Journal of KONES Powertrain and Transport, Vol. 17, No. 1 2010

ON THE MODELLING OF PENETRATION/PERFORATION PROBLEMS

Andrzej Morka

Military University of Technology
Gen. S. Kaliskiego Street 2, 00-908 Warsaw
tel.: +48 22 6837610, fax: +48 22 683 9355
e-mail: amorka@wat.edu.pl

Abstract

The aim of this paper was to present the main aspects of the numerical modelling within the scope of penetration/perforation problems. The most important stages of the computer model development were discussed in detail. They include the study of the hypervelocity impact physics, selection of the numerical solution method, problem discretization in time (time step) and space (mesh/grid), constitutive models consideration, Initial Boundary Conditions (IBC) and finally choice of the results form for analysis and discussion.

The Computer simulations were performed with the Element Free Galerkin Method (EFG) implemented in LS-DYNA code. An impact of the 12.7x108 mm B32 armour piercing projectile on the selected targets was analyzed. Full 3D models of the projectile and targets were developed with strain rate and temperature dependent material constitutive relations. The models of the projectile, ceramic and aluminium alloy targets were validated with utilization of the experimental in field tests and data found in literature.

The obtained results confirm that EFG method can be considered for numerical solving of the penetration/perforation problems. The errors in Depth of Penetration have not exceeded 20% as compared numerical and experimental results.

The conclusions presented in this paper can be applied to develop modern impact protection panels where the appropriate balance between the mass and protection level must be accomplished.

Keywords: *computational mechanics, impact problem, armour perforation, penetration, ballistic resistance*

1. Introduction

A description is given in this paper of the computer simulation of the penetration/perforation problems. Modern armours, especially for lightweight vehicles, are consisted of many layers made of different materials like ceramic, steel, aluminium alloys etc. There are so many options that the proper armour structure selection can be realized by applying computer modelling and simulation.

The definitions of perforation and penetration are related to the impact problems when the structural integrity of the body called a target is broken. The problem can be considered as the perforation if the target thickness is comparable or smaller than the impactor length, otherwise it is the penetration. The impact physics differs for the penetration and perforation problems. The last one involves the wave effects like reflection at free surface and rarefaction wave propagation across the target. It may lead to failing called spall effect. The spalling is often observed for the hypervelocity impacts.

The quantitative assessment of the models was based on the calculated value of the kinetic energy versus time – $E_k(t)$ of the integral part of the projectile. The numerical simulations were performed with the Element Free Galerkin Method (EFG) implemented in LS-DYNA code [2, 7]. Three dimensional numerical models for each analysed case were developed. The only considered were the perpendicular impacts because of the most dangerous expected results. An explicit time integration algorithm was used as a method for the problem equations solution.

Currently the most expected ballistic resistance is related to the 12.7x108 mm B32 projectile. Therefore this paper focuses on this kind of threat. That type of projectile consists of the soft metal jacket, incendiary material and the hard steel core. The last one part is the crucial element in penetration effectiveness. It carries overwhelming part of the projectile kinetic energy, more than 12 kJ with the impact velocity equals about 850 m/s. The geometric characteristic of the hard steel core is presented in Fig. 1.

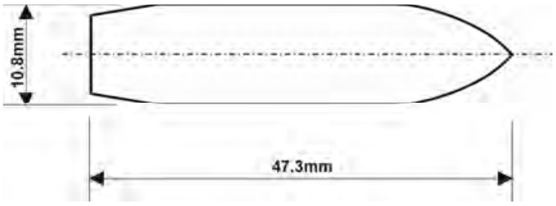

Fig. 1. A scheme of the 12.7x108mm B32 projectile's hard steel core

2. Problem description

Modelling of the penetration/perforation problems should take into account number of physical phenomena and factors. The most important of them are: high strain rate (10^5 1/s), temperature softening, extremely large deformation, material failure, short time scale of the problem (tens of microseconds), strong shock wave propagation, different properties of applied materials (ductile and brittle). The valid materials behaviour is realized by application of the proper constitutive models with correct model constants and/or relations. The occurrence of the wave effects enforces very dense model space discretization (a huge number of nodes and elements). The extremely large deformations turn the attention to the meshless numerical methods. A special caution must be keep to describe the material failure and eroding. The strain and stress (spall effect) based failing criteria should be considered. Otherwise, the improper final results may be expected e.g. overestimated or underestimated depth of penetration or residual projectile velocity. The short time scale of the problem causes that the adiabatic process assumption is almost always sufficient to describe the penetration/perforation problems.

