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Determination the Stress and Deformation of the Cannon Barrel When Fired

The Luc NGUYEN[1], Minh Phu NGUYEN[2*], Thanh Tuan LAI[3]
[1,2,3]Faculty of Special Equipment, Le Quy Don Technical University, 236 Hoang Quoc Viet street, Hanoi, 100000, Viet Nam

ABSTRACT: This paper presents a calculation process of the stress field of the 130M46 cannon barrel when firing under the load of gas pressure and temperature. The paper will focus on calculating the stress of a barrel and solving some disadvantages of previous methods using the finite element method and the simulation tools of the CFD software. The calculation results are the stress and deformation parameters of the barrel such as normal stress, tangential stress, average stress, radial deformation, tangential deformation, and total displacement. These stress values are determined when firing 1 shot and 8 consecutive shots to determine the allowable durability limit of the gun barrel material. The result of this research can be used to study and analyze some similar technical issues in weapons.

KEYWORDS*:* stress, defomation, cannon, barrel, interior ballistics

I. INTRODUCTION

The main cause of deformation of the gun barrel under shot load is the temperature and pressure of combustion gases during firing. Because during the firing process, the barrel is heated due to cutting the bullet belt, due to friction between the bullet belt and the barrel, and due to the heat pulse of the gun gas, so the temperature of the innermost layer of the barrel can reach 800 ÷ 1000K. Heating of the barrel wall causes increased barrel wear and negatively affects barrel durability. In addition, high temperatures will reduce the abrasion resistance of the barrel, leading to damage to the barrel after a period of use. Practice shows that the higher the combustion gas pressure in the barrel, the greater the amount of barrel wear. Because then the moving speed of the bullet also increases, causing the normal reaction force N of the bullet belt acting on the tightening wall of the spiral groove to also increase. This is the main cause of increased stress and deformation of the cannon barrel [1-3]. The survey of stress field and deformation of a cannon or a gun's barrel is a difficult issue being studied by many scientists and being calculated by many different methods. One of those methods is the simulation using the finite element method (FEM). By using the CFD software (ANSYS), the stress field of a barrel can be explored after firing one or many bullets.

There have been many studies on the stress and deformation of gun and artillery barrels in the world. In general, these studies assume that the cannon barrel is a cylinder with thick walls to provide the stress and deformation domain of the barrel over time [4-9]. The calculations involved are simple and straightforward using this assumption. However, there is not only gas pressure but also heat load, contact pressure and friction of the bullet when fired. With the development of finite element analysis, stress analysis of artillery barrels is mainly expressed in applying loads gradually closer to reality. Some researchers have calculated the stress state of the entire barrel according to the gas pressure distribution in the barrel [10-16]. Some researchers focus on the heat load of combustion gases acting on the barrel [17]. Documents [18,19] have studied the temperature field, thermal stress and deformation of a gun barrel with water cooling. Based on the results of the above analysis, many studies have been carried out on the subject of the effects of combustion gases parameters on the barrel, but research suggests that the combined effect of pressure and temperature of combustion gases is very rare. Therefore, it is very necessary to have a specific theory about the simultaneous impact of this issue in research on gun barrels and artillery. This paper presents the calculation process of the stress field and deformation of a 130mm cannon's barrel (with steel O-1200) when firing. The outside of 130mm cannon is shown in Figure 1.

Figure 1. The overview of 130mm cannon

The research process is divided into two phases. First, solve the system of internal ballistic equations to determine the law of pressure and thermodynamics in the cannon barrel when fired. Then, this result is used as input parameters for the problem of determining the stress and deformation of the cannon barrel. By using the finite element method and CFD software, the stress field of the barrel is studied under the load of both gas pressure and temperature simultaneously.

II. SET UP A PROBLEM MODEL

A. Set up the system of interior ballistic equations

The process of firing is a very complex process, so if all the influencing factors are taken into account, solving the interior ballistic problem will be difficult. Therefore, to simplify the calculation and still give accurate results, within the allowable range, some assumptions are used as follows:

- The barrel material is considered homogeneous and isotropic;
- The gas pressure acting on the barrel wall is static, evenly distributed throughout the barrel length;
- The before and after barrel deformation remains in shape;
- All the elements of the barrel are always in equilibrium;
- The gas constant R, the adiabatic exponent k, the coefficient of thermal expansion of the material barrel α do not depend on temperature.

The system of interior ballistic differential equations for conventional artillery includes the following equations: equation describing the burning law of propellant; equations of motion of bullets in the barrel; energy equation; air injection equation; connecting equations and auxiliary equations. These equations have basically been fully established and detailed in the document [7]. The system of equations is presented specifically as follows:

$$\begin{cases} \dfrac{dv}{dt} = \xi_3 . \dfrac{s}{\varphi . m} . p \\ \dfrac{dl}{dt} = \xi_3 . v \\ \dfrac{dz}{dt} = \xi_2 . \dfrac{P}{I_k} \\ \dfrac{d\omega}{dt} = \xi_2 . \omega . (1 + 2.\lambda . z) \\ \dfrac{dW}{dt} = \xi_2 . \dfrac{1 - \alpha . \delta}{\delta} . \chi . \omega (1 + 2\lambda . z) . \dfrac{p}{I_k} + \xi_3 . s . \dfrac{dl}{dt} \\ \dfrac{dp}{dt} = \left[f \dfrac{d\omega}{dt} . g - \left(k_t + k \dfrac{dW}{dt} \right) \right] . \dfrac{p}{W} \\ \dfrac{dT}{dt} = \dfrac{\theta T_1}{f \omega \psi} \left[\dfrac{f \omega d\psi}{\theta dt} - T \dfrac{f \omega}{\theta T_1} \dfrac{d\psi}{dt} - \varphi m v \dfrac{dv}{dt} \right] \end{cases} \quad (1)$$

