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Analysis of Sliding Wedge Breech Mechanism and Response of 100mm Gun upon Firing

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Abstract:

The paper deals with numerical and analytical analysis of sliding wedge breech mechanism response during one shot fired from 100mm cannon. The model of the breech together with gun tube was modelled in LS-Dyna environment using available commands for mesh generation and for handling boundary conditions including contact surfaces. Only the components that significantly affect the force redistribution are modelled for the analysis. The explicit finite element method was used to retrieve stresses and deformations of the breech. The emphasis was put on the breech block which was the critical phenomenon. The numerical results were compared to analytic solution which is commonly used in the process of designing sliding wedge breech blocks. The response of the gun as a whole was also analysed.

Keywords:

Sliding wedge breech block, 100mm cannon, simulation, finite element method, LS-Dyna

1. Introduction

One of the most important components of a gun is breech mechanism. The breech mechanism is located at the breech end of the gun and is responsible mainly for opening and closing the breech, allowing reload and preventing the propellant gases to escape through the back of the gun, thus ensuring proper function of a gun during firing. The breech mechanism consists of breech ring, breech block, firing mechanism, gearing to open and close the breech, extractors to remove empty cartridges and safety devices to prevent the gun from firing until the breech is fully closed. There are two main types of breech mechanisms, namely the sliding block mechanism and breech

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screw mechanism. There are also several other types of breech mechanisms which are not so widely used in artillery. The paper is focused on the sliding block mechanism as the analysis described in the paper is performed on sliding wedge breech block. This mechanism is widely used in quick firing cannons. The main principle of their operation is rather simple, nonetheless in modern cannons there are many additional subsystems which contribute to the complexity of such mechanisms [1]. The sliding block is housed in the breech ring in which the block can perform translational sliding movement with the aid of the breech mechanism gearing. Before firing, the sliding block is wedged into the breech ring so as to provide support for the cartridge case. The breech block can be mechanically locked and afterwards the shot can be fired. After the firing, the sliding block is unlocked and moved into open position and the cartridge is extracted with the help of extractors. New round is then loaded and the cycle repeats for the next shot. To withstand the huge pressure of the propellant gas, the back face of the sliding block is firmly supported by the breech ring whereas the breech ring is firmly attached to the gun barrel. The sliding wedge breech block is designed to be of slightly wedged shape which also prevents its movement during firing.

The finite element method is utilised to analyse the response of the breech block during firing. It is a well-known method which has been successfully used in computational mechanics for over forty years to analyse material response under loading. Over the decades, the method has been constantly developed and lots of software packages have been created to aid the engineers in the numerical analysis of various problems. One of such packages with excellent history report is LS-Dyna which is commonly used to study high speed events like crash tests [2-4], hyper velocity impacts [5-7], ballistic resistance of advanced protection plates [8-10], explosions [11-13] etc. LS-Dyna utilizes explicit finite element formulation including large strains and large displacements with finite rotations.

2. Model of the 100mm Gun

The model was completely created in the LS-Dyna software using available commands. It consists of the gun barrel, breech ring, wedge breech block, cartridge case and of a lever that is responsible for moving the breech block into open and closed position and also for locking the breech block before the gun is fired. As of now only the elements are modelled that contribute to the analysis of the sliding wedge breech block response when the gun is fired. The whole model can be seen in Fig. 1. Altogether 128,000 elements and 172,000 nodes were used to discretize the model of the 100mm gun.

A cross-section along the axis of the gun is shown in Fig. 2 together with detail of the breech mechanism without and with finite element mesh shown. Note that the breech block is not cut in order to see the operation lever responsible for sliding the breech block into open or closed position. In this particular gun the sliding breech block is wedged with a slope 1:50. The gun is shown in configuration right before the shot is fired. The breech of the gun is closed by the breech block which supports the cartridge. The operation lever is in the locked position where a negative angle is formed by the mechanism, thus the wedge is pushed into the closed position even during the shot when the pressure acts on the breech block.

The HE shell is not modelled in this case, as it is of no interest and the internal ballistic equations were calculated by numerical means. The finite element mesh is distributed with the aim to describe the stresses and displacements in the breech block. The characteristic size of the finite elements of the breech block is close to 4 mm whereas the barrel is discretized by more coarse mesh.

