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Numerical Aspects of Penetration Simulation

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Abstract. Several numerical methods were studied as means of solution to a penetration problem. The Element Free Galerkin (EFG), Smooth Particle Hydrodynamics (SPH), Finite Element Analysis (FEA) methods were considered. The above mentioned algorithms implemented in the LS-DYNA code were applied. Additionally, the mesh density was taken into consideration. The reference case assumed an average node to node distance of 1 mm. The finer and coarser mesh densities were analysed. The full 3D models of the projectile and target were developed with a strain rate and temperature dependent material constitutive relations. An impact of 12.7x108 mm B32 armour piercing projectile on a 80 mm thick block of 7017 aluminium alloy was modelled. The results obtained by a computer simulation were validated and then verified by experimental data. The study of the erosion criteria involves defining the most efficient and reliable way of removing the failed and extremely deformed parts of the projectile and targets. Generally, EFG method applied to solve the perforation/penetration problems can be characterized as a very stable, reliable and effective method.
Keywords: computer simulations, EFG, SPH, FEM, penetration problem, model validation

1. INTRODUCTION

The paper concerns different numerical methods including EFG (Element Free Galerkin Method), SPH (Smooth Particle Hydrodynamics), FEM (Finite Element Method) of research on modern, protective layers, which are used in the armours of tanks, combat vehicles and aeroplanes. Computer modelling methods have been an important element of the research process for years and areas of their utility are still being extended. Their popularity is related to the fact that they are an intermediate link between experimental research and theoretical analysis. Computer simulations allow simple observations of physical properties changing in time and space. The results of simulations can be easily and comfortably presented as charts, etc. An experimental setup (geometry, mechanical properties, boundary and initial conditions) can be modified in a rather simple way. Numerical models behave similarly to real, physical objects (3D models) and can include many physical properties such as friction, compressibility, temperature, deformation dynamics, cracking and structure erosion. Numerical methods provide approximate solutions of equation system for given boundary and initial conditions. The reasons of possible differences between simulation and experimental results are investigated and removed by modification of initial assumptions (constitutive models of materials, initial and boundary conditions, etc.) or numerical parameters. This operation, called validation, is a necessary phase of any numerical modelling process.

In a numerical model of the penetration problem the different mesh and meshless methods are applied. For this kind of research FEM is most commonly used, but there are also other numerical methods that can be applied. In this paper an influence of the numerical method on the result is discussed. The quantitative assessment was based on the calculated value of the kinetic energy versus time – $E_k(t)$ of the undestroyed part of projectile. Three dimensional numerical models for each numerical method were developed. An explicit time integration algorithm was used for the solution of the problem equations.

The initial stage of the problem is presented in the Fig. 1. The full 3D models of the projectile and target were developed with strain rate and temperature dependent material constitutive relations. A perpendicular impact of the 12.7x108 mm B32 armour piercing projectile on 80 mm thick block of the 7017 aluminium alloy was modelled.

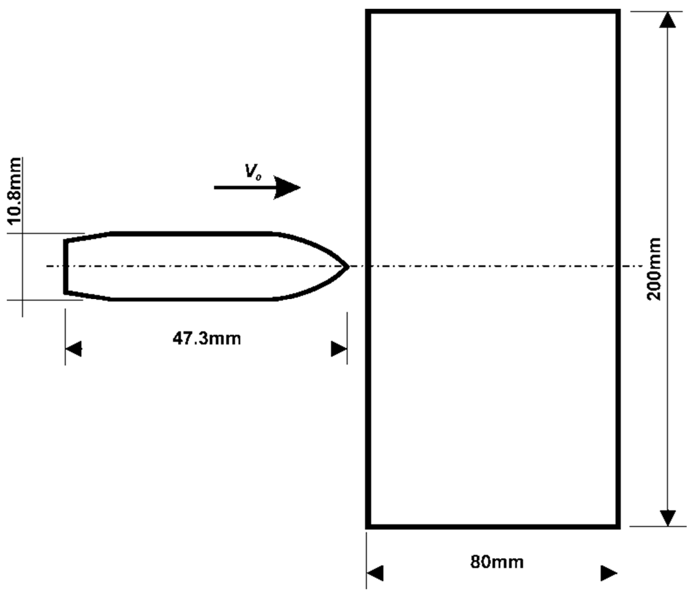

Fig. 1. The initial stage of the problem

The projectile model was reduced to the steel core. Geometry of the projectile: length equals 47.3 mm and diameter equals 10.8 mm. The target is a square 200x200 mm and its thickness is 80 mm.