Where

$$\varphi = k + \frac{\omega}{3.m_d} \quad (2)$$

$$k_t = \frac{(k-1).A.v_1.\delta_t (F_k - \pi dl)}{R} \quad (3)$$

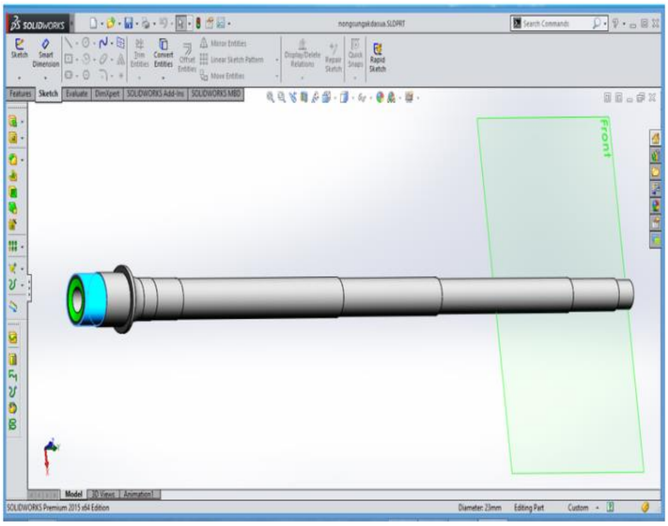
m is the mass of the warhead; *v* is the moving speed of the bullet in the barrel; *l* is the length of the moving bullet in the barrel; *z* is the relative burning thickness of the propellant; ω is the weight of the propellant; *p* is the pressure of the combustion gas in the barrel; *W* is the volume of combustion gas in the barrel; φ là hệ số kể đến công thứ hai; ξ_2 is the control variable that determines the time of complete combustion of the propellant; ξ_3 is the control variable that determines the time it exits the barrel of the warhead; α is the co-volume of propellant; *f* is the powder force; δ is the density of the propellant; I_k is the propellant impulse; λ, χ is the form factor of the propellant; k is the adiabatic exponent.

The system of differential equations (1) is solved using the initial conditions: $t_0 = 0$, $z = z_0$, $l_0 = 0$, $v_0 = 0$, $p = p_0$. Matlab software is used to solve the above system of equations.

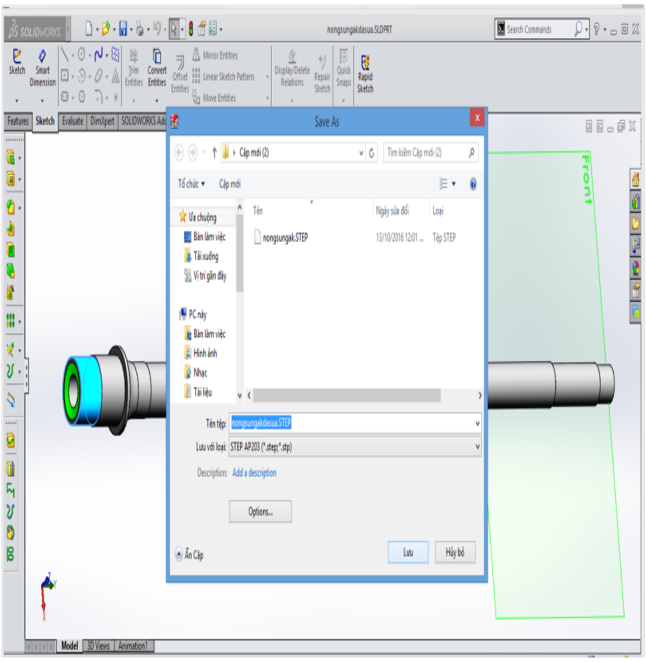
B. Set up the problem of determining the stress and deformation of a cannon barrel in the Ansys CFD softwave

The procedure for constructing the problem of determining stress and deformation of a cannon barrel in Ansys CFD software is carried out according to the following steps:

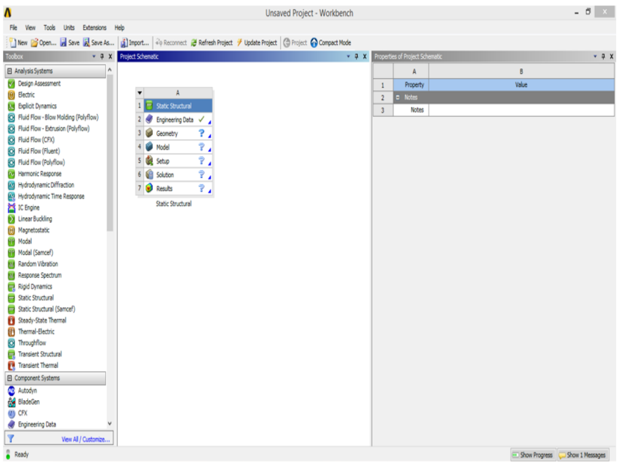
Step 1: Simulate 3D cannon barrel on Solidworks software



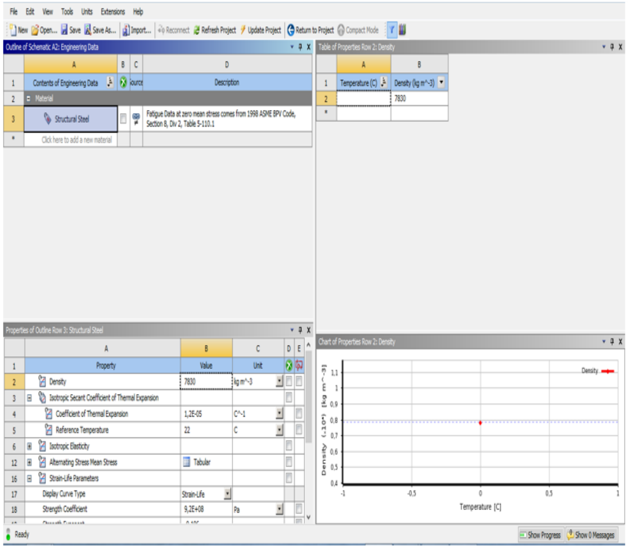
Step 2: Save the model as .STEP file



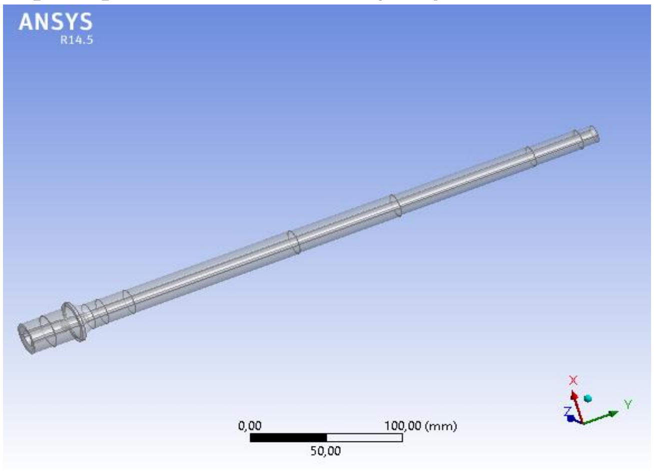
Step 3: Open Ansys Workbench and select analysis type: Static Structural