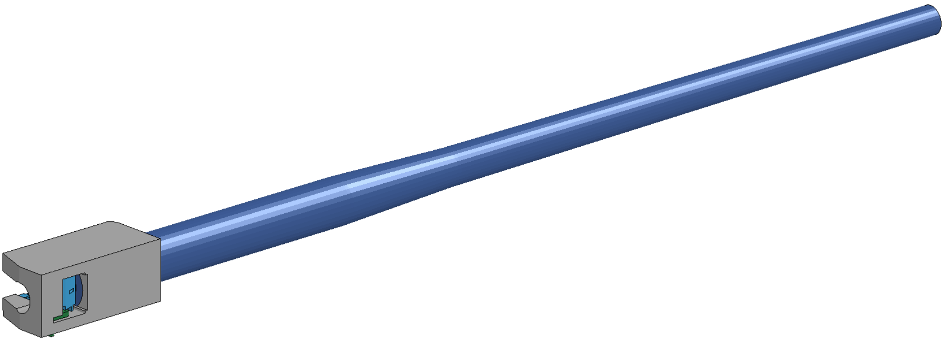

Fig. 1 Model of the 100mm gun

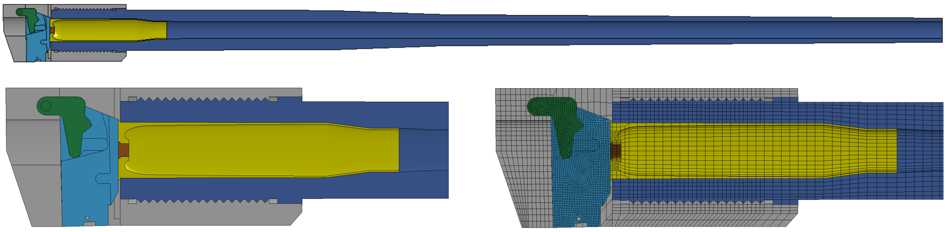

Fig. 2 Cross section of the gun with detail of the breech mechanism (left) and finite element mesh (right)

The meshed breech block is shown in Fig. 3. The contact surfaces are defined between all moving parts and also between the cartridge case and the barrel. The breech ring is attached to the barrel through threaded surface. The thread surfaces are also defined in the contact conditions. The rifling of the barrel is neglected as for this type of analysis the rifling would not have a significant impact.

The material models are chosen according to the expectations of behaviour of the parts. For example the barrel and the breech block are made of high strength steel and expected stresses should fall below the limit of yield strength. The same can be said about other parts of the gun except that these are made of medium grade steels. Nonetheless deformation into a region of plastic flow is not permissible. On the other hand, the cartridge case is made of highly malleable mild steel in a process called cold drawing and in order for the cartridge to obturate the barrel breech, the deformations have to be in the region of a plastic flow. Therefore, it was concluded that for the components of the gun which work in the area of elastic law, an elastic material model is utilised which is in one dimension governed by Hook’s law

$$S = Ee \tag{1}$$

which states that the stress S is proportional to Young’s modulus E and strain e. The power law plasticity model is used to describe the behaviour of the cartridge case expressed as

$$S = ke^{n} \tag{2}$$

where k is the strength coefficient and n is the hardening exponent. Material parameters used in the model are summarized in Tab. 1.

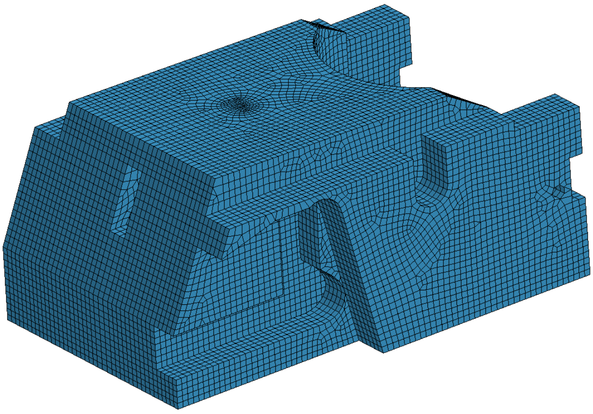

Fig. 3 Breech block with finite element mesh

Tab. 1 Material parameters used in the model

Component	Density [kg·m^{-3}]	E [GPa]	Poisson's ratio [-]	k [MPa]	n [-]
Gun barrel Breech ring Breech block Handling lever	7850	210	0.3	–	–
Cartridge case with primer	7833	206.8	0.29	545.43	0.18645

The high strength steel used for construction of breech blocks has increased yield strength where the minimum yield limit starts from approximately 600 MPa upwards.

