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The Influence of a Finite Element Mesh on the Reliability of the Results of Dynamic Processes of Armor Penetration of a Steel Plate by a Bullet

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Abstract. This paper investigates the influence of finite element mesh parameters on the accuracy of modeling the penetration of a steel plate by a bullet in the ExplicitDynamics ANSYS WB computational module. The best results were obtained for the 3rd type of mesh, which included 180 finite elements in the contact zone. For the plate made of impact-resistant S-7 steel, the maximum stresses for the 2nd type of mesh at the attempted penetration reached 1 572,7 MPa, but no penetration was observed. For the S-7 steel plates, penetration was observed only when using the third type of mesh, which confirms the importance of density in the contact zone for an adequate description of dynamic processes. The analysis showed that the Sweep method with density is optimal for modeling steel plate penetration due to the balance of calculation performance and accuracy of the results.

Introduction

Approaches Ensuring the reliability and safety of structures used in military, industrial, and civilian facilities [1, 2] is an important scientific and practical task [3, 4]. One of the key aspects of this research is the analysis of the behavior of materials and structures under dynamic impact loads, in particular, bullet penetration through steel plates [5, 6].

Modern approaches to studying this problem actively use the finite element method, which allows modeling complex processes with high accuracy [7]. However, one of the determining factors affecting the reliability of modeling results is the parameters of the finite element mesh. A mismatch in the size of the elements, their geometry, and mesh density can lead to errors in the representation of the stress-strain state and energy characteristics of the process.

Scientific research in this area demonstrates a high interest in optimizing mesh parameters to accurately model bullet penetration. However, to date, there are no universal recommendations that would ensure high reliability of the results for different scenarios of loading [8, 9]. At the same time, this issue is relevant for solving the problems of designing structures that must withstand dynamic impacts and developing new materials with increased resistance [10, 11].

This study considers the influence of finite element mesh parameters on the reliability of the results of modeling the penetration of a bullet through a steel plate. There was presented an analysis of the dependence of the accuracy of the results on the size and shape of the mesh elements, which allows improving modeling techniques and increasing the validity of engineering decisions.

Literature Review

The processes of modeling the dynamic impact on steel structures have received a lot of attention in scientific research, which creates the basis for further study of this topic.

For example, in [12], a study was conducted on the penetration of a bullet through an aluminum plate. In the paper [12], the influence of plate thickness and the angle of contact between the bullet and the surface on the process of its penetration was considered. However, despite the fact that the finite element mesh of the plate was generated using hexahedral finite elements with density at the contact point, the finite element model of the bullet itself was made using tetrahedral elements. This can lead to inaccuracies and does not guarantee reliable results in the contact zones of the plate and bullet finite elements. Because tetrahedral elements often require more nodes to achieve the same accuracy as hexahedra. This leads to possible errors at the contact boundaries due to the different order of approximation.

The implementation of practical tests of the dynamic impact of a bullet on a plate, as described in [13], is complicated by the need to use specialized equipment that provides accurate impact conditions taking into account the actual speeds and angles of contact between the bullet and the plate. In addition, high-precision measuring equipment is required to record the parameters of the penetration process, such as speed, deformation, etc.

The paper [14] investigated the process of penetrating a steel plate with a bullet using computer modeling with the SPH method. Despite the fact that this method is suitable for modeling large deformations, it often demonstrates sensitivity to particle size, which requires additional research to determine their optimal parameters. This makes it difficult to obtain stable and reliable results, especially in areas with high stress and deformation gradients.

In the paper [15], a numerical method was used to model the impact of an armor-penetrating shell on an armored steel plate. The applied finite element method in [15] allows obtaining detailed data on the dynamic behavior of plates during impact, but when conducting numerical modeling, it is important to analyze the sensitivity of the results to the mesh parameters (element size, their type), but this aspect is not covered in the paper.

In [16], the mathematical modeling of the dynamic interaction of a bullet with a perforated steel plate was performed in the LS-Dyna software package using the finite element method. The validation of the mathematical model showed an error in the range of 2,6 – 4,8 %, which confirms its adequacy. However, the use of small elements significantly increases computational costs and calculation time, which requires optimization of mesh parameters to achieve a balance between accuracy and efficiency of modeling.

The paper [17] presents the results of mathematical modeling performed in the ANSYS/LS-DYNA software package. For modeling, the finite element method with mesh density in the area of contact between the bullet and the plate was used. However, the paper [17] does not provide information on the size and type of finite elements used, and there is no detailed analysis of the model's sensitivity to mesh parameters. This makes it difficult to determine the most optimal finite element mesh for modeling.

Thus, studying the effect of a finite element mesh on the reliability of the results of bullet penetration through a steel plate is an important task. It will allow determining the optimal mesh parameters for mathematical modeling of the dynamic impact of a bullet on a steel plate.

