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METHODS, MODELS, AND METHODOLOGIES FOR NUMERICAL MODELING OF PROJECTILE IMPACT ON A PLATE

Mihaela-Cristiana BADEA*, Anton HADĂR*, Vasile NĂSTĂSESCU, Ghiță BÂRSAN***, Alina ADETU****, Cătălin ADETU******

***University POLITEHNICA of Bucharest, Romania**
****"Ferdinand I" Military Technical Academy, Bucharest, Romania**
*****"Nicolae Bălcescu" Land Forces Academy, Sibiu, Romania**
******Romanian Air Force, Bucharest, Romania**
radu.cristianamihaela@yahoo.com

Abstract: *This article presents the most modern and efficient methods for numerical computation of structures. Analyzing the impact phenomenon requires a special approach with high-performance software products capable of modeling complex phenomena, such as the impact of kinetic projectiles on armor plates. The numerical methods for structural analysis considered and presented in this report include the finite element method, the Galerkin's free element method (ELG), and the free particle method (MPL) - also known as the Smoothed Particle Hydrodynamics (SPH) method. In addition to using these methods, consideration was given to using the most efficient software product, selecting the ANSYS/LS-DYNA program for this purpose.*

Keywords: Finite Element Method (FEM), Galerkin's Free Element Method (ELG), and Smoothed Particle Hydrodynamics (SPH) method

1. Introduction

The objectives of this article consist of understanding, handling, and interpreting the results of numerical simulations through the three methods.

The analysis of the impact phenomenon requires a special approach with high-performance software products that model complex phenomena, such as the impact of armor plates with kinetic projectiles. The numerical methods for analyzing the considered structure, presented in this article, are the finite element method, the Galerkin free element method (ELG), and the free particle method (MPL) - also known as the Smoothed Particle Hydrodynamics (SPH) method. The finite element method focuses on a particularly important approach in the field of engineering and structural analysis, representing a numerical technique used to approximate solutions to partial differential equations that describe the behavior of physical systems, such as mechanical or thermal structures. This method provides an efficient way to model and analyze the behavior of complex systems by dividing them into smaller portions called "elements". Each element is described by a set of algebraic equations, and the assembly of these elements allows the simulation of the system's behavior as a whole. By discretizing the domain into elements, FEM provides a numerical approximation of solutions to complex problems, such as stress distribution, deformation, or temperature distribution within a structure [1, 2]. The Smoothed Particle

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Hydrodynamics (SPH) method represents a relatively new approach to the approximate integration of partial differential equations. Being a meshless method, in a Lagrangian approach, it relies on pseudo-particles attached to nodes to define an interpolation method used in calculating smoothed field variables. The SPH method stands out in solving problems characterized by large distortions of the domain, distributions of continuous media and their history, the occurrence of discontinuities, diffusion and solidification phenomena, as well as temperature influence [3]. The Element-Free Galerkin (EFG) method is an advanced technique in the field of numerical methods, used for solving partial differential equations in engineering and applied sciences. The main characteristic of EFG lies in the use of a set of flexible and local shape functions that extend beyond the discretized domain of the problem. These shape functions are determined through the method of moving least squares [4, 5].

EFG allows solving problems with complex geometries and adapting to various boundary conditions. Within this method, the problem domain is described by control nodes that are not confined to a predetermined grid, unlike traditional methods. This gives EFG significant flexibility in addressing dynamic problems, such as fractures or deformations [6, 7]. In addition to using these methods, consideration was given to using the most efficient software product, opting for the ANSYS/LS-DYNA program. This program, besides providing facilities related to implementing the respective methods, also has an extensive material library dedicated to various types of materials and their respective demands. ANSYS, with its comprehensive approach, specializes in simulating the structural, thermal, fluidic, and electromagnetic behavior of systems. It is a versatile and user-friendly tool, providing an extensive range of functionalities to model and analyze various engineering scenarios. With its ability to simulate complex effects in structures and systems, ANSYS is essential in detailed and predictive analysis of material and structural behavior.