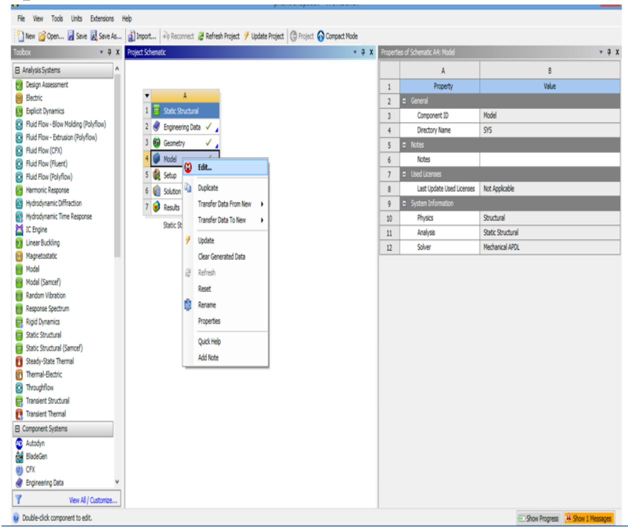
Step 4: Enter material parameters



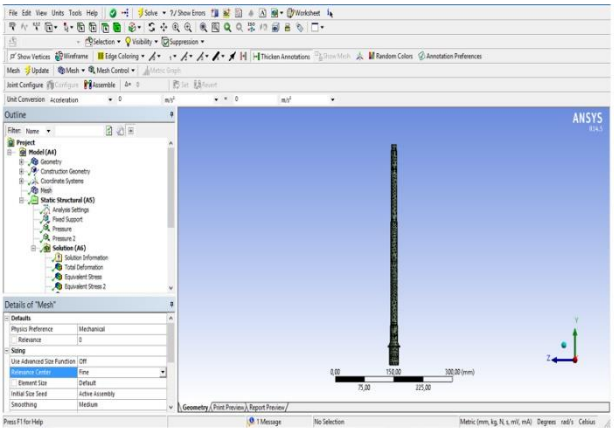
Step 5: Open the 3D model on Ansys software



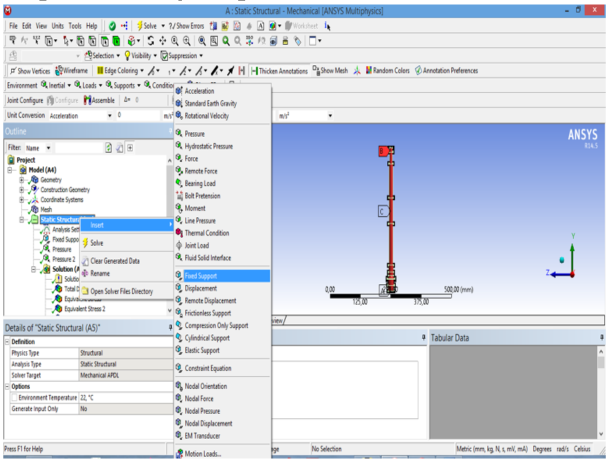
Step 6: Edit the model



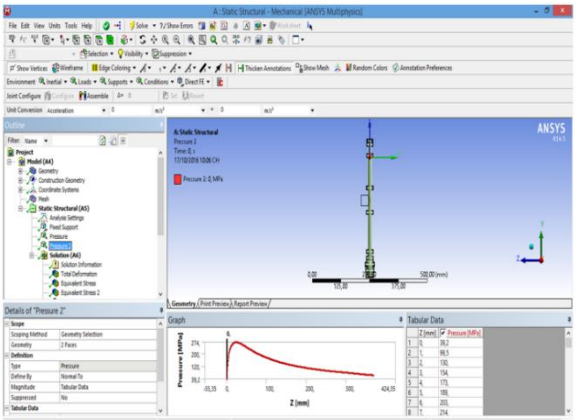
Step 7: Meshing the cannon barrel model



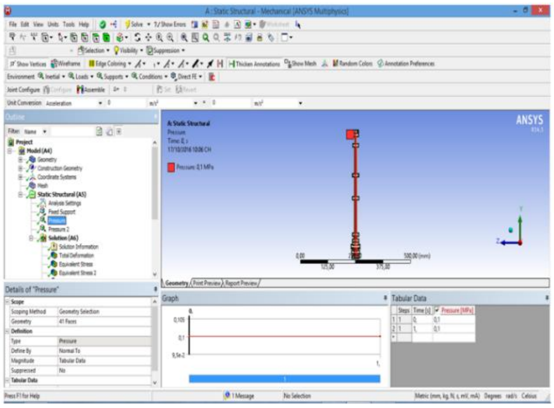
Step 8: Choose fixed positions



Step 9: Set the pressure on the inside of the cannon barrel. This pressure law is taken from the results of solving the problem of the interior ballistics of cannon.



Step 10: Set the outside pressure equal to the environmental pressure



After setting up all the steps to determine the stress and deformation of the cannon barrel, select "SOLUTION" to set up the calculation solution and select the parameters to display.

III.RESULTS AND DISCUSSION

A. Solve the interior ballistics problem

The results of solving the interior ballistic problem is to find the variation law of gas pressure, gas temperature inside the barrel based on time.

On the basis of data on the structural parameters of the 130mm gun, which are presented in detail in document [6], the interior ballistic problem is calculated by using the Matlab software. The results of the pressure inside the barrel and the velocity of the warhead are shown in Figure 2.

