski fakultet Univerzitet u Kragujevcu: Kragujevac, 2005.