For the cartridge case, mild steel is used so that the breech is obturated as well as possible efficiently. The material curve of the cartridge case material is shown in Fig. 4. The yield limit is at 139 MPa after which the material behaves plastically according to the power law plasticity model. The tensile strength of the material is approximately 400 MPa with elongation of 18 %. The strain rate effects were incorporated in the form of modified Johnson-Cook model which calculates the dynamic stress S_D from the static stress S using normalised total plastic strain rate term as follows

$$S_D = S\left(1 + C \ln \dot{\varepsilon}^p\right) \tag{3}$$

where $\dot{\varepsilon}^p$ is the normalised total plastic strain rate and C is the strain rate parameter which is dimensionless. For the analysis, the strain rate parameter was chosen to be $C = 0.01$. The strain rate effects cause that the dynamic stress during rapid events is higher compared to the static stress which is commonly obtained from the simple tension test under quasi-static conditions. Note that the material curve in Fig. 4 was obtained from the tension test with very low loading speed, i.e. under quasi-static conditions.

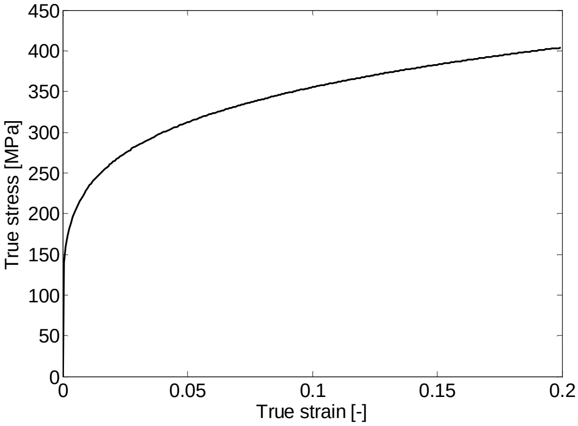

Fig. 4 Material curve for the cartridge case

The internal ballistics was calculated numerically by simple technique which calculates the internal ballistics equations by numerical means [14]. The method uses time stepping procedure where in each time step all ballistic parameters are incrementally calculated from values in the previous time step. The propellant is nitroglycerine double based powder present in the form of tubular shape grains with outer diameter 5 mm and wall thickness 1.78 mm. The fraction of propellant burnt is

$$\phi = (1 - f)(1 + \theta f) \tag{4}$$

where $0 \le f \le 1$ represents the reduction in thickness of the grain wall and θ was set to 0.6 for this particular grain shape including the consideration for heat losses. The shell travel distance was set to 467 cm, the chamber length is 68 cm and the cross-sectional area for the 100mm gun is equal to 78.5 cm^2. The loading density of the propellant is 0.68 g·cm^{-3} with the total weight of the propellant set to 5.6 kg and the propellant internal energy 3286 J·kg^{-1} (i.e. 785 kcal·kg^{-1}). The friction force acting on the shell during the travel down the bore was accounted for in the form of effective shell mass

$$M_{eff} = \frac{M}{1 - \mu} \tag{5}$$

where M is the real mass of the shell and μ is the friction coefficient between the shell and the barrel which was set to 0.2 in the analysis. Also the shot-start pressure reflecting the forcing of the shell into the rifling was set to 47 MPa and the shot starts to move only after the prescribed pressure value was reached.

The shell of mass 15.6 kg is accelerated to the velocity 900 m·s^{-1} in 11.5 ms in the gun, see Fig. 5. Note that according to the calculation the shell was accelerated to a slightly higher muzzle velocity 907 m·s^{-1}, but this might be due to the fact that the recoil movement of the gun was neglected.

3. Results

Upon firing the shot, the gun performs sliding movement backwards. The recoil brake is not implemented in the model, thus the gun supported only by plain bearings slides freely. The rigid body displacement of the gun in the axial direction is –14.58 mm at time 6.2 ms where the maximum chamber pressure occurs. At time 11.48 ms, when the shell leaves the barrel, the rigid body displacement of the gun is –69.6 mm and the rigid body velocity of the gun is –13.6 m·s^{-1}. With the recoil brake implemented the velocity would be slightly reduced and the muzzle velocity of the shell would then be approximately 900 m·s^{-1}. These numbers have to be mentioned because the deformations of the breech block and all other parts of the gun are total deformations including rigid body displacements. The rigid body displacement and rigid body velocities of the gun in the axial direction as a function of time are shown in Fig. 6.