Research Methodology

The aim of the research is to develop and optimize methods for mathematical modeling of the dynamic impact of a bullet on a steel plate using the finite element method. Particular emphasis is placed on analyzing the influence of finite element mesh parameters on the accuracy and reliability of modeling results to improve the efficiency and reliability of engineering solutions.

1. To create mathematical models in the Explicit Dynamics ANSYS WB computational module to study the penetration of a plate by a bullet made of structural nonlinear steel and S-7 steel using different types of finite element meshes:

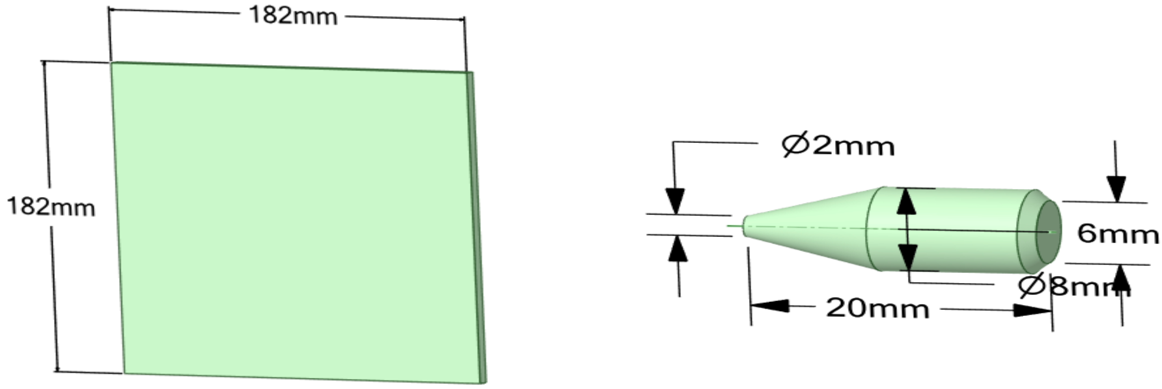
- type 1: automatic by default settings using hexahedral finite elements;
- type 2: using the Sweep method without density at the point of contact between the bullet and the plate using hexahedral finite elements;
- type 3: using the Sweep method with density at the point of contact between the bullet and the plate using hexahedral finite elements.

2. To analyze the stress-strain state of a steel plate made of structural nonlinear steel and S-7 steel under the influence of dynamic processes using three types of finite element models, and determine the optimal one for further use in solving similar problems.

Object of research: the process of dynamic penetration of a steel plate by a bullet.

Subject of research: the influence of finite element mesh parameters on the accuracy and reliability of the results of modeling the process of penetration of a steel plate by a bullet.

To study the dynamic processes of penetration of a steel plate, the steel plate with density of 5 mm and a bullet were used in the simulation, the appearance of which is shown in Fig. 1.



a b

Fig. 1. The appearance of the instruments used to study dynamic processes: *a* – steel plate, *b* – bullet

In the mathematical modeling of the process of penetrating a steel plate by a bullet, the parameters of materials were taken, as shown in Table 1 and Table 2.

Table 1. Material parameters of the plate made of structural nonlinear steel (Structural Steel NL) for the study of dynamic penetration processes

Material	Density (kg/m^3)	Specific Heat (J/kg·°C)	Yield stress (MPa)	Tangent Modulus (MPa)
Structural Steel NL	7 850	434	$2{,}5 \cdot 10^8$	$1{,}45 \cdot 10^9$

Table 2. Bullet material parameters for the study of dynamic penetration processes

Material	Density (kg/m^3)	Specific Heat (J/kg·°C)	Bulk Modulus (MPa)	Shear Modulus (MPa)
Structural Steel	7 850	434	$1{,}6667 \cdot 10^5$	$7{,}6923 \cdot 10^4$

When reproducing a computational experiment using impact-resistant S-7 steel, the Johnson-Cook Strength model for describing the strength of a steel plate was used [18, 19]. S-7 steel is assumed to have a density of 7 750 kg/m^3 and a heat capacity of 477 J/kg·°C.

This mathematical model is physically grounded for describing the behavior of materials under plastic deformation, especially under high-speed impacts, dynamic loads, and thermodynamic effects [20].

The chosen model allows us to quickly and relatively accurately predict the behavior of materials under complex dynamic conditions [21].

The model parameters are shown in Table 3.

Table 3. The Johnson-Cook Strength parameters

Parameters	Value	Unit of measurement
Initial Yield Stress	$1{,}539 \cdot 10^9$	Pa
Hardening Constant	$4{,}77 \cdot 10^8$	Pa
Hardening Exponent	0,18	-
Strain Rate Constant	0,012	-
Thermal Softening Expong	1	-
MeltingTemperature	1489,9	°C
ReferenceStrainRate	1	(1/s)

The graph of Yield Stress dependence on Plastic Strain in a steel plate for different strain rates is shown in Fig. 2.