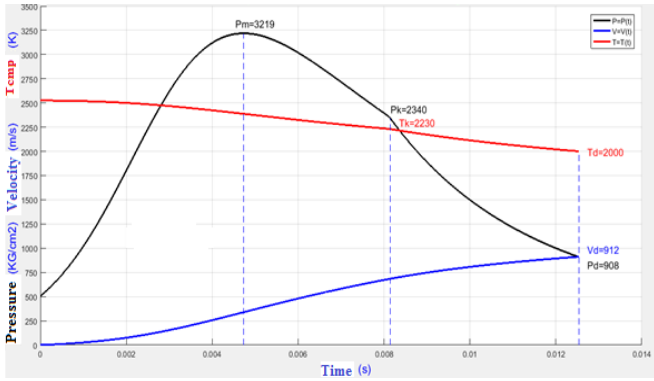


Figure 2. The gas pressure, temperature and the warhead velocity in the barrel

The gas pressure inside the barrel reaches the maximum level of 3219 kg/cm^2 at the time of above 0.0047 s. The velocity of the warhead is increasing inside the barrel and reaches the maximum level of 912 m/s at the muzzle. Meanwhile, the gas temperature is decreasing inside the barrel and reaches about 2388K at the maximum gas pressure cross section. These variation laws are suitable for the real tests and the other calculations of interior ballistics [3], [7]. The distribution of temperature on the barrel wall as shown in Figure 3:

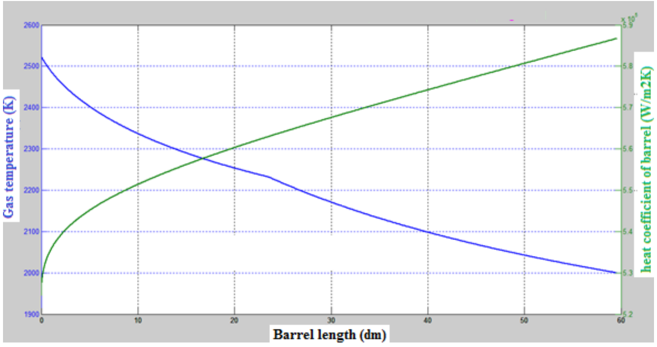


Figure 3. Distribution of temperature on the barrel for length

Based on Fig 3, the gas temperature has the opposite direction to the transmitting heat coefficient from air to barrel inside the barrel. This law is suitable for the real situation.

B. Determine the stress and deformation of the cannon barrel

1. Stress

The input parameters using for calculating the barrel's stress field are shown in Table 1 [18].

Table 1. The input parameters using for calculating the barrel's stress field

Parameter	**Symbol**	**Unit**	**Value**
Caliber	d	m	0.13
Elastic modulus of the material barrel	E	N/m^2	$2.14 \cdot 10^{11}$
The coefficient of thermal conductivity of the material barrel	λ	W/mK	48
Poisson coefficient	μ		0.3
The coefficient of thermal expansion of the material barrel	α	1/K	$10.1 \cdot 10^{-6}$
Density of material barrel	ρ	kg/m^3	7820
Specific heat	C	J/kg.K	440
The pressure in the outer barrel	p_n	MPa	101.32
The temperature at the outside of the barrel section	T_{bd}	K	295.15
The inner diameter at sectional	d_t	m	0.130
The outer diameter at sectional	d_n	m	0.292
Coefficient of heat from gas into the barrel	α_k	$W/m^2.K$	546570.8
Coefficient of heat from the barrel into the air	α_b	$W/m^2.K$	2010.7

The stress of the barrel due to only the load of pulse gas pressure

After meshing the model, loading forces and running programs on ANSYS [1], [4], the map of radial stress distribution at the maximum gas pressure cross section is shown in Figure 4 and Figure 5.

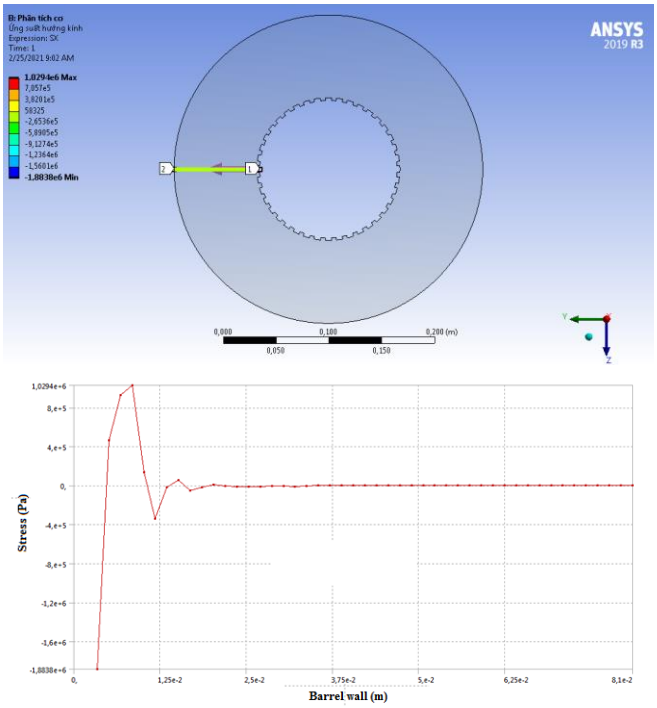


Figure 4. Radial stress field and graph

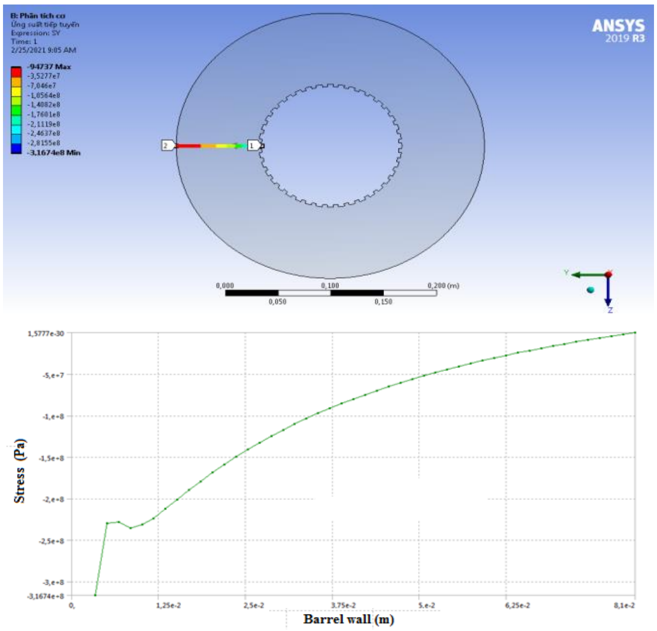


Figure 5. Tangential stress field and graph

Calculation results of stress at the maximum gas pressure cross section under the load of gas pressure are expressed in Table 2.