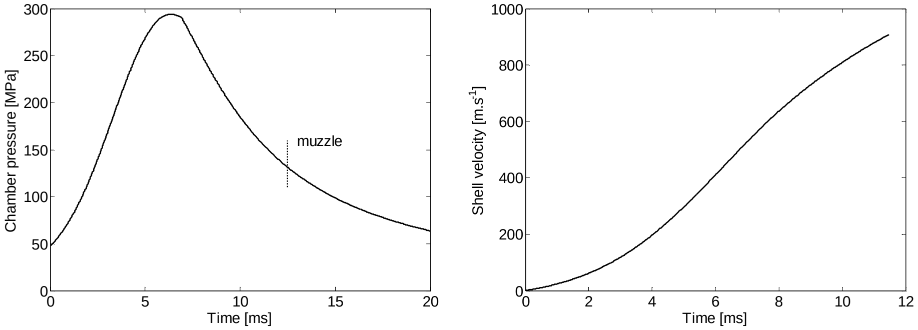

Fig. 5 Pressure curve (left) and the shell velocity (right)

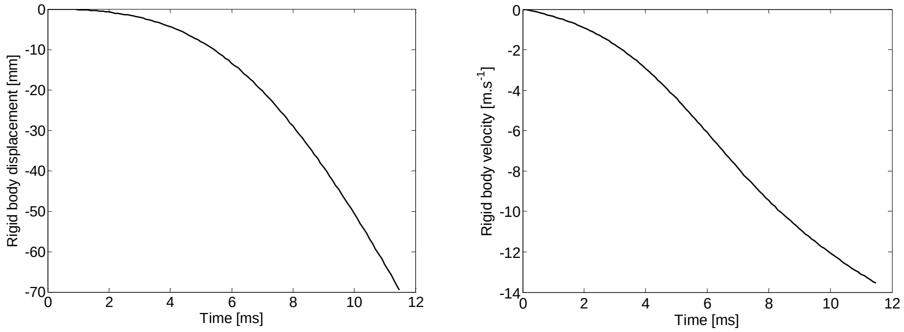

Fig. 6 Rigid body displacement (left) and rigid body velocity (right) of the gun

3.1. Deformation of the Breech Block and Breech Ring

The deformation of the breech block and breech ring in the axial direction is shown in Fig. 7. The axial direction is chosen so that the rigid body displacements can be subtracted. The minimum in the deformation field of the breech block can be seen to be –14.98 mm, while the maximum is –15.21 mm. If we subtract the rigid body displacement, then the minimum deformation is –0.4 mm and the maximum deformation is –0.63 mm so it can be said that due to the deformations of the gun the breech block as a whole is displaced relatively to the gun by 0.4 mm in negative direction. The difference between the maximum and minimum deformation is –0.23 mm. This might be taken as an actual deformation of the breech block if the breech block would not perform rigid body motion.

The extent of the deformation is minimal compared to the dimensions of the gun. Nonetheless the deformation is not symmetric, as the breech block is weakened on the right side by the guiding groove for the operation shaft. This can have negative impact on durability of the gun as the wear of the breech block in connection with the breech ring would be unevenly distributed. Moreover this might negatively affect the accuracy of the gun as will be shown later where the oscillation of the gun will be analysed. The deformation of the breech ring is evidently not symmetric relatively to the axis of the gun barrel. It was speculated first that this might be due to varying thickness in the breech ring walls but upon closer inspection of the behaviour of the gun it was found that the gun performs oscillatory movement in vertical plane. Note that the deformations in Fig. 7 are only axial deformations, not total deformations calculated from all directional components.