2. NUMERICAL MODELS

The numerical methods used in presented work are characterized below. The first of them is EFG [5, 6]. It only uses a set of nodal points describing the geometry of the body, no mesh in a classic sense is needed to define the problem. The nodes can be generated regularly or they can be concentrated locally. The connectivity between the nodes and the approximation functions are entirely constructed by the method. It uses Moving Least Square Approximation technique for the construction of the shape function. The Galerkin weak form is applied to develop the discretized system of problem equations. Either a regular background mesh or a background cell structure is used for solving partial differential equations, in order to calculate the integrals in the weak form.

The second method is SPH [1]. In this method the medium is divided to a randomly distributed set of discrete elements referred to particles for which physical properties are defined. The most important parameter of this method is the smoothing length which describes the mean distance between particles. For smoothing properties between the particles, kernel functions are used. Flow variables are calculated with allowance of all particles located within the finite radius related to the smoothing length. This method is used in the cases of extreme deformations, where classical finite elements methods would be limited by mesh tangling.

The last of these methods is FEM [8]. The idea of FEM is the division of the given continuous area into a finite number of sub-areas (finite elements) connected with one another in nodal points and approximation of solution inside the finite elements using interpolation functions and function values in nodes. FEM equations are obtained from problem's integral formulation using a variational rule or a weighted residues method. The variational method is based on the definition of minimization of certain functional. The weighted residues method converts the local formulation of the boundary problem into a weak integral form for solution on which Galerkin or Ritz methods can be used. The tetrahedron element topology with one integration point was applied in the case of finite element analysis.

In the presented model a two mesh size concept is used (Fig. 2). The interior and external meshes can be recognized. The interior mesh is located near the impact point and external mesh surrounds the interior one. They are connected together by applying a specialized tied contact method available in the LS-DYNA solver.

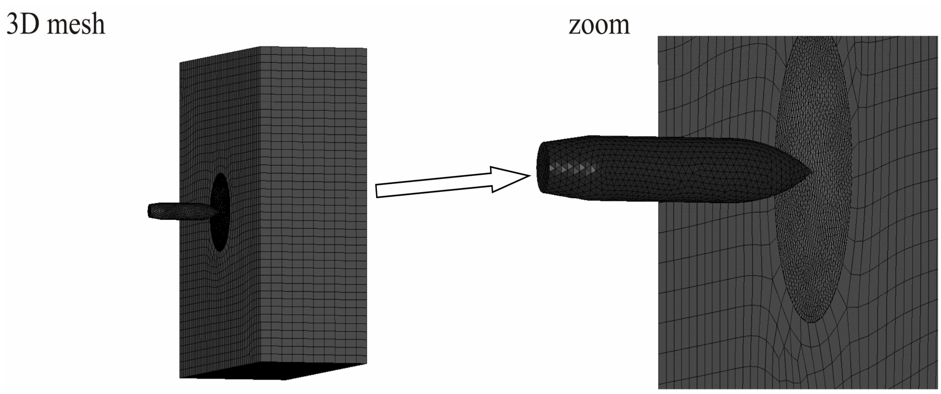

Fig. 2. A 3D view of the numerical model mesh

Depending on the mesh density, there are different numbers of elements and nodes for given node to node distances. This is shown in Table 1.

Table 1. Considered densities of the mesh

Mesh density	**Node to node distance**	**Total number of nodes**	**Total number of elements**
Reference	1 mm	170 000	850 000
Coarse	1.25 mm	80 000	425 000
Fine	0.75 mm	350 000	1 450 000

The proper dynamic behaviour of metal alloys (hard steel, 7017 aluminium alloy) was realized by application of Johnson–Cook constitutive model with Gruneisen form of the equation of state. The values of appropriate parameters are included in Table 2. The cold term of the Gruneisen equation is based on an experimentally observed relationship of the shock wave velocity versus particle velocity with this dependency being assumed linear.