On the other hand, LS-DYNA specializes in simulating dynamic events and material behavior under extreme conditions. With a particular focus on dynamic analysis and complicated interactions between structures, this program is essential in fields such as dynamic testing for the automotive industry, impact simulations, or explosions. LS-DYNA stands out for its detailed approach to numerical analyses and precision in dynamic simulations, offering solutions for complex applications that require a deeper understanding of material behavior under large loads. Together, ANSYS and LS-DYNA meet the diverse needs of engineers and researchers, covering both static and dynamic simulations.

The ANSYS/LS-DYNA software product is perhaps the most powerful software product for analyzing continuous media, structures, fluid media, etc., both in static and dynamic regimes. The richness of the finite element library, as well as the richness of the material model library, allows for a numerical modeling close to reality of extremely complex phenomena, such as projectile-plate impact [8, 9].

2. Models for Numerical Analysis of Projectile-Plate Impact

The accuracy of the numerical analysis results obtained with any of the methods mentioned earlier critically depends on the accuracy of the geometric and numerical calculation model, according to the methods used: the finite element method, the free particle method or SPH (Smoothed Particle Hydrodynamics), and the Galerkin's free element method (ELG) [10]. The following presents a case of impact of a virtual projectile caliber 20 mm, with a fictitious geometry, but close to the geometry of the real projectile. The impacted plate is a 10 mm thick aluminum plate, with the elastic characteristics from Table 1 [11].

Table 1 Physical and elastic properties of the target material

Elastic Property	Density	Longitudinal Elastic	Transverse Elastic Modulus	Poisson's Ratio
Plate Material	2710	69e9	25,94e9	0.33
Projectile Material	7830	2.1e11	0.81e11	0.30

For the purpose of reducing computer processing time and considering the analysis goal - the target effects of the projectile - it has been modeled as a rigid material. The projectile is made of steel, with properties presented in Table 1 [12].

2.1. Modeling and Simulating Normal Impact

The mechanical structure, analyzed numerically with any of the methods mentioned earlier, can be modeled either entirely or partially depending on the existence of symmetry planes. In the case of normal impact, one can work with the entire model, with half of the model, or with a quarter of it because the projectile-plate structure in normal impact exhibits two planes of symmetry.

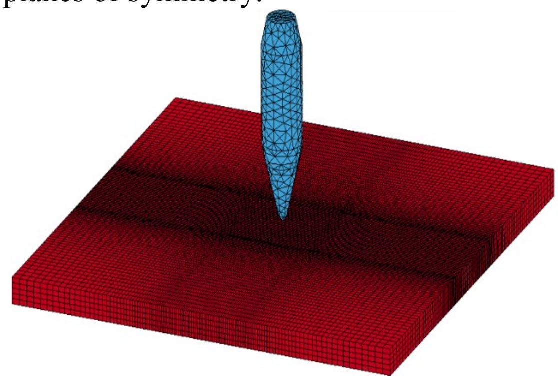

Figure 1: The finite element model for the entire structure

These models, including both the geometric model and the one with finite elements are presented in Figures 1-3.

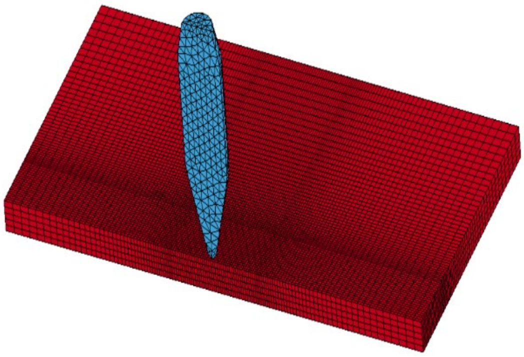

Figure 2: The finite element model for half of the structure.