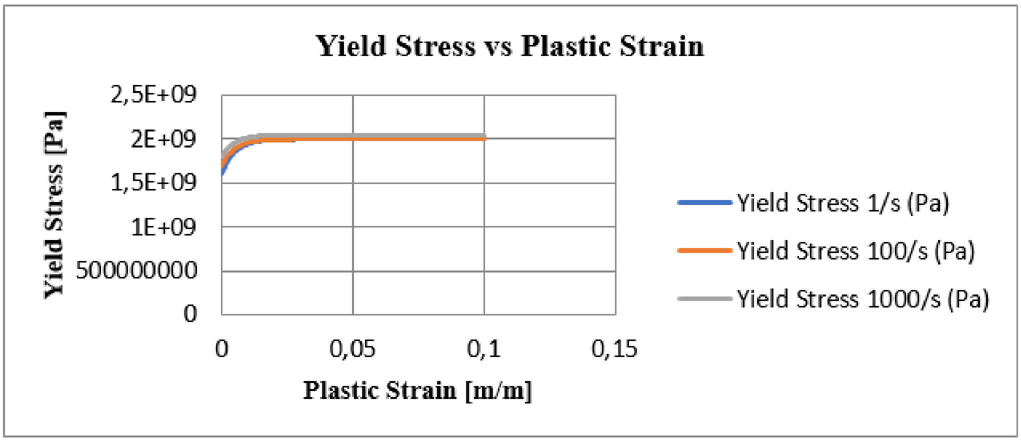


Fig. 2. Graph of Yield Stress dependence on Plastic Strain for different strain rates

The creation of a finite element mesh and computational experiments were carried out in the Explicit Dynamics ANSYS WB module.

Fig. 3 shows three types of generated finite element meshes for studying the dynamic processes of penetration by a steel bullet.

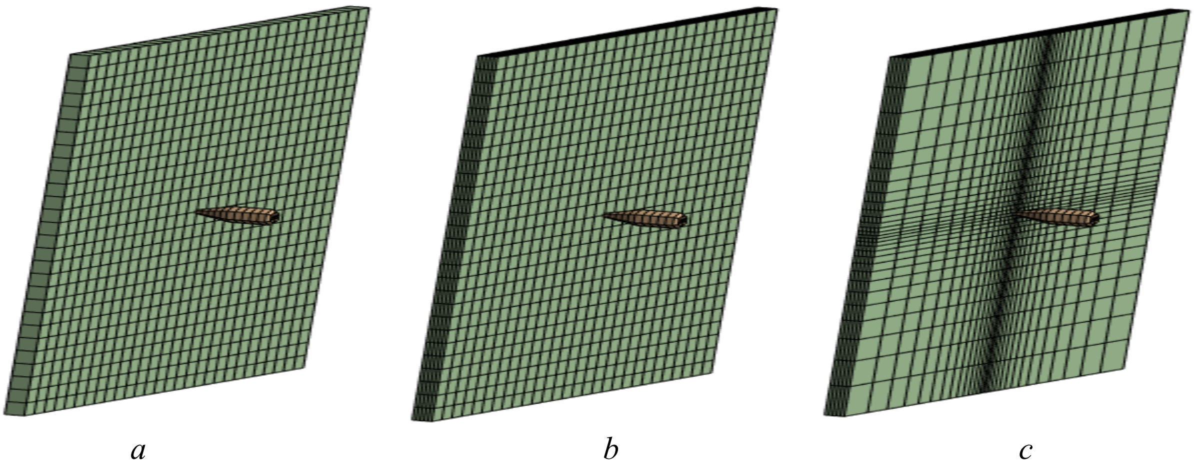


Fig. 3. Finite element meshes for studying the dynamic processes of steel bullet penetrating generated by three methods: a – automatically, b – using the SWEEP method with the formation of 5 finite elements in the plate thickness layer, c – using the SWEEP method, but with density at the point of contact between the bullet and the steel plate

The 2nd type of mesh was generated using the SWEEP method with the formation of 5 finite elements in the plate thickness layer. When creating the mesh for the steel plate, the Edge Sizing approach was used, which divides the edges into a specified number of segments. To do this, the

Number of divisions parameter was selected, according to which all 8 edges were divided into 90 segments, as shown in Fig. 4.