Two kinds of fracture models were assumed. These are the spalling model and the failure model. The spalling model is based on maximum principal stress, it occurs only in case of strong dynamic action, when a wave character appears. The selected option of this model checks on every time step the maximum principal stress value. The critical value of principal stress is given in the model. If this value is exceeded the deviatoric stresses are reset to zero. Such an element behaves like sand. The spall type fracture leaves the destroyed element in the model. The failure model is based on plastic deformation. There is a limit value of the effective plastic strain assumed. This type of model deletes the destroyed element. In a high strain rate impact environment, one can argue that a strain controlled failure model is more realistic than a stress controlled failure model [7].

Table 2. Johnson–Cook model parameters for hard steel and 7017 Al [6, 9,10]

Parameter	**Units**	**Hard steel**	**7017 Al alloy**
Johnson–Cook			
ρ	kg/m^3	7790	2470
A	GPa	1.235	0.435
B	GPa	3.34	0.343
C		0.0114	0.01
m		0.94	1.0
n		0.89	0.41
T_m	K	1800	878
T_r	K	293	293
C_p	J/kgK	460	893
Gruneisen Equation of state			
c	m/s	4570	5240
S_1		1.49	1.4
S_2		0.0	0.0
S_3		0.0	0.0
Γ_0		1.93	1.97
a		0.5	0.48

The initial condition was reduced to the given projectile velocity of 829 m/s. The target block was fixed at its back edges.

The penalty type of contact was applied to characterize the model parts interaction, projectile-target and target-target. The penalty function was applied to assess the normal contact force. The contact force value is proportional to the depth of penetration. The segment – based penalty formulation contact algorithm checks for segment versus segment penetration rather than node versus segment one.

3. ANALYSIS OF THE RESULTS

The numerical models were developed by exploitation of the data found in [4]. The authors of that paper carried out the experimental test with the 12.7x108 mm B32 projectile impacting the 7017 aluminium alloy block. They studied the depth of penetration in the 7017 aluminium block. A numerical experiment is focused on the depth of penetration and kinetic energy of the projectile. The case names from Table 3 will be used later in charts.

Table 3. The case names, which describe the mesh density and type of numerical model

Method\Mesh density	**Fine**	**Reference**	**Coarse**
EFG	EFG_F	EFG_R	EFG_C
SPH	SPH_F	SPH_R	SPH_C
FEM	FEM_F	FEM_R	FEM_C

In Figure 3 the influence of the type of a numerical method on the results is shown on cross-section views. In order to simplify the comparison of all methods, the nodes are only presented, even in case of finite element method. Hereabouts the projectile, there is an interior mesh (high density) and a farther external mesh (grayscale area) is visible. Figure 3 (a) presents the initial stage, which is the same for all analysed methods. The result, which is the closest to the experimental observation is obtained in cases (b) and (c) for EFG and FEM method, respectively. However, in case of FEM method, there is a large erosion of the projectile comparing to other methods. The SPH method leads to significant reduction of the crater depth, much differing from the experimental result.

The Depth of Penetration (DOP) in the aluminium plate was analysed and compared with appropriate experimental results – Figure 4. In the chart, a horizontal axis describes the type of method (EFG, FEM, SPH) and an axis of ordinates describes the depth of penetration in millimetres. The dashed line indicates the experimental result. The EFG method is not much sensitive to mesh density. The main part of numerical results are close to the experimental ones expect the SPH method (Fig. 4), where the relevant sensitivity to mesh density was observed.

