Impact of ballistic parameters of used ammunition on stress distribution on the parts of the short recoil operated weapon

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Abstract. Estimation of stress distribution on the parts of a weapon is one of the most important stages of designing and optimization of firearms. The paper describes the finite element numerical model of the short recoil operated weapon and results of parametric analysis of the stress distribution on weapon parts. Considered changes in loading courses can be the result of differences in applied ammunition (produced in accordance with various standards or self-elaborated rounds). Conducted works allowed for estimation of approximate critical value of propellant gas pressure, which can be dangerous for pistol structure. Moreover, the paper presents the results of the kinematic characteristics investigation of the weapon using the finite element method and by way of the experimental tests, which proves the correctness of the assumptions made for the numerical model.

1. Introduction

Determining of stress distribution on parts of weapon is one of the most important stages during designing of firearms. There are a few interesting examples of using Finite Element Method (FEM) to estimate stress distribution, failure analysis, kinematic and dynamic characteristics.

In paper [1], FEM software was used to determine stress distribution on the locking block of shotgun under static and dynamic conditions. The authors also conducted fatigue analysis of the locking block. In order to determine the stress distribution of the bolt due to the firing process, the FE analysis was performed in paper [2]. The article [3] presents a research methodology of determining the causes of extractor mechanical damage in newly designed 5.56 mm assault rifle. It combines FEM and material science research. The works [4, 5] present the possibility of FEM in a process of investigation of a weapon dynamic response during single [4] and burst firing [5]. The authors of the paper [6] tested numerically the stiffness parameters of an elastomeric bumper and its influence on kinematic characteristics and dynamic response of a weapon. The main concern was focused on finding the optimal parameters of elastomeric element during FE analysis. The article [7] focuses on the NR-30 air cannon. The authors present a method of testing the canon based on CAE software like multibody systems and FEM to determine stresses distribution on selected parts of the weapon. Examples of kinematic and dynamic characteristics for selected parts of the cannon obtained using numerical approach and exemplary results of failure analysis are presented.
2. FEM description
The finite element method used the classical Lagrangian description of the material motion. The application of classical FEM formulation in mechanics results in the following matrix equation [8]:

\[
[M][\ddot{u}] + [C][\dot{u}] + [K][u] = [F]
\]

where \([M]\) – mass matrix; \([C]\) – damping matrix; \([K]\) – stiffness matrix; \([\ddot{u}]\) – nodes acceleration matrix; \([\dot{u}]\) – nodes velocity matrix; \([u]\) – nodes displacements matrix; \([F]\) – force matrix.

Lagrangian FEM formulation was applied because of the elastic character of modelled phenomenon – i.e., small deformations of material.

Penalty formulation of the contact was used to calculate the normal contact force between elements [9]:

\[
F_{\text{cont}} = 0.1 \frac{M_N M_F}{M_N + M_F} \frac{D}{\Delta t}
\]

where \(F_{\text{cont}}\) – normal contact force; \(M_N\) – effective mass of the node; \(M_F\) – effective mass of the face; \(D\) – depth of penetration; \(\Delta t\) – time step.

In case of slowly-changing phenomena, the main criterion for time step is the numerical scheme stability condition [9]:

\[
\Delta t \leq CFL \frac{h}{C_{\text{min}}}
\]

where \(\Delta t\) – time step; \(CFL\) – time step safety factor (\(CFL < 1\), for slowly-changing phenomena – approx. \(0.8 \div 0.9\)); \(h\) - element characteristic dimension; \(c\) – sound speed in the material.

In case of under-consideration, friction is represented by Coulomb model described by the following Equation [9]:

\[
\mu = \mu_d + (\mu_s - \mu_d) e^{(-\beta v)}
\]

where \(\mu\) – friction coefficient; \(\mu_d\) – dynamic friction coefficient; \(\mu_s\) – static friction coefficient; \(\beta\) – exponential decay coefficient, \(v\) – relative sliding velocity at point of contact.

3. Short description of numerical model
3.1. Development of numerical model
The numerical model was developed using ANSYS environment. It consists of six parts shown in Figure 1. The numerical model included simplifications in geometry complexity and number of parts, which resulted in noticeable reduction of calculation time. The grip module was adopted as a small piece that cooperates with the slide as it reaches the rearmost position. The frame was simplified to the runners.

The system is loaded with the following forces (Figure 1):
- \(F_p\) – force of gas pressure acting on the bottom of the case – measured experimentally,
- \(F_{rs}\) – force of recoil spring – treated as a discrete element, the spring characteristics from technical documentation of the pistol,
- \(F_{bc}\) – force extracting bullet from case – adopted from the literature [10],
- \(F_{bb}\) – force of bullet engraving into barrel – adopted from the literature [10].

The following forces were additionally imported from results of multibody systems investigation described in the paper [11]. Their calculation in FEM approach was impossible, because of the necessary model simplifications:
- \(F_{sh}\) – force of interaction between the slide and the hammer,
- \(F_{sd}\) – force of interaction between the slide and the disconnector,
- \(F_{ec}\) – forces of extraction and ejection of case,
- \(F_{fc}\) – force of feeding and chambering of the next cartridge.
The initial position of the parts of the numerical model at time $t = 0$ and the forces acting on the moving elements: 1 – slide, 2 – grip module, 3 – barrel, 4 – frame, 5 – barrel disconnector, 6 – takedown pin.

The materials applied in FEA (Finite Element Analysis) investigation were assumed to be elastic, linear elasticity for steel and non-linear one for Itamid B-GF35. The main parameters describing the numerical model applied in the simulation are summarized in Table 1.