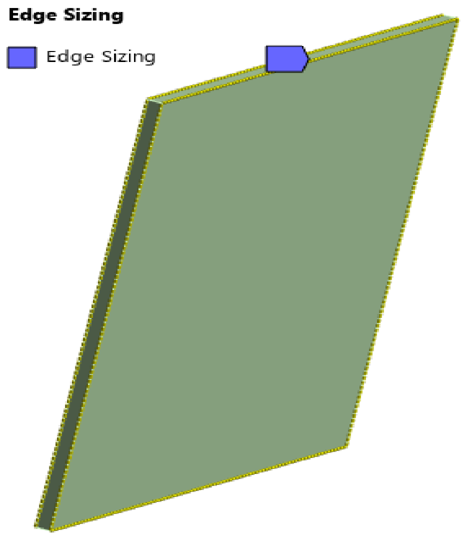


Fig. 4. Displaying the applied approach Edge Sizing by type Number of divisions with a value of 90 when using the 1st SWEEP method

The total number of elements for this type of mesh generation is 37 955, and the number of nodes is 46 632, respectively.

The 3rd type of mesh was also generated using the SWEEP method, as in the 2nd type, but with additional density of the elements in the area of contact between the bullet and the steel plate. In this case, using the Edge Sizing approach, the Number of divisions parameter was 30, but with the Bias Factor option for density in the center of the plate, where the bullet contacts the steel plate, as shown in the figure. 5.

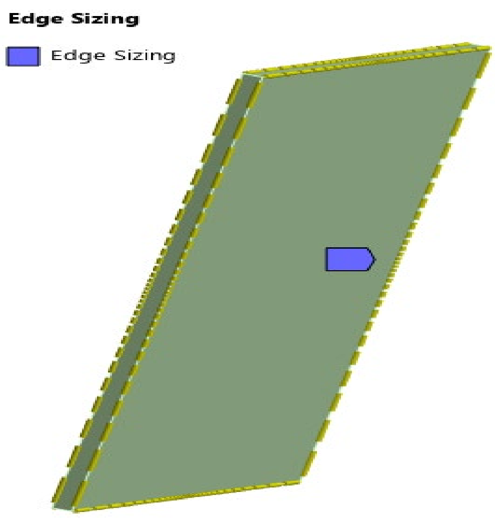


Fig. 5. Display of the applied Edge Sizing approach by type Number of divisions with a value of 30 when using the 2nd SWEEP method

The total number of elements is 4 610, and the number of nodes is 5 934.

The plate was rigidly fixed along the thickness contour during all computational experiments, as shown in Fig. 6.

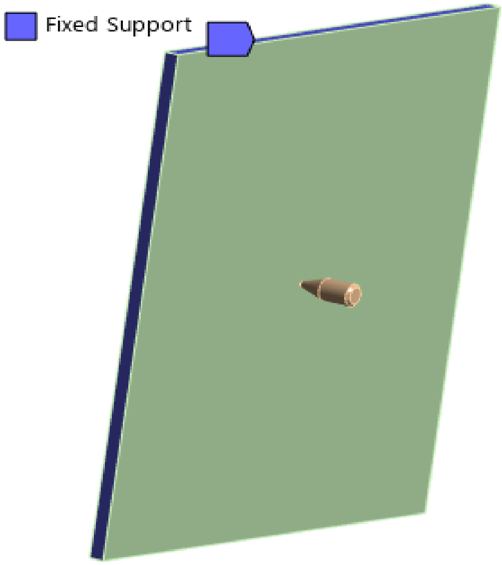
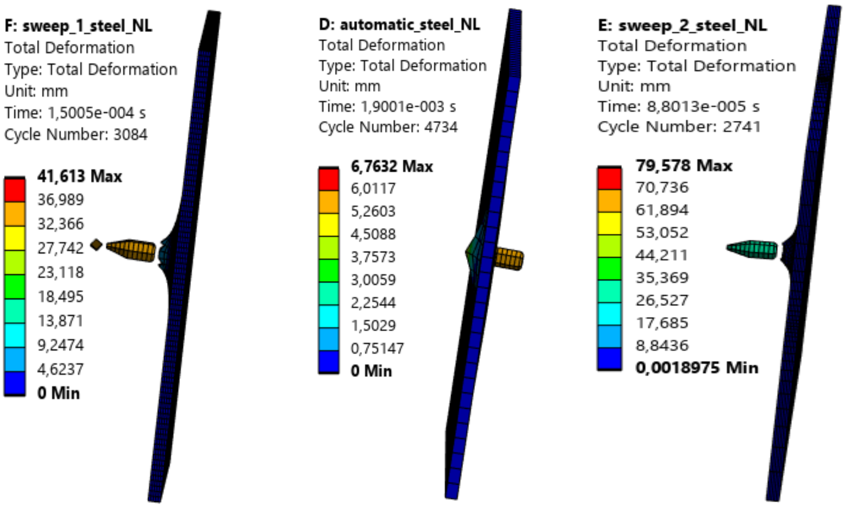


Fig. 6. Displaying the conditions for fixing the steel plate

At the beginning of the experiment, the bullet is at a distance of 0,01 mm from the steel plate at an angle of 90°. The bullet speed is set at 650 m/s. The bullet is modeled as an absolutely rigid body, and the steel plate is modeled as a flexible body. The duration of the experiment is 0,01 s.