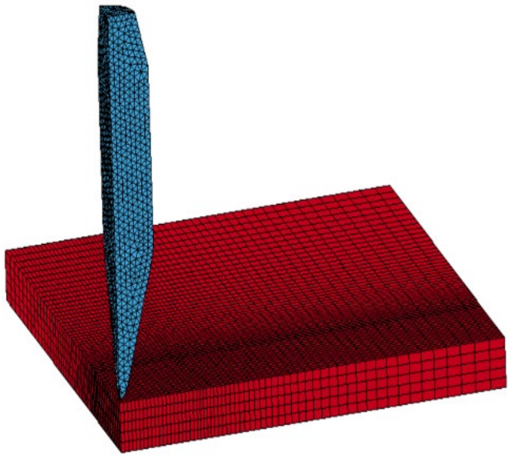

Figure 3: The finite element model for the quarter of the structure

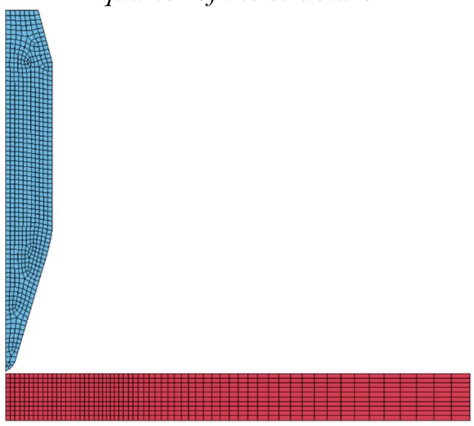

Figure 4: The finite element model with symmetric axial plane elements

The simplest calculation model for normal impact is represented by the symmetric axial plane model, depicted in Figure 4.

2.2 Finite Element Analysis of Normal Impact

In the geometric models in Figures 1-3, solid brick finite elements with eight nodes and three degrees of freedom per node from

the ANSYS/LS-DYNA program library were used for modeling the plate. The projectile, in the case of the models shown in Figures 1...3, was modeled with solid tetrahedral elements, with ten nodes and three degrees of freedom per node.
The finite element model with symmetric axial plane elements is presented in Figure 4. In the conducted research, the finite element models presented above were created in three ranges of minimum finite element sizes: 0.50 mm, 1.00 mm, and 2.00 mm.
The characteristics of the finite element models for normal impact, modeled with axial-symmetric finite elements, are presented in Table 2 [13].

Table 2 Characteristics of 2D finite element models for normal impact

Model No.	**F.E. size [mm]**	**Nodes & Elements**	**Projectile**	**Plate**	**Model Type**
1	0,50	ND	2831	2541	Plan (2D) axial-simetric
		EL	2666	2400	
2	1,00	ND	788	671	
		EL	705	600	
3	2,00	ND	216	186	
		EL	173	150	

The characteristics of 3D finite element models for normal impact are presented in Table 3.

Table 3 Characteristics of normal impact models, 3D models

Model No.	**Min. finite element size [mm]**	**Nodes & Elements**	**Projectile**	**Plate**	**Model Type**
4	0,50	ND	17667	348486	Whole
		EL	12123	288000	
5	1,00	ND	3529	87846	
		EL	5391	72000	
6	2,00	ND	7984	22326	
		EL	5152	18000	
7	1,00	ND	4299	44286	A half
		EL	2576	36000	
8	2,00	ND	4299	11346	
		EL	2576	9000	
9	1,00	ND	4299	44286	A quarter
		EL	2576	36000	
10	2,00	ND	2289	6081	
		EL	1273	4500	

2.3. Galerkin Free Element Calculation of Normal Impact

The penetration process of the plate resulting from the projectile impact is a complex phenomenon that, from a numerical analysis perspective, leads to significant distortion of finite elements, sometimes causing the solution process to halt. This inconvenience has been largely reduced and even eliminated by the emergence of meshless/mesh-free numerical methods [10]. For the use of the Element Free Galerkin Method (EFGM), the calculus model is similar to the finite element model - Figures 5…8.