Table 1. Main parameters applied during FEA simulations

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Steel density                                  | 7850 kg/m$^3$ |
| Steel Young’s elastic modulus                  | 200 GPa        |
| Itamid B-GF35 density                          | 1410 kg/m$^3$  |
| Itamid B-GF35 Young’s elastic modulus          | 11 500 MPa     |
| Steel – steel static / dynamic friction coefficient | 0.15 / 0.08    |
| Exponential decay coefficient                  | 2.749          |

The numerical model is represented by 57 555 nodes and 42 609 finite elements. The element characteristic dimension is between 0.088 mm and 0.497 mm. Division into finite elements is presented in Figure 2.

Figure 2. Numerical model divided into finite elements.

The approximate average time step was 35.05 ns, and the total calculation time was: 17 hours, 10 minutes and 15 seconds. During the calculations the 4-core / 8-threads Intel E5-1620V3 CPU was used. The time step safety factor was equal to 0.9.
3.2. Validation of numerical model
In order to validate the numerical model, experimental tests were carried out and the kinematic characteristics obtained by both methods were compared.

A laboratory stand used for the experimental tests is shown in Figure 3. The stand consists of the investigated pistol (1) and the triangulation displacement sensor (2) rigidly mounted on the ballistic mount (3). The plate (4) screwed to the slide of the weapon (1) provided a perpendicular plane to the laser beam. The triangulation laser displacement sensor has the maximum frequency of 49.14 kHz and the resolution of 3 µm.

![Figure 3. Stand for measuring a slide displacement during a shot: 1 – weapon; 2 – triangulation laser displacement sensor; 3 – ballistic mount; 4 – plate.](image)

The results of the experiment and the numerical investigation were shown in Figure 4 and Figure 5. The executed validation proved the correctness of applied conditions and stated assumptions during development of the numerical model.

![Figure 4. Displacement of the slide versus time obtained experimentally and using FEM.](image)

![Figure 5. Velocity of the slide versus time obtained experimentally and using FEM.](image)
4. Stress distribution depending on propellant gas pressure

4.1. Applied propellant gas pressure to numerical investigation

Numerical investigation was conducted for five variants of propellant gas pressure (Figure 6). Nominal value was adopted from an experimental measurement of gas pressure for the same ammunition that was used to the experimental test of kinematic characteristics.

For calculations there were assumed propellant gas pressures 60%, 40% and 20% (which corresponds the most powerful 9x19 mm +P ammunition according to SAAMI standard, maximum gas pressure is equal 265 MPa) higher than nominal and 10% lower than nominal. Pressure values lower than 10% were not taken into account as they cause incomplete operation cycle of the weapon.

Figure 6. Propellant gas pressure variants adapted to numerical investigation.

4.2. Stress distribution on parts of the weapon

For the purposes of the stress analysis, three main elements of the weapon subjected to the greatest loads were selected: slide, barrel and barrel disconnector. The result of stress analyses was shown in Figure 7-12 and comparison of obtained stresses values was contained in Table 2. Areas of maximum stresses on the parts were marked with the "Max" marker in Figures 7-9 shows Von-Misses stress distribution. For these areas stress curves were presented in Figures 10-12.

For the slide, the highest stress is located at recoil spring support area, on the front of the slide. The maximum stress in the barrel occurs at the locking lug and in the barrel disconnector at the edges of the support of this part in the hole of the frame.

The highest stress in the slide and barrel occurs when the slide with barrel have the highest velocity or during the unlocking and locking process. In the barrel disconnector, the highest stresses are at the moment of unlocking, while during locking, the increase of stresses is not so high.

The barrel is only loaded with the forces of cooperation of the parts, it is not loaded with the force of propellant gas pressure. The Figure 8 shows stress during its locking and unlocking.
Figure 7. Von-Misses stress distribution on the slide.

Figure 8. Von-Misses stress distribution on the barrel.

Figure 9. Von-Misses stress distribution on the barrel disconnector.

Figure 10. Curves of von-Misses stress of the slide.
Figure 11. Curves of von-Misses stress of the barrel.

Figure 12. Curves of von-Misses stress of the disconnector.

Table 2. Comparison of stress distribution depending on propellant gas pressure

| Propellant gas pressure | Slide   | Barrel | Barrel Disconnector |
|------------------------|---------|--------|---------------------|
| +60%                   | 853*    | 480    | 817*                |
| +40%                   | 628     | 448    | 664                 |
| +20%                   | 532     | 472    | 607                 |
| Nominal                | 495     | 428    | 431                 |
| -10%                   | 418     | 430    | 475                 |

*The values marked in red mean maximum value of Von-Misses stress is higher than yield strength for material (780 MPa).
5. Conclusions
After carrying out the above investigations, the following conclusions can be drawn:

- Numerical analysis of stress distribution enables to prove the construction of a weapon during designing process, reducing number of models and prototypes being timesaving and economically effective.
- Impact of used ammunition on stress distribution allows checking construction behavior during shooting by ammunitions made according to various standards and different quality.
- Maximum stress occurring on the parts for the higher pressure 9x19 mm ammunition is 607 MPa when for the materials of the parts yield strength is 780 MPa.
- The conducted analysis proved that the considered weapon can be used to fire the highest pressure 9x19 mm +P ammunition according to SAAMI standard.
- Approximate critical value of propellant gas pressure which can be dangerous for pistol construction is slightly below 60% higher than nominal value.

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