Results

Based on the results of the experiments that modeled the dynamic processes of bullet penetration through a steel plate made of Structural Steel NL and impact-resistant steel S-7, the data on the stress-strain state of the steel plate were obtained. Fig. 7 shows the results of experiments on the bullet penetration through a steel plate made of StructuralSteel NL using different finite element meshes.



a *b* *c*

Fig. 7. The results of dynamic processes for bullet penetration of a steel plate made of Structural Steel NL using different finite element meshes: a – automatic, b – using the Sweep method without density, c – using the Sweep method with density at the point of contact between the bullet and the plate

Fig. 8 shows the stress distribution on the side of the bullet penetration of a steel plate made of Structural Steel NL during the mathematical modeling of dynamic processes.

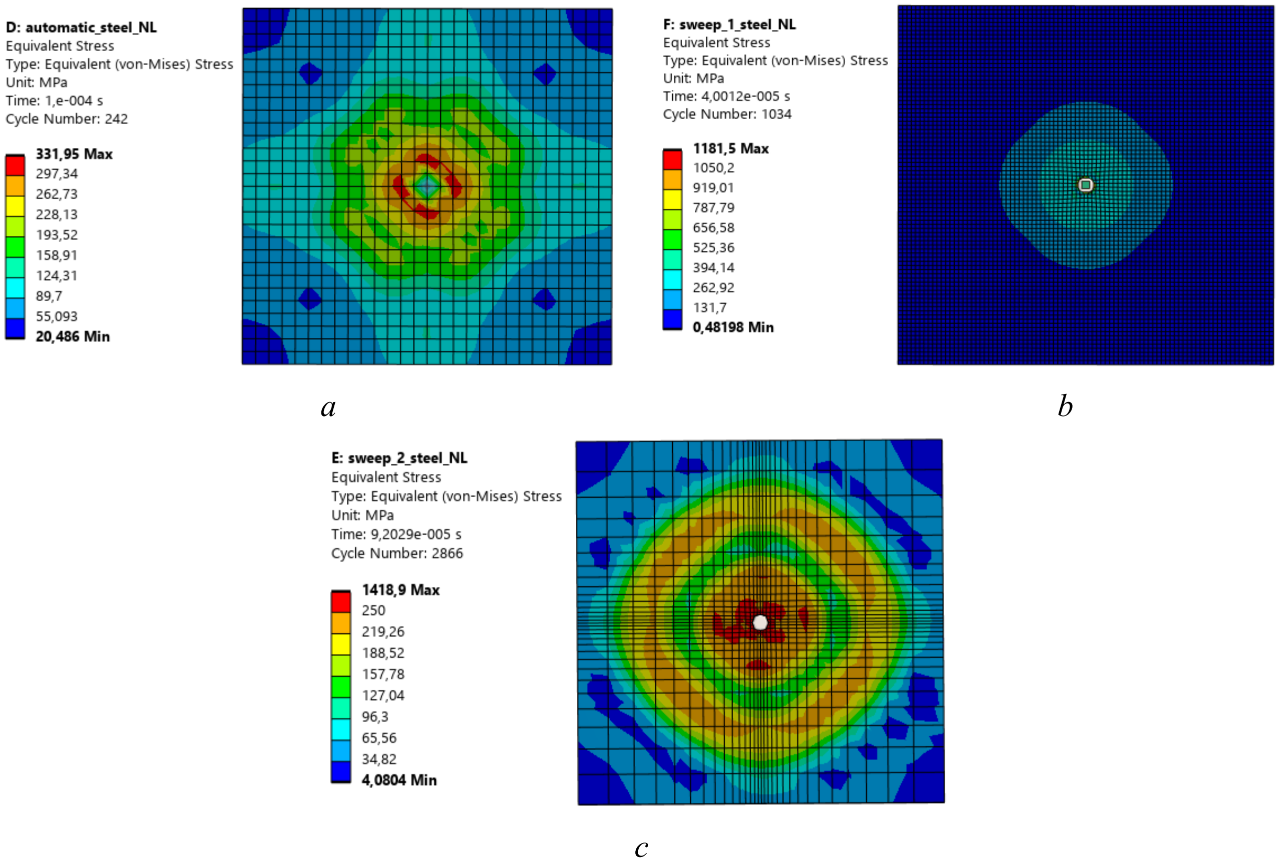


Fig. 8. Stress distribution on the side of a bullet penetration of a steel plate made of Structural Steel NL during mathematical modeling of dynamic processes using different finite element meshes: a – automatic, b – using the Sweep method without density, c – using the Sweep method with density at the point of contact of the bullet with the plate.