3. Description of the numerical model

The excessive deformations often met in the perforation/penetration issues caused the choice a meshless method as the method for the problem solution. The Element Free Galerkin (EFG) method implemented in the LS-DYNA solver was selected. EFG only uses a set of nodal points describing geometry of the body, no mesh in the classic sense is needed to define the problem [1, 7]. Nodes can be generated regularly or they can be locally concentrated. The connectivity between the nodes and the approximation functions are entirely constructed by the method [5]. It uses Moving Least Squares Approximation (MLSA) technique for the construction of the shape functions. 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 spatial discretization of the problem is presented in Fig. 2 from a to c. The uniform node distributions were achieved by application of the popular meshing software. All of them were built with application of the four node tetrahedron solid element topology except the external mesh for the aluminium alloy block (Fig. 2. c) where the brick topology was employed. The typical node to node distance was equal about 1mm in all cases of targets and projectiles. The total number of nodes per single case exceeded 600k including 3.5 k of the nodes belonging to the steel core.

The proper dynamic behaviour of metal alloys (hard steel, 7017 aluminium alloy) was realized by application of the Johnson-Cook (JC) constitutive model [6, 9] with the Gruneisen form of the Equation of State (EOS). The values of appropriate parameters are included in Tab. 1. The ceramic material was described by Johnson-Holmquist ceramic model (JH-2) [7, 5]. The material constants for high purity Al_2O_3 are presented in Tab. 2.

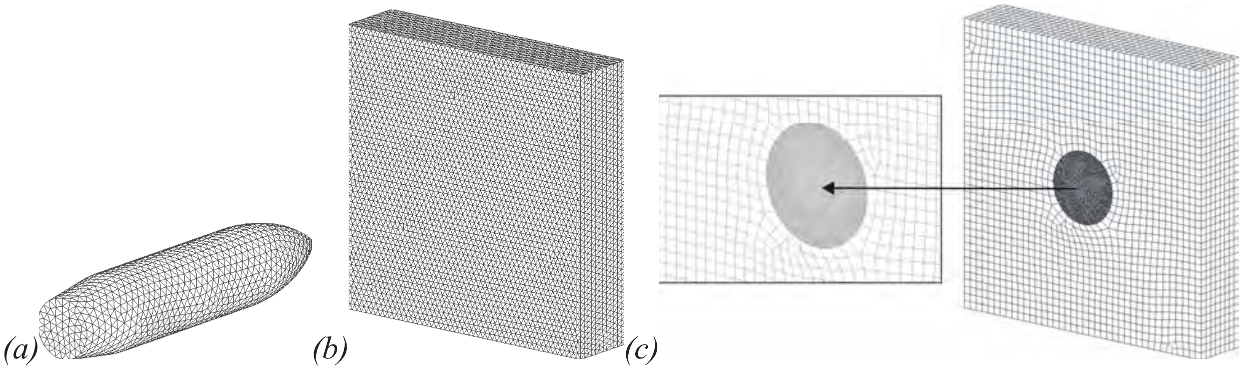

Fig. 2. A problem discretization: (a)-the projectile, (b)-the ceramic tile, (c)- the 7017 aluminium alloy block

Tab. 1. Johnson-Cook model and Gruneisen EOS constants [7]

parameter	units	*hard steel*	*7017 Al alloy*
JC			
ρ	kg/m³	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
EOS			
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

Tab. 2. Johnson-Holmquist model constants [7]

parameter	units	*high purity Al_2O_3*
JH-2		
ρ	kg/m³	3840
A		0.88
B		0.45
C		0.007
m		0.6
n		0.64
T	GPa	0.462
HEL	GPa	7.81
D_1		0.0125
D_2		0.7
EOS		
k_1	GPa	210
k_2	GPa	0.0
k_3	GPa	0.0

The initial condition was reduced to the given projectile's velocity. The boundary condition was assumed as the full fixing on the lateral edges of the backing plate. The penalty type of contact was applied to characterize the model parts interaction, projectile/target and target/target. The eroding criteria thresholds, needed to reduce the calculation time, were defined at the validation stage. They are selected this way to minimize the result perturbations and keeping the acceptable agreement with the experimental data.