Table 2. The stress of the barrel under the load of gas pressure

Wall thickness (m)	Radial stress (Pa)	Tangential stress (Pa)	Equivalent stress (Pa)
0,0000			
1,6875e-003			
3,375e-003	-1,8838e+006	-3,1674e+008	7,7897e+008
5,0625e-003	4,6694e+005	- 2,3015e+008	6,4439e+008
…………… 7,9312e-002	…………….. -289,9200	……… - 2,1784e+006	…………… 1,7770e+008
8,1000e-002	-123,8600	-94737	1,7457e+008

The stress of the barrel due to only the load of pulse gas temperature

The map of stress distribution at the maximum gas pressure cross section is shown in Figure 6, 7 and 8.

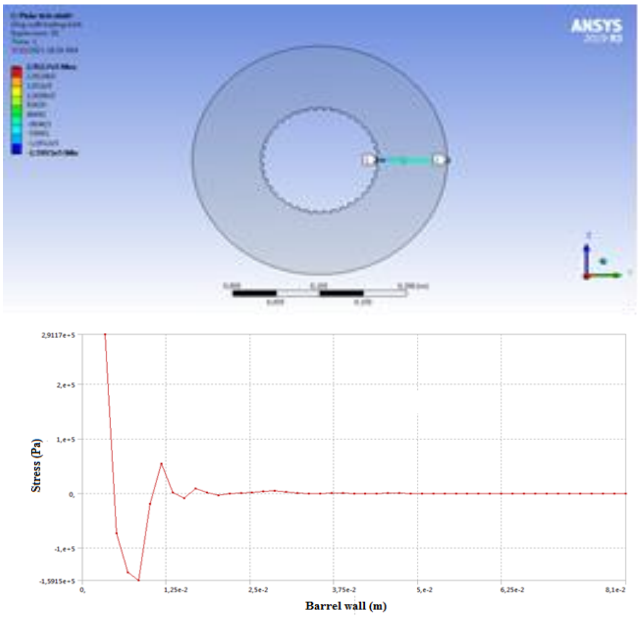


Figure 6. Radial stress field and graph

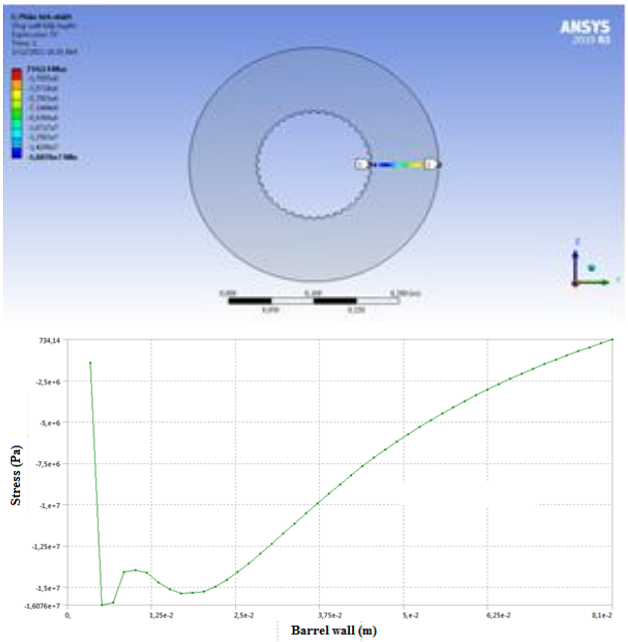


Figure 7. Tangential stress field and graph

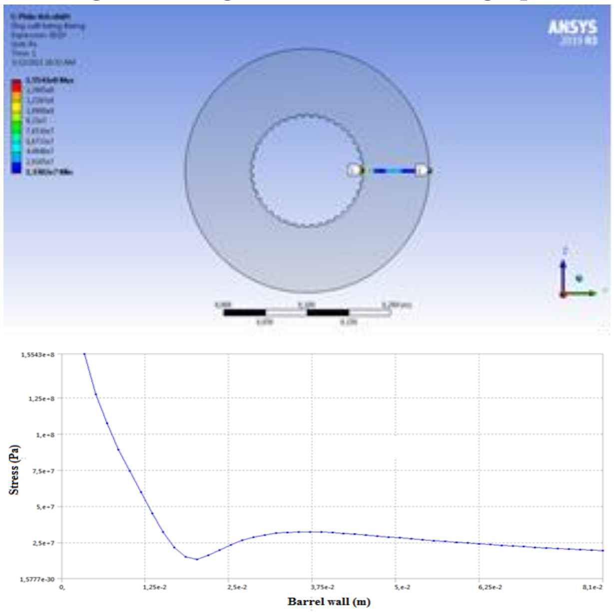


Figure 8. Equivalent stress field and graph

Calculation results of stress at the maximum gas pressure cross section under the load of gas temperature are expressed in Table 3.

Table 3. The stress of the barrel under the load of gas temperature

Wall thickness (m)	Radial stress (Pa)	Tangential stress (Pa)	Equivalent stress (Pa)
0			
1,6875e-003			
3,3750e-003	2,9117e+005	- 1,3944e+006	1,5543e+008
5,0625e-003	-72800	- 1,6076e+007	1,2759e+008
…..	…..	……	…….
6,7500e-003	- 1,4441e+005	- 1,5919e+007	1,0760e+008
7,9312e-002	48,927	- 2,3010e+005	1,9691e+007
8,1000e-002	20,389	734,14	1,9344e+007

The stress of the barrel under the action of both pulse gas pressure and temperature simultaneously

Using the result of calculating the interior ballistics as the input parameters for the simulation process, the stress of the barrel under the action of both gas pressure and gas temperature is stimulated by ANSYS program. The stress of the barrel is different from the stress under the action of only gas pressure or gas temperature and it is different from firing different shots.