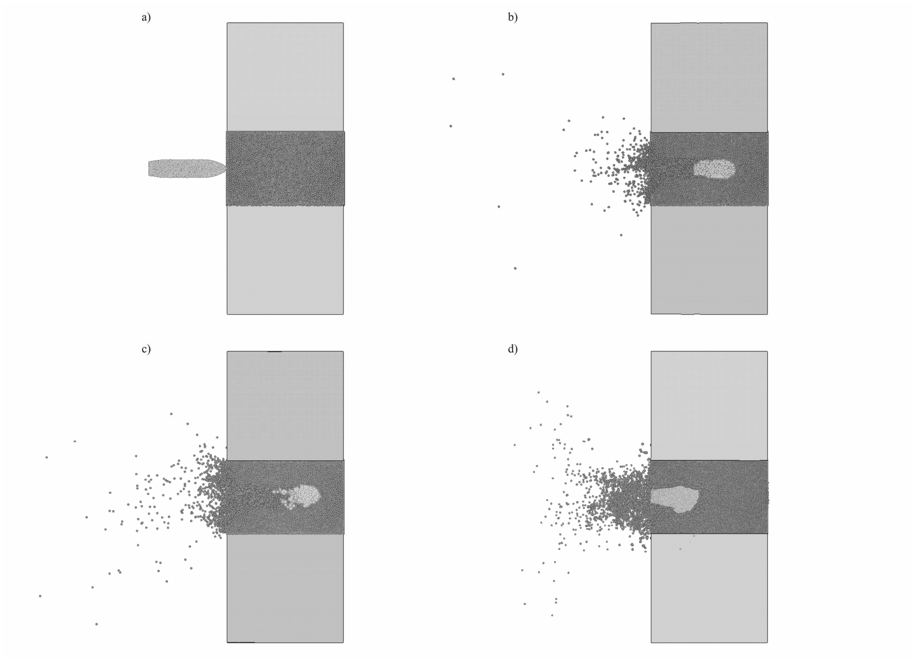

Fig. 3. Initial (a) and final stages of the penetration process obtained by (b) EFG, (c) FEM, (d) SPH methods

The residual length of the projectile was analysed and compared with each other for the different methods applied – Figure 5. In the chart, a horizontal axis describes the type of method and a vertical axis describes the residual length of the projectile in millimetres. The shortest residual length of the projectile is identified for FEM method irrespective of a kind of the mesh, and the longest one is for SPH method. The finite element method requires including erosion because of geometrical deformation of elements. SPH method allows extreme deformation, larger than EFG method.