4. Validation of the numerical model

The developed numerical models were validated by exploitation of the data found in [8]. The authors of this paper carried out numerous of the experimental tests with the 12.7x108 mm B32 projectile impacting the 7017 aluminium alloy block and ceramic/aluminium alloy sets. They studied the depth of penetration in the 7017 alloy block for the different impact velocities and ceramic tile thickness. The results were presented in the form of tables.

A couple of the numerical models were prepared. They included: steel core of the 12.7x108 mm projectile, 20x20x40 cm and 20x20x80 cm block of 7071 aluminium alloy, ceramic tile 50x50x(12)10 mm. The models of component layout are showed in the Fig. 5a, 5b. The remaining assumptions of the model were left unchanged regarding the chapter 3. It was decided to apply a two mesh density regions in the target plates: very dense mesh close to the impact point, and coarse mesh elsewhere.

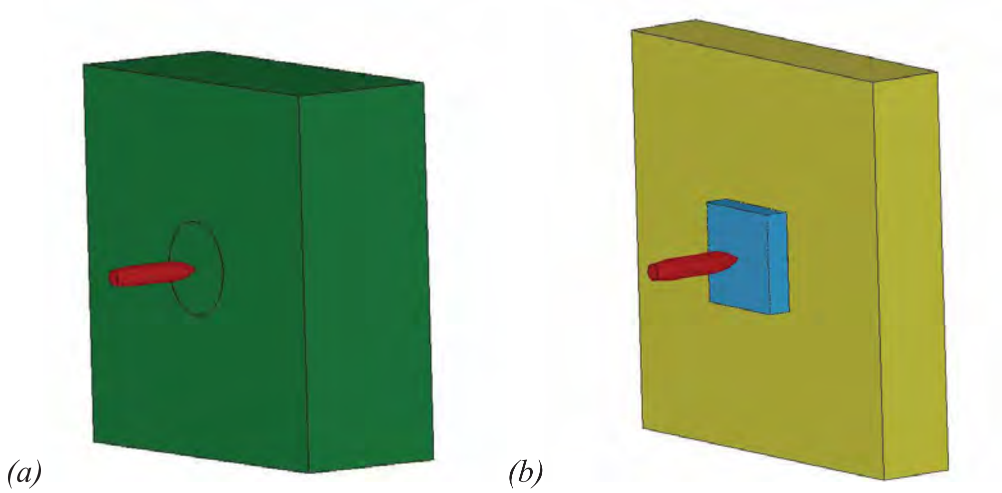

Fig. 3. Numerical models configuration for the validation stage. (a) penetration study of the 7017 aluminium alloy block, (b) penetration study of the ceramic/aluminium alloy set