*** The stress of the barrel after firing 1 shot**

After firing 1 bullet, the barrel of the cannon is affected by both gas pressure and gas temperature simultaneously in the real situation. Therefore, in this situation, the stress of the barrel is different from the stress under the action of only gas pressure or gas temperature.

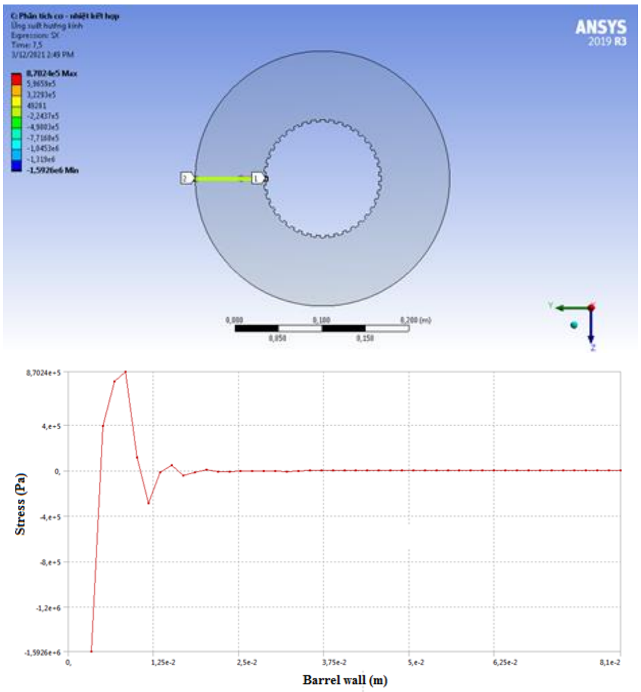


Figure 9. Radial stress field and graph after 1 shot

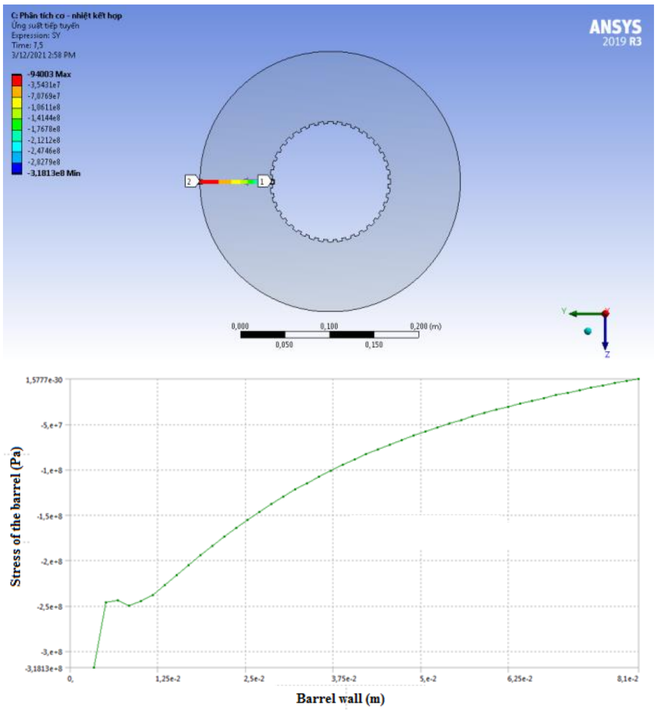


Figure 10. Tangential stress field and graph after 1 shot

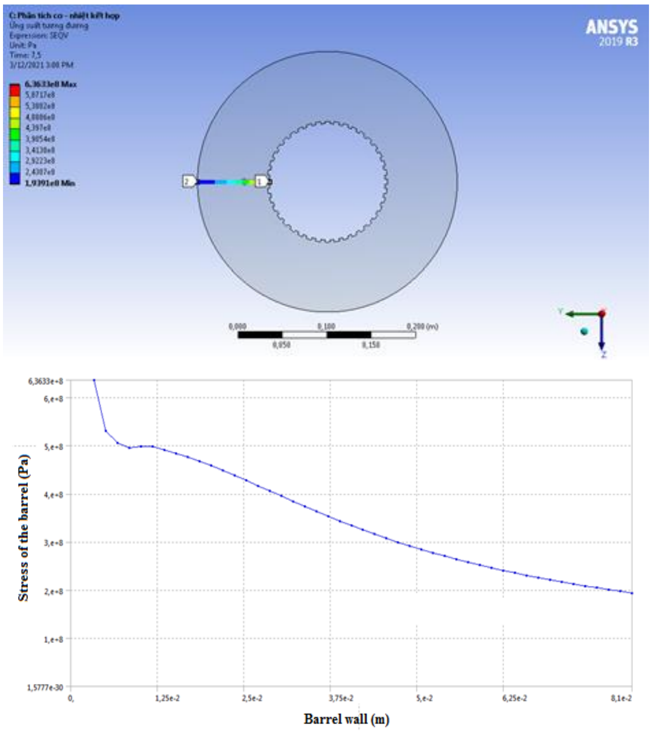


Figure 11. Equivalent stress field and graph after 1 shot

*** The stress of the barrel after firing 8 shots**

After firing 8 bullets, the barrel of the cannon is affected by both gas pressure and gas temperature simultaneously and the stress of the barrel after previous shot is different from the stress after the next shot. Therefore, in this situation, the stress of the barrel is changed after each shot.

The stress of the barrel after firing 8 shots is shown in Figure 12, 13, 14.