The next step was to study the behavior of a steel plate made of S-7 steel. The model parameters are shown in Table 3 and Fig. 2.

Fig. 9 shows the results of a bullet penetration of a steel plate made of S-7 steel using different finite element meshes.

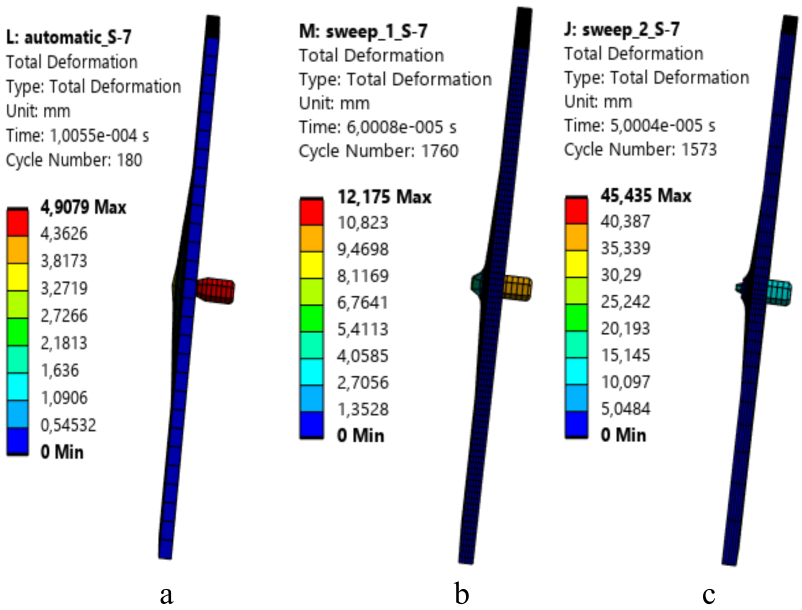


Fig. 9. Display of dynamic processes of a bullet penetration through a steel plate made of S-7 steel using different finite element meshes: a – automatic, b – using the Sweep method without density, c – using the Sweep method with density at the point of contact between the bullet and the plate.

Fig. 10 shows the stress distribution on the side of a bullet penetration of a steel plate made of S-7 steel during the mathematical modeling of dynamic processes using different finite element meshes.