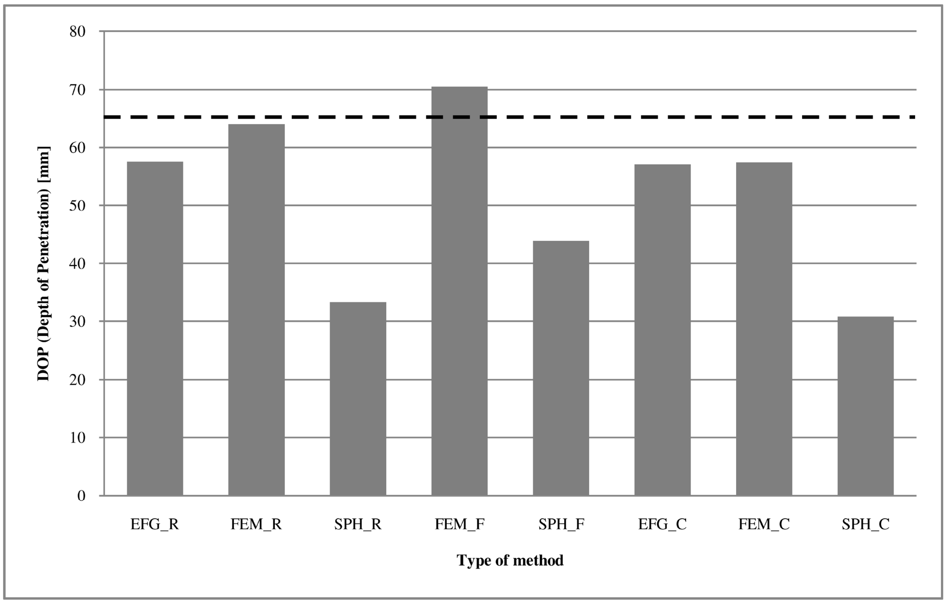

Fig. 4. Comparison of numerical and experimental results of penetration's depth

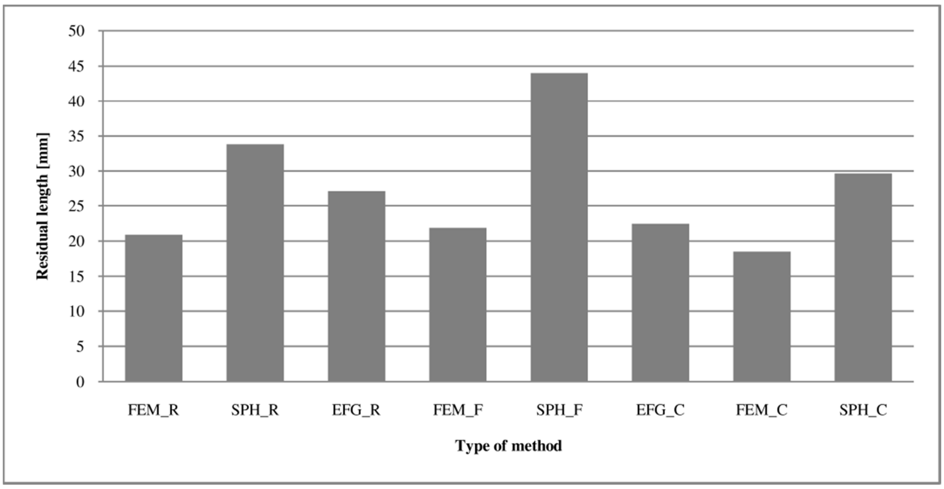

Fig. 5. Comparison of numerical results of residual length of projectile

The kinetic energy of the integral part of the projectile for all analysed cases was depicted in Figure 6. Kinetic energy is the most important element for the assessment of the ballistic panel effectiveness.

Effectiveness of projectile resisting is the highest in case of SPH method, but it may be a symptom of non-physical behaviour as it is compared to DOP value. EFG and FEM methods cause similar character of changes in kinetic energy of the projectile.

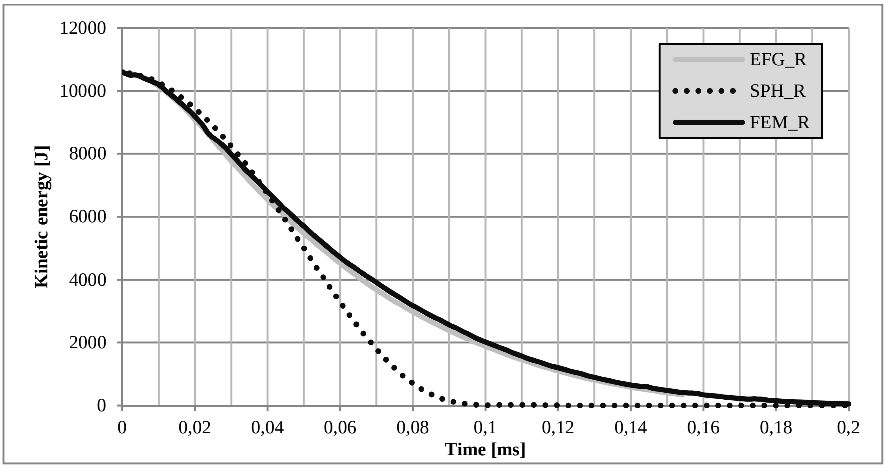

Fig. 6. Time histories of kinetic energy of the projectile's integral part

4. CONCLUSION

The studies conducted in this paper identified very interesting and promising dependencies with regard to a role of the numerical method (EFG, SPH, FEM) in the simulation of the penetration problems. The meshless algorithms are very time consuming, so a special treatment is needed to solve the problems with hundreds of thousands of nodes. It is called an adaptive technique. It allows significant reduction of calculation time.

It turned out that the SPH method is very sensitive to grid density. Generally, EFG method applied to solve the perforation/penetration problems can be characterized as a very stable, reliable and effective method. It delivers accurate results even with medium mesh size and extremely large deformations. EFG method can be considered as an alternative to other meshless methods like SPH [1], Free Particles Method [2], Finite Volume Particle Method [3] or classical FEM. It is a good compromise between accuracy and effectiveness of FEM and permitting extreme deformations meshless methods.

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