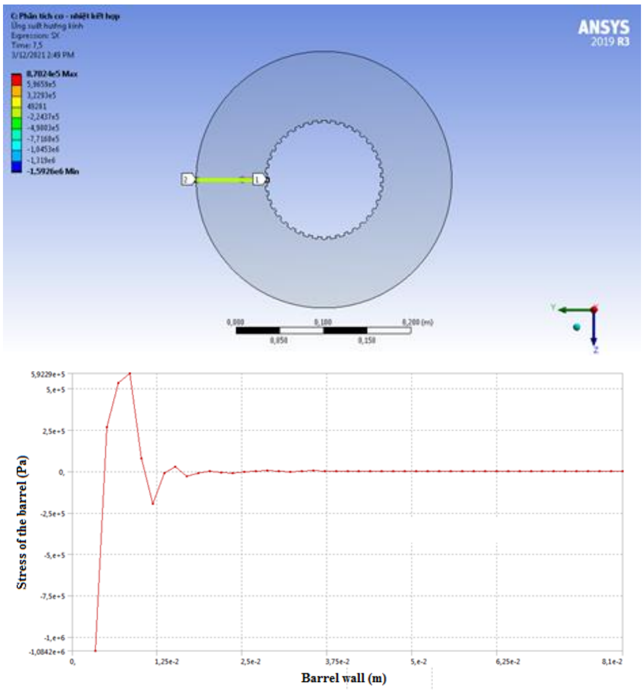


Figure 12. Radial stress field and graph after 8 shots

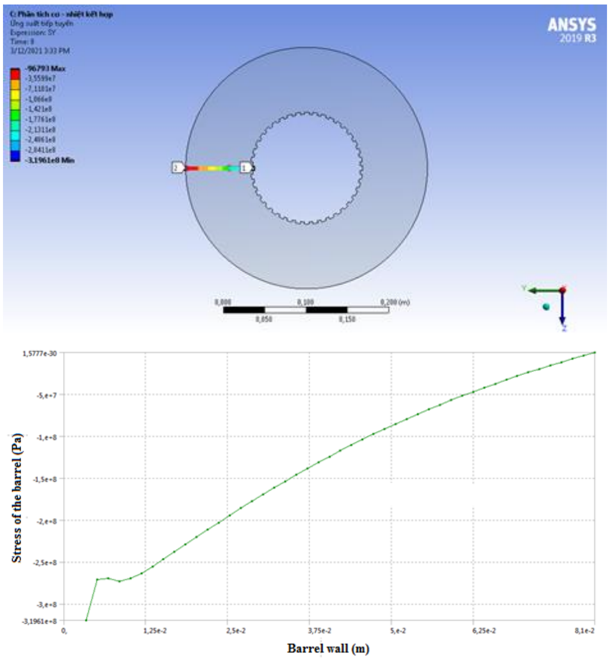


Figure 13. Tangential stress field and graph after 8 shots

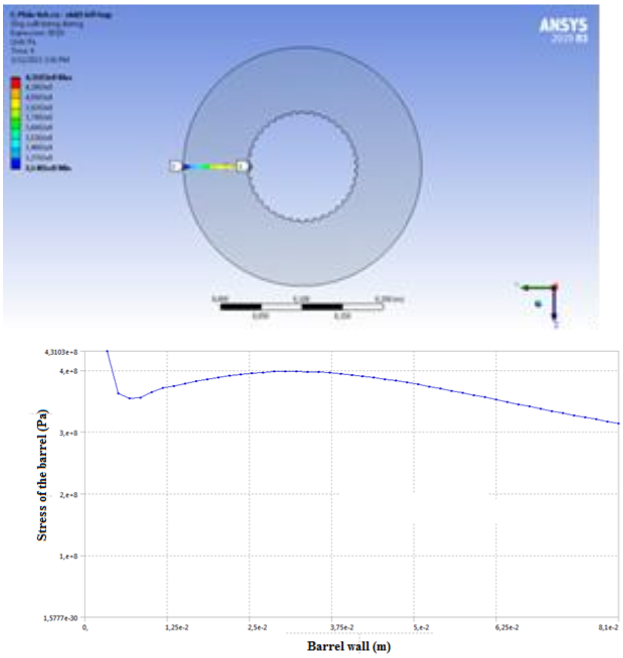
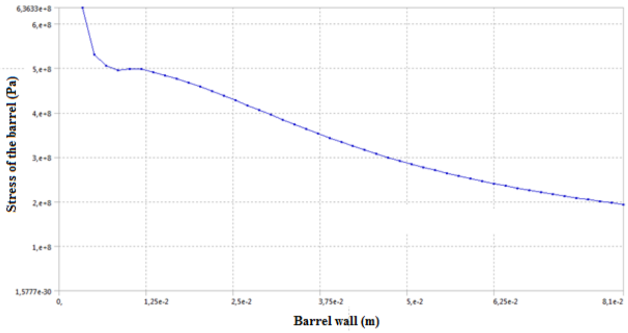
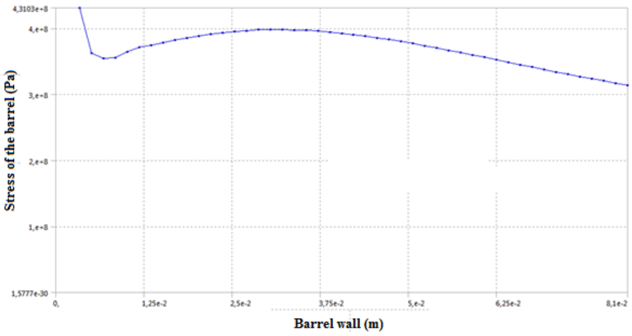


Figure 14. Equivalent stress field and graph after 8 shots

Based on the Figure 11 and Figure 14, the stresses of the barrel after firing 1 shot and 8 shots are different. After 1 shot, the stress of the barrel is decreasing. However, when firing 8 continuous shots, the stress of the barrel is increasing at first, reaching the maximum value and then decreasing. This result is suitable with the real situation. The comparison between two stresses is shown in Figure 15.



a) After 1 shot



b) After 8 shots

Figure 15. Equivalent stress after firing 1 shot and 8 shots

2. Deformation

The radial and tangential deformations of the cannon barrel are shown in Figures 16, 17 and Table 4.