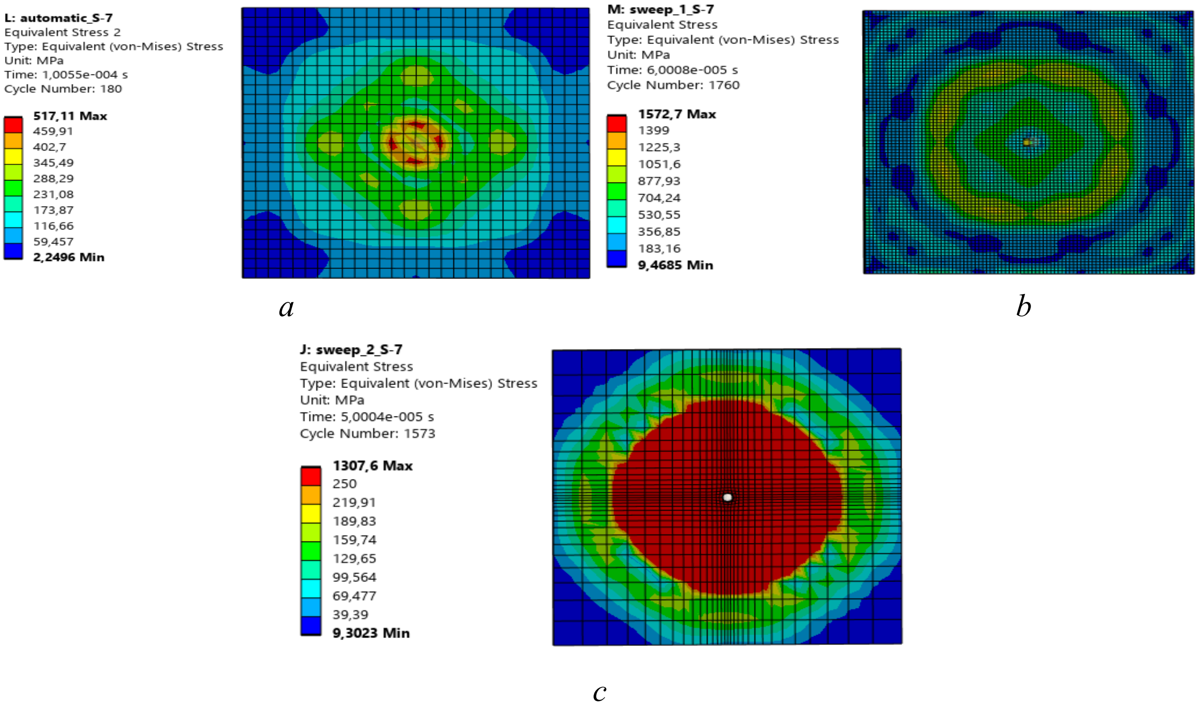


Fig. 10. Stress distribution on the side of a bullet penetration of a steel plate made of Steel S-7 during mathematical modeling of dynamic processes using different finite element meshes: a - automatic, b - using the Sweep method without density, c - using the Sweep method with density at the point of contact of the bullet with the plate

Fig. 11 shows the plastic deformations obtained by a steel plate made of Steel S-7 due to the dynamic impact of a bullet using different finite element meshes.

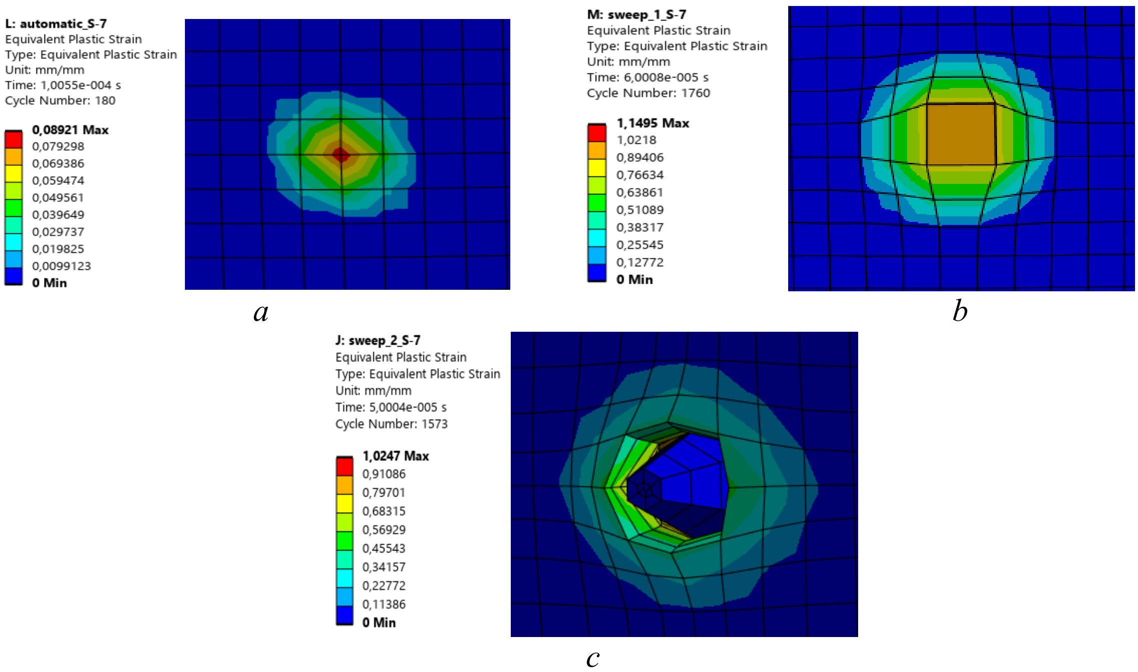


Fig. 11. Plastic deformations obtained by a steel plate made of Steel S-7 due to the dynamic impact of a bullet using different finite element meshes: a – automatic, b – using the Sweep method without density, c – using the Sweep method with density at the point of contact between the bullet and the plate

Thus, the experiments conducted using computer modeling allow us to analyze the obtained results to determine the optimal finite element mesh.

Discussion

In the process of studying the influence of finite element mesh parameters on the modeling of a steel plate penetration by a bullet, it was found that the accuracy of the results obtained largely depends on the type of mesh and its settings. When applying the automatic method of creating a finite element mesh, it was found that the bullet did not penetrate the steel plate. This is observed both when conducting studies on a plate made of impact-resistant S-7 steel (Fig. 9a) and on nonlinear steel (Fig. 7a). This is due to the fact that the entire armor penetration zone consists of only four finite elements. That is, there are 4 elements in the zone of contact between the bullet and the plate, and the thickness of the plate consists of one row of elements. Thus, an insufficient number of finite elements were used within the proposed hole when creating the mesh by the automatic method, which is insufficient to reliably reproduce these dynamic processes during modeling.