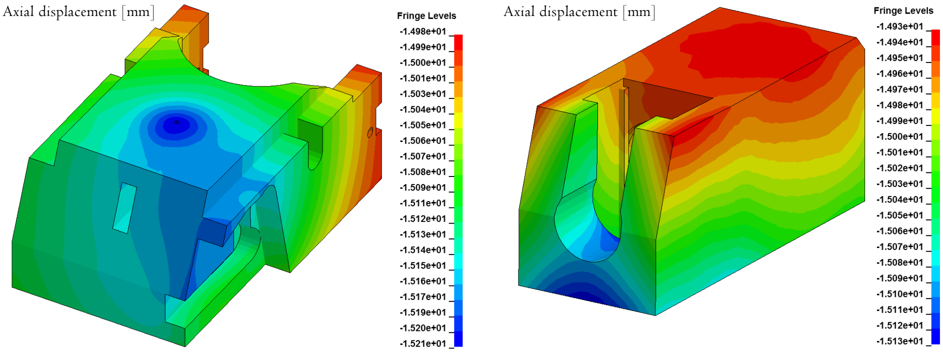

Fig. 7 Deformation of the breech block (left) and of the breech ring (right)

3.2. Analysis of the Gun Oscillation

In Fig. 8 the vertical displacements of the entire gun are shown which confirms the hypothesis. At time 6.2 ms when the chamber pressure is maximal, the vertical displacement of the barrel is 0.15 mm and the displacement keeps rising with time. At time 11.48 ms the shell leaves the barrel with the base of the shell being at the muzzle. Here the muzzle has vertical displacement equal to –0.4 mm and the middle of the barrel moves in the opposite direction with the displacement of 0.6 mm. It can be seen from the distribution of the displacement field that the gun also tends to rotate slightly around its axis. Interestingly, the oscillation of the gun occurs only in the vertical direction, or y-axis (see Fig. 8). This may be due to several reasons. Firstly the numerical aspect might be considered. It is known that the numerical integration is not exact and also the finite precision error might contribute to numerical artefacts. But it is also known that for symmetrical problems the solution tends to be symmetric. In this case the pressure loads are applied symmetrically with regard to the gun axis onto the cartridge case, which is also symmetric and moreover the mesh of the gun barrel and of the cartridge case is also axially symmetric. Thus the numerical aspect should be minimized.

The second aspect might be considered to be the uneven deformation of the breech block which can cause that the purely axial force arising from the chamber pressure acting on the cartridge casing is projected partly into the vertical plane. The result is that the gun is excited into oscillation exactly in the direction of the y-axis. The third aspect is worth considering results from the work of other authors. It has shown that the gun barrel is forced into oscillation during the shot which affects the accuracy of the gun [15, 16]. The gun is forced to oscillate with the natural frequency of its eigenmodes in this case. To the final oscillation of the gun can contribute one or any combination of the above mentioned factors.

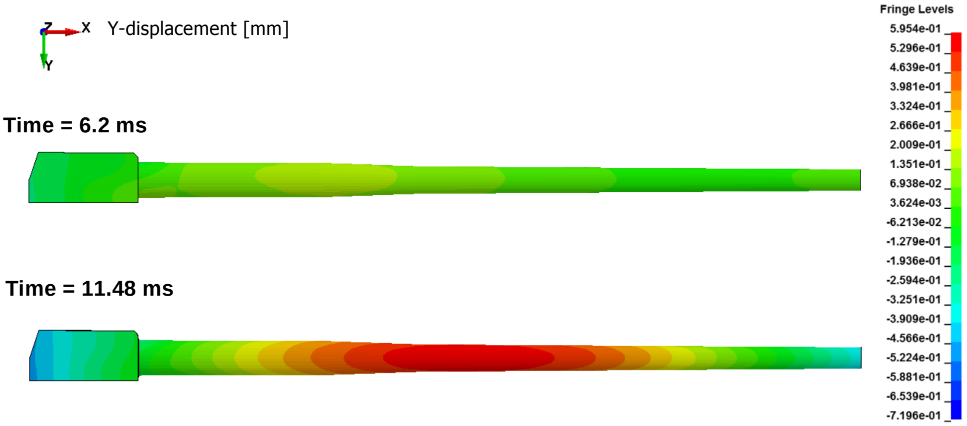

Fig. 8 Vertical displacements of the gun at time 6.2 ms (top) and 11.48 ms (bottom)

The y-displacement as a function of time in two points on the outer surface of the barrel is shown in Fig. 9. One point is located approximately in the middle of the barrel and the other one is located directly at the muzzle. The tendency of the oscillation can be seen from the graph up to the time when the shell leaves the bore.