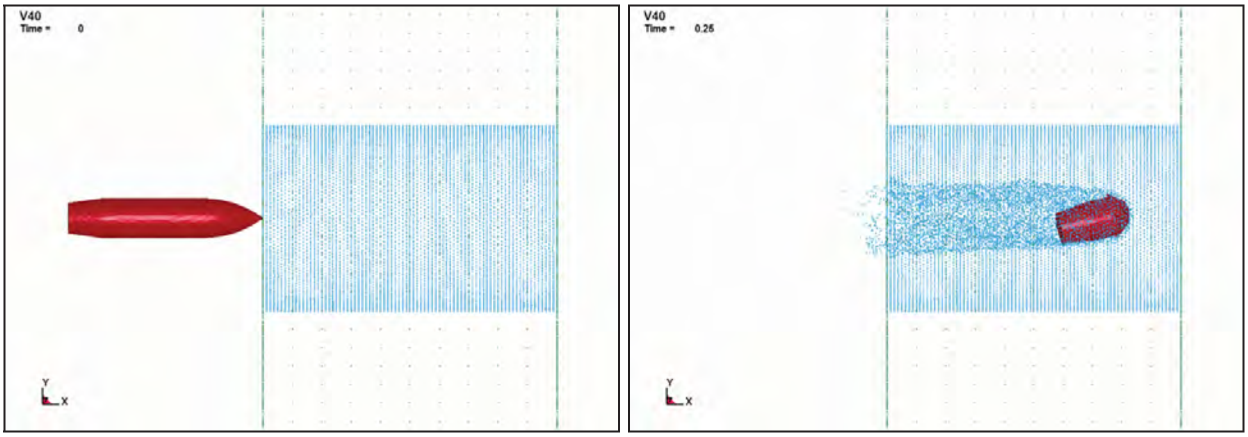

Fig. 4. Penetration of the 7017 aluminium alloy block by 12.7x108 B32 hard core. Impact velocity 829 m/s

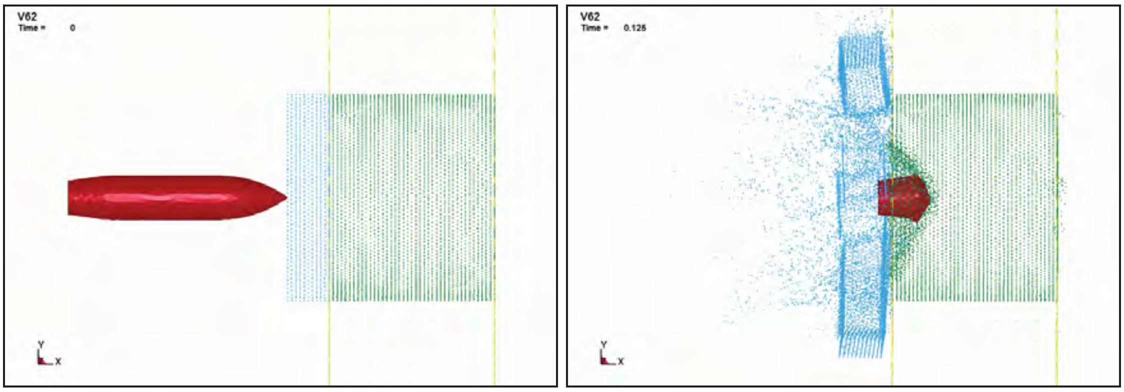

Fig. 5. Penetration of the ceramic tile/aluminium alloy plate set by 12.7x108 B32 hard core. Impact velocity 840 m/s, ceramic tile thickness 10mm

Tab. 3. Model validation and verification: (a) Depth of Penetration in the 7017 aluminium alloy block, (b) Depth of penetration in the ceramic tile/7017 alloy plate set, impact velocity 840 m/s

(a)

	Experiment [mm]	Simulation [mm]	Error [%]
validation case - impact velocity 829 m/s	67	66	2
verification case - impact velocity 511 m/s	33	40	21

(b)

	Experiment [mm]	Simulation [mm]	Error [%]
validation case – ceramic tile thickness 12 mm	5.8	5	14
verification case - ceramic tile thickness 10 mm	11.8	10	15

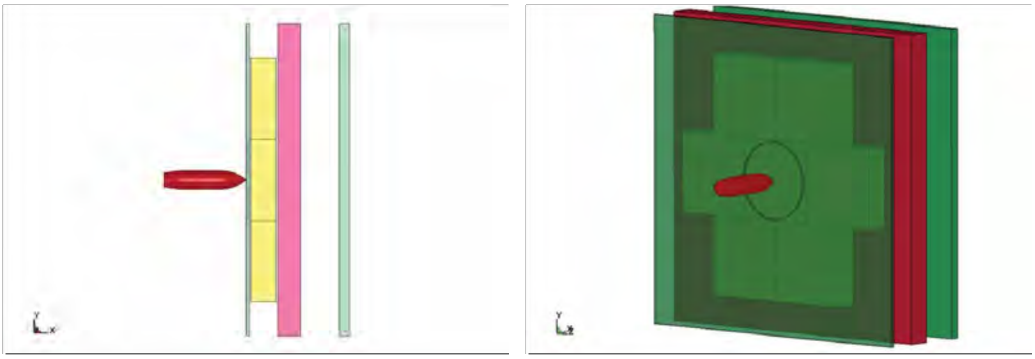

Fig. 6. The overview of the complete multilayer ballistic panel, side and 3D view together with the protected plate