In addition, during the computational experiment using the first type of finite element mesh, maximum stresses of 206,18 MPa were observed on the plate, which were concentrated in the area around the proposed hole at a distance of more than 25 mm from the contact point (Fig. 8a). At the same time, at the contact point itself, the stresses in the plate were only 3,2161 MPa (Fig. 8a), even under the condition of maximum plate deformation (Fig. 7a). This distribution of stresses also confirms the assumption that the results obtained when using an automatic mesh are unreliable, since the stress-strain state is averaged when solving this problem, which does not lead to armor penetration of the plate.

In contrast, for the other two types of meshes, the destruction of the nonlinear steel plate occurs (Fig. 7b, c). This confirms the importance of using a more detailed mesh, especially in the area of contact between the bullet and the plate, to adequately reproduce physical processes and thus obtain reliable results.

It should be noted that in the case of using the SWEEP method without mesh densification, during penetration of the armored plate, the fragment is observed to fly away in front of the bullet (Fig. 7b). This result is less plausible compared to the result obtained when using a mesh with densification at the contact point (Fig. 7c). This is explained by the physical properties of the plate material, since nonlinear steel is an isotropic plastic material characterized by significant plastic deformation before destruction.

Thus, analyzing the results obtained for armor penetration of a plate made of nonlinear steel, Fig. 7 shows that the most adequate mesh model is the variant using the SWEEP method with densification in the contact zone. This approach makes it possible to more accurately take into account the peculiarities of the stress-strain state of the material and better reproduce the actual physical processes of bullet penetration of a steel plate. Based on the analysis of the results obtained for the armor penetration of a steel plate modeled from impact-resistant S-7 steel, ambiguous results were also observed. Thus, the penetration of a steel plate made of S-7 steel was observed only when using the 3rd type of finite element mesh generated using the Sweep method with densification at the point of contact between the bullet and the plate (Fig. 9c). The behavior of the steel plate made of S-7 steel is fundamentally different when using the type 3 mesh compared to the other two types. When studying the distribution of stresses in the steel plate when using a type 2 mesh, it was found that the maximum values when trying to penetrate the plate were 1572,7 MPa (Fig. 10b). At the same time, the plate penetration does not occur using this method of creating a mesh, in contrast to studies using a type 3 mesh (Fig. 10b, c).

The maximum stresses in the model with the mesh created by the Sweep method with densification at the plate penetration are 1307,6 MPa (Fig. 10c), while for the mesh generated by the 1st method, they are 517,11 MPa (Fig. 10a). Analyzing the results obtained, it was found that according to the 1st and 2nd methods of mesh generation, the number of finite elements in the contact zone of the plate with the bullet is insufficient (Fig. 3a, b), which does not allow us to reliably describe the dynamic impact of the bullet on the plate.

Based on the results of the analysis of the distribution of plastic deformations (Fig. 11), it was found that the value of 0,08921 when using the 1st type of mesh (Fig. 11a) is typical for many scenarios of deformation of such plates, i.e., it indicates that the plate has undergone a noticeable change in shape, but remained functional.

However, this does not reproduce the actual physical processes of plate penetration, as shown in Fig. 11c. According to the second type of mesh creation, the value of plastic deformations of the plate is 1,14, which indicates the presence of destruction in local areas of the plate, but this is not visually confirmed as in Fig. 11c. Thus, according to the results of the analysis, it was found that the most optimal mesh is the mesh created by type 3, i.e., using the SWEEP method with densification of the contact zone between the steel plate and the bullet. This is due to its performance and reliability, due to the number of finite elements in the armor penetration zone, which is about 180 units. This allows for a more reliable description of dynamic processes compared to a model consisting of 125 finite elements obtained by generating a mesh by the second method using SWEEP without densification.

In addition, the performance of calculations using a type 3 mesh is higher than for a type 2 mesh, since the number of finite elements in the first case is 8,2 times higher than in the second case.

Conclusion

1. Based on the results of the constructed geometric three-dimensional model of a steel plate and a bullet, three types of finite element models with different numbers of hexahedral finite elements in the contact zone of the bullet with the steel plate were generated in the Explicit Dynamics module of ANSYS WB to study dynamic processes:

- automatic by default settings: 4 finite elements;
- using the Sweep method without densification at the point of contact between the bullet and the plate: 125 finite elements;
- using the Sweep method with densification at the point of contact between the bullet and the plate: 180 finite elements.

2. The results of the study of the dynamic processes of the impact of a bullet on a steel plate showed that the finite element mesh created by the Sweep method with densification (3rd mesh type) is the optimal approach for modeling the penetration of steel plates made of structural nonlinear steel and impact-resistant S-7 steel in the Explicit Dynamics module of ANSYS WB. This approach ensures high accuracy of the results due to a sufficient number of finite elements in the contact zone (180 units) and a balance between calculation performance and reliability of dynamic process modeling.

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