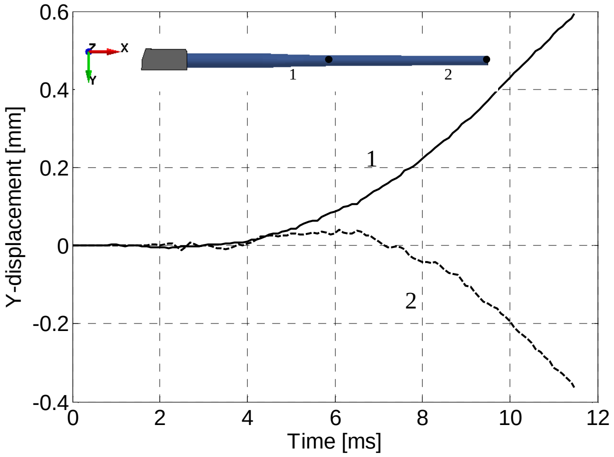

Fig. 9 Vertical displacements at two points on the barrel

The point in the middle of the barrel moves in the direction of positive coordinate while the point at the muzzle travels in the opposite direction. The peaks are not yet formed, so the amplitude of the oscillation can be expected to be larger than the maximum values presented in Fig. 8 when the base of the shell is at the muzzle. All in all the accuracy of the gun will be definitely affected.

To more accurately model the vibrations of the gun, the rifling had to be included and also the shell should be modelled accordingly to account for the contribution from the shell – barrel interaction.

3.3. Breech Block Stresses

The stress in the breech block is triaxial and it is a combination of bending, shear and compression. The compression stress should be propagated by chamber pressure and therefore its maximum value should not exceed the chamber pressure. The shear stress occurs in the plane between the cartridge case and the side of the breech ring which supports the breech block. The shear surface in the case of the breech block is so vast that the shear stress can be neglected. Its maximum value can be estimated in tens of MPa. The most critical is the bending stress and therefore in the design process this is the starting point [17]. According to the law of action and reaction, the force acting on the breech block should be the same as the force acting on the shell but it is a recommended practice to calculate the force from the projected surface of the bottom of the chamber

$$F = p\pi \frac{D^2}{4} \tag{6}$$

where p is the maximal pressure and D is the breech chamber diameter. Here D was estimated from the model to be 120 mm and the force acting on the breech block is 3325 kN. The force is assumed to be uniformly distributed on the circular surface which represents the contact surface between the cartridge case and the breech block and for the calculation of force moment, the distributed force is substituted by two equal point forces $F/2$ acting in distance 0.21 D from the centre of the circular surface (Fig. 10). The support of the breech block is considered as a worst case scenario. As the breech ring which supports the breech block is not rigid but allows for some deformations, the exact point of support is uncertain. Thus for analytical solution the support was assumed along the outer edges of the breech block.

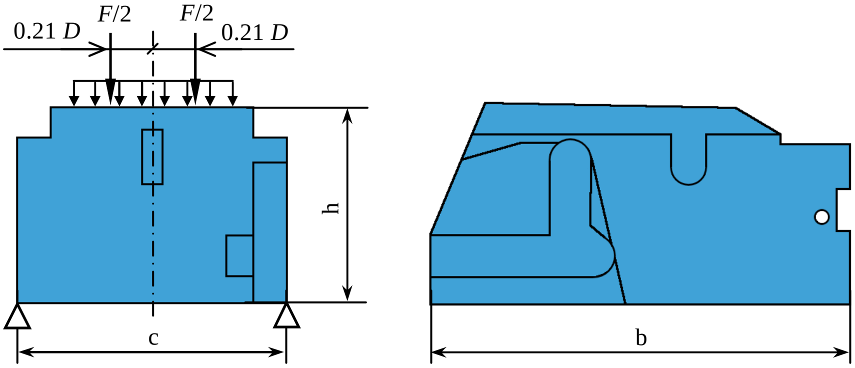

Fig. 10 Forces acting on the breech block and dimensions

The maximal bending moment to which the breech block is subjected is located in the area between the two concentrated forces.

$$M_{\max} = \frac{F}{2}\left(\frac{c}{2} - 0.21D\right) \tag{7}$$

The elastic section modulus W is calculated by modified formula accounting for the weakening of the breech block by holes, grooves, notches and slopes.