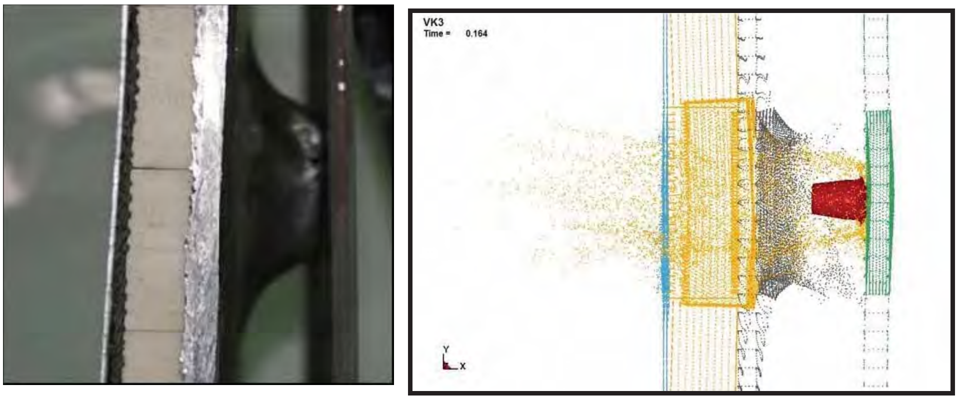

Fig. 7. Perforation of the selected structure of the panel, experiment (left), simulation (right)

The initial and final stages of the penetration problems were depicted in the Fig. 4 and 5 for the 7017 alloy block alone and ceramic/aluminium alloy set suitably. These pictures present the side view with the impact point area enlarged. The dense and coarse meshes can be recognized. They are suitably connected together by applying specialized tied contact method available in the LS-DYNA solver. It is interesting the appearance of the distortions in the axial-symmetric movement of the projectile, Fig. 4, which is often observed in the experimental tests. The ceramic material fracture and fragmentation very similar to the real behaviour is showed in the Fig. 5. The quantitative analysis is based on the comparison of the Depth of Penetration (DoP) in aluminium alloy between numerical results and ballistic tests, Tab. 3 (a) and (b). The validation cases were used to model behaviour improvement especially by defining the proper failing and eroding thresholds for ceramic and metals materials. The verification cases should confirm the valid model behaviour. The obtained results, Tab. 3, showed that the maximal error in DoP reached 20% for both validation and verification cases, which are acceptable for that kind level of numerical analysis. It should be noticed that the DoP in the cases with ceramic tiles included, Tab. 3 (b), was measured only in aluminium alloy plate.

Finally, the validation was performed with a complete ballistic panel structure, Fig. 6. It consists of the front layer, seven ceramic tiles and backing plate. The protected steel plate is also included in the model. The front and backing plates are made of PA11 aluminium alloy. An impact of the by 12.7x108 mm B32 projectile were analysed experimentally and compared to the numerical results, Fig. 7. It is observed a good agreement of the final stage of the perforation that is a small deformation of the protected plate by residual part of the projectile core. A similar deformation of the backing plate in experimental test and simulation should be also noticed.

4. Analysis of the results

The computer simulations were performed for the selected cases. High performance computing system based on the cluster architecture was used. It let to assign 4 to 8 CPUs per single job limiting the total computing time to reasonable level. During the calculations the time history of the projectile kinetic energy was stored with given time interval, Fig. 8. Only the integral part of the projectile was considered. The specific value of this parameter was identified at the moment when the projectile completely perforates the backing plate. This value can be used as a measure of the panel effectiveness e.g. in the studied case it is equal 2 kJ.