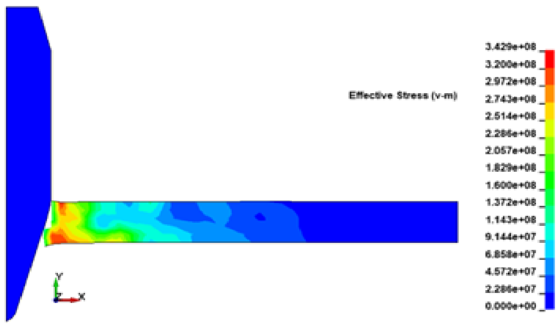

Figure 5: Equivalent von Mises Stress Field, ELG Method, Model 1

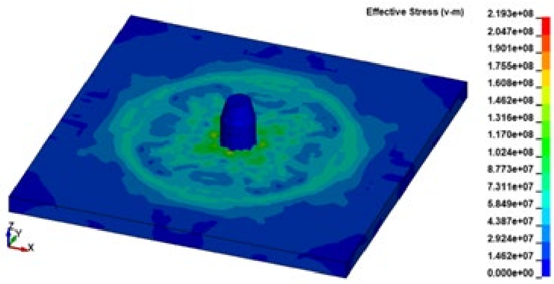

Figure 6: Equivalent von Mises Stress Field, ELG Method, Model 5

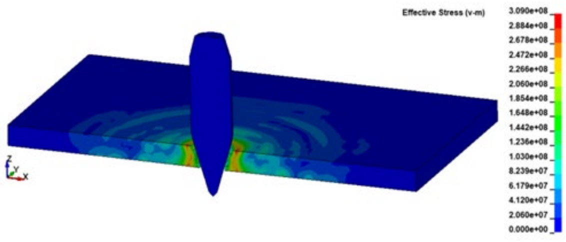

Figure 7: Equivalent von Mises Stress Field, ELG Method, Model 7

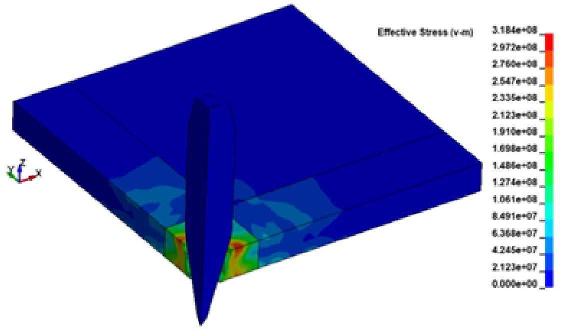

Figure 8: Equivalent von Mises Stress Field, ELG Method, Model 9

It is known that mesh-free/meshless methods, using a weighting function that depends on certain parameters that can strongly influence the results, by appropriately choosing their values (there are no precise rules), can lead to higher accuracy of results compared to the finite element method.

2.4. Smoothed Particle Hydrodynamics (SPH) Calculation of Normal Impact

The Smoothed Particle Hydrodynamics (SPH) method, also known as the Smoothed Particles Hydrodynamics Method, is a meshless method that can be used in the numerical analysis of mechanical structures. Impact problems are suitable for this method, but the best results are obtained when modeling certain categories of materials, such as ceramics or generally highly brittle materials [3].

The accuracy of the results is determined, as with the Galerkin Free Element method, by the choice of certain parameters for which there are no precise rules or strict criteria. For modeling normal impact (as presented so far), a 3D model can be used, as shown in Figure 9. The method allows for mixed modeling, meaning part of the structure is modeled with finite elements and another part with free particles, as shown in Figure 10. Total modeling with free particles (as in Figure 9) has the advantage that contact modeling is no longer necessary. As in all other models and numerical calculation methods, the projectile was modeled using the rigid material model. This leads to computer time savings and is suitable if the purpose of the analysis is not the projectile itself, but its effects on the target.

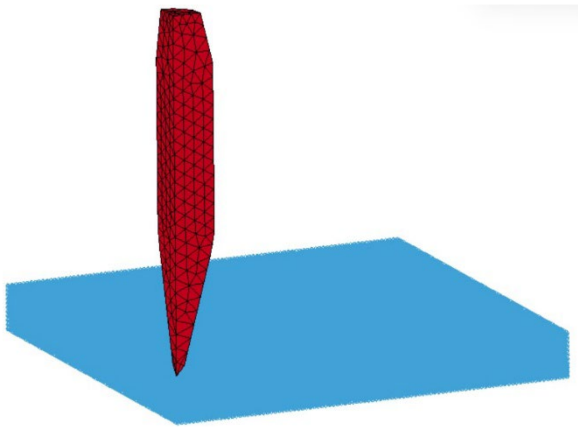

Figure 9: Finite Element and Free Particle (SPH) Model - View 1