$$W = \frac{1}{7} b h^2 \tag{8}$$

The dimensions are according to Fig. 10, where c is equal to 200 mm, b is equal to 300 mm and h is equal to 142 mm. Evaluating (7) and (8) using the dimensions, we get maximal bending moment value 124 kN·m and the elastic section modulus value which is equal to 864,171 mm^3. The maximal bending stress is than calculated according to the formula

$$S_{\max} = \frac{M_{\max}}{W} \tag{9}$$

which after substituting the corresponding values is equal to 143.9 MPa. This is the stress reflecting static loading conditions, which needs to be multiplied by dynamic loading coefficient. The coefficient is recommended to be at least 2.5 but the higher the coefficient, the higher is the probability that the elastic limit will not be exceeded as the safety allowance is increased [17]. If this coefficient is used then the maximum dynamic stress calculated according to the analytic method accounting for stress concentrators is 359.75 MPa. This is below the yield stress which should be at least 600 MPa, so it can be stated that the breech block is designed to work in the limits of elasticity. By the analytic solution only the maximal stress can be estimated.

The stress distribution can be obtained by numerical means only. The breech block stresses from simulation are shown in Fig. 11. While it can be seen that the stress in most of the volume of the breech block is modest, there are present stress concentrators where the stress reaches maximum value. The effective stress in a point on the breech block where a maximum occurred as a function of time is shown in Fig. 12. The curve is very similar in shape to the chamber pressure curve and the position of the peak is similarly at 6.2 ms.

The maximal value of the stress according to the numerical analysis is 374.8 MPa which is very close to the analytic solution and the result and conclusion is confirmed. The gun itself is constructed to handle various types of ammunition. The response for HE ammunition is only shown because the data were available for this particular type.

4. Conclusion

A model of the 100mm gun is presented in the paper. The model consists only of components necessary for stress analysis of the breech during firing and these are the gun tube, breech ring, breech block, operation shaft and cartridge case. The gun is assembled in battery position, ready to be fired. The pressure due to propellant is applied on the inner surface of the cartridge case, which is accordingly forced onto the breech block and acts on it. The asymmetry in geometry clearly contributes to uneven deformation and the recommended solution is to modify the operating shaft into symmetric pattern so as to prevent excessive wear between contact surfaces. Oscillations of the gun tube were detected upon analysing the results. This might be due to several reasons but the main reason might be the asymmetric breech where the upper side is cut into an angle but also the breech block skewed deformations might contribute to oscillations. The breech might be rebalanced and in the future symmetric distribution of the mass might be considered to eliminate undesirable effects. The breech block was the component with maximum stress in the analysis. Numeric and analytic solution did converge to a safe value of maximum stress which is in the elastic limit range including space for safety allowance. It can be concluded that the gun is safe and the accuracy can be further improved.

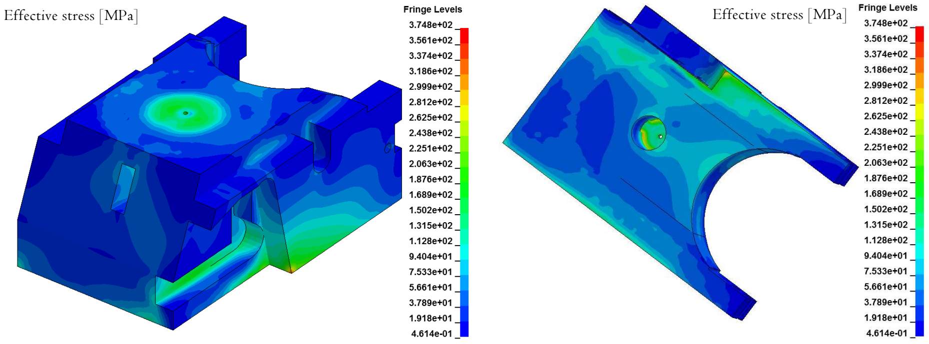

Fig. 11 Stress distribution in the breech block

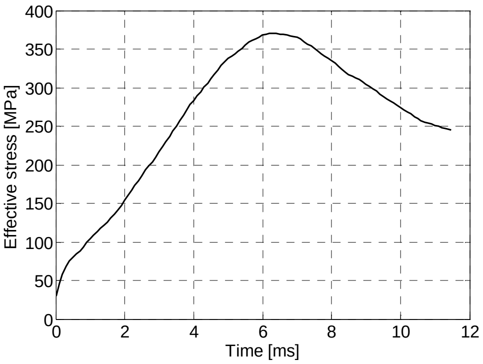

Fig. 12 Stress at a point with maximum

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