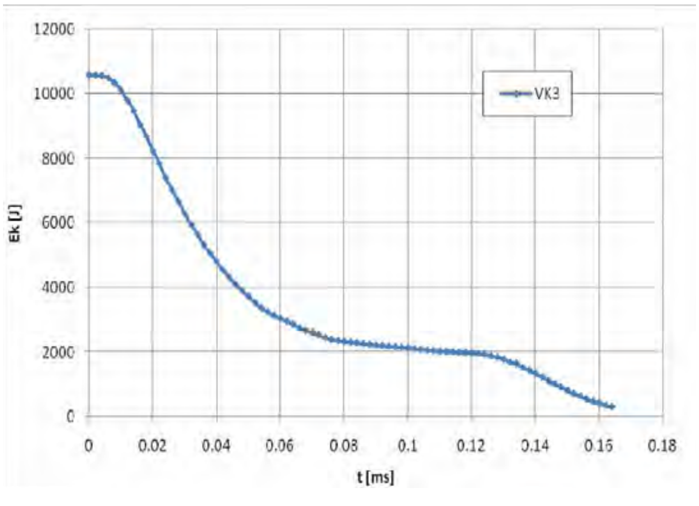

Fig. 8. Typical time history of the projectile kinetic energy

The curve presented in Fig. 8 describes several phases of the perforation problem: initial phase when the projectile nose is destroyed, the main most effective phase of the projectile retardation by ceramic material. Third phase initiates while the backing plate starts to plastic deformation and the effectiveness of the projectile retardation falls down. This phase may be continued till the complete panel perforation and than residual part of the projectile travels without any resistance-fourth phase. The kinetic energy of the residual part of the projectile during this phase may be used to assess the effectiveness of the panels with different internal structure. Finally the projectile reaches the protected plate (Fig. 8), and is retarded till complete stop.

5. Conclusions

The obtained results confirm that EFG method can be considered for numerical solving of the penetration/perforation problems. The errors in Depth of Penetration have not exceeded 20% as compared numerical and experimental results.

The offered method of the assessment of the ballistic panel effectiveness seems to be reliable and efficient even for more general cases within the scope of the ballistic protection.

The all performed calculations should provide reliable data because they are based on the good validated and verified numerical models.

The conclusions presented in this paper can be applied to develop modern impact protection panels where the appropriate balance between the mass and protection level must be accomplished.

Bibliography

[1] Belytschko, T., Lu, Y. Y., Gu., L., *Element free Galerkin methods* , International Journal for Numerical Methods in Engineering, pp. 229-256, 1994.

[2] Hallquist, J. O., *LS-DYNA Theory Manual* , Livermore Software Technology Corporation (LSTC), March 2006.

[3] Holmquist, T. J., Templeton, D. W., Bishnoi, K. D., *Constitutive modeling of a luminium nitride for large strain, high-strain rate, and high –pressure applications* , International Journal of Impact Engineering, Vol. 25, pp. 211-231, Minneapolis 2001.

[4] Jaśkowiec, J., *Integracja metody elementów skończonych z bezelementową metodą Galerkina*, Proceedings of the XIII Scientific conference on numerical methods, Korbielów 2001

[5] Kambur, C., *Assessment of Mesh-free Methods in LS-DYNA: Modeling of Barriers in Crash Simulation*, Master of Science Thesis, Institute for Structural Mechanics, Stuttgart 2004.

[6] Lee, M., Yoo, Y. H., *Analysis of ceramic/metal armour systems* , International Journal of Impact Engineering, Vol. 25, pp. 819-829, Seoul 2001.

[7] *LS-DYNA Keyword User's Manual* , Version 971, Livermore Software Technology Corporation (LSTC), May 2007.

[8] Madhua, V., Ramanjaneyulua, K., Bhata, T. B., Gupta, N. K., *An experimental study of penetration resistance of ceramic armour subjected to projectile impact*, International Journal of Impact Engineering 32, pp. 337-350, 2005.

[9] Park, M., Yoo, J., Chung, D. T., *An optimization of a multi-layered plate under ballistic impact,* International Journal of Solids and Structures, Vol. 42, pp. 123-137, Seoul 2004.

[10] Wiśniewski, A., *Pancerze budowa, projektowanie i badanie,* Wydawnictwo Naukowo-Techniczne, Warszawa 2001.

Acknowledgements

The paper supported by a grant No. O R00 0011 04, financed in the years 2007-2010 by Ministry of Science and Higher Education, Poland.