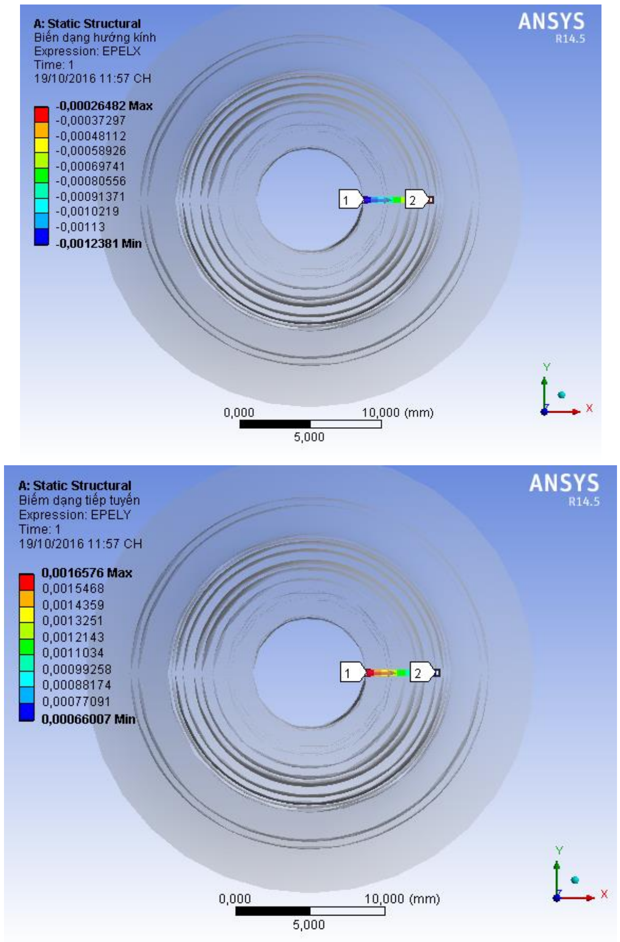


Figure 16. Deformation field according to barrel thickness due to the shot’s loading

Table 4. Radial deformation and tangential deformation due to the shot's loading

Wall thickness (mm)	Radial deformation (m)	Tangential deformation (m)
0	-1,24E-03	1,66E-03
1,6875e-003	-1,22E-03	1,64E-03
3,3750e-003	-1,20E-03	1,62E-03
5,0625e-003	-1,18E-03	1,60E-03
…..	…	…
6,7500e-003	-3,05E-04	7,02E-04
7,9312e-002	-2,85E-04	6,81E-04
8,1000e-002	-2,65E-04	6,60E-04

The equivalent strain field and total displacement are determined as shown in Figure 18, 19 and Table 5.

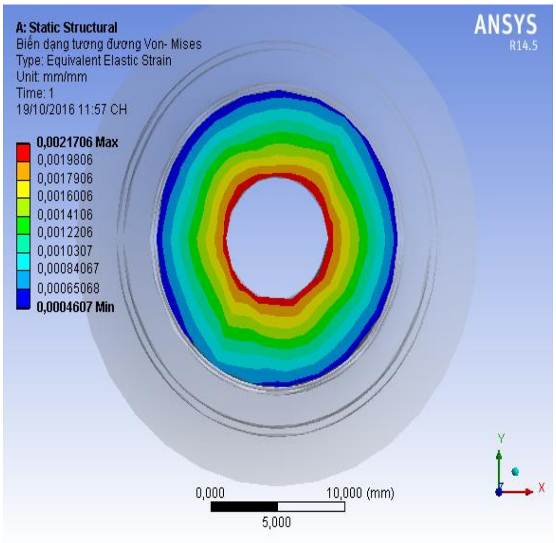


Figure 18. Equivalent strain

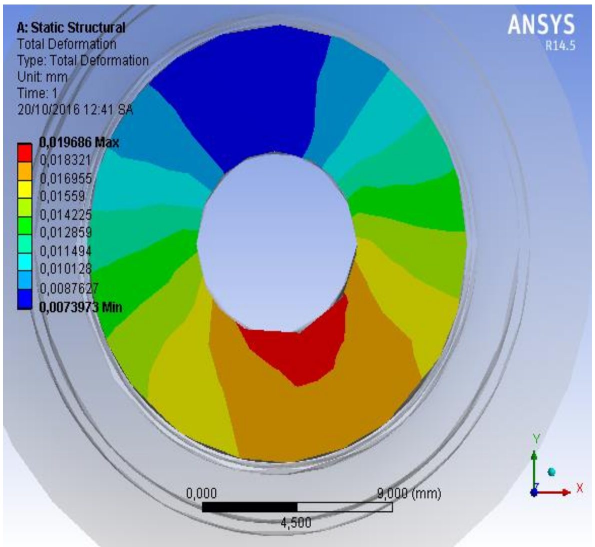


Figure 19. Total displacement

Table 5. Total displacement along the thickness of the barrel due to the impact of the shot

Barrel thickness (mm)	Total displacement (mm)
0	1,60E-02
1,6875e-003	1,59E-02
3,3750e-003	1,59E-02
5,0625e-003	1,58E-02
…..	…
6,7500e-003	1,45E-02
7,9312e-002	1,45E-02
8,1000e-002	1,45E-02

Calculation results show that the largest total displacement occurs at the inner wall of the barrel. This value gradually decreases with barrel thickness.

CONCLUSIONS

The content of the article focuses on solving the interior ballistics problem of a 130mm cannon to determine the loads acting on the barrel when fired. These parameters are the initial data of the problem of determining the stress and deformation of a cannon barrel using the finite element method. On the basis of the calculated results, the following conclusions are drawn:

- The stress of the barrel is calculated under the action of both gas pressure and gas temperature simultaneously.
- The stress of the barrel under the action of both gas pressure and gas temperature simultaneously is greater then the one of under the action of each gas pressure or gas temperature. This result is suitable for the real situation.
- The maximum stress of the barrel must be smaller than the limitation stress. This is one of the safety conditions in firing. That is the reason why the rate of fire of the 130M46 cannon is 8 shots per minute in the real situation.
- When firing, it is necessary to choose a reasonable rate of fire in order to increase the life of the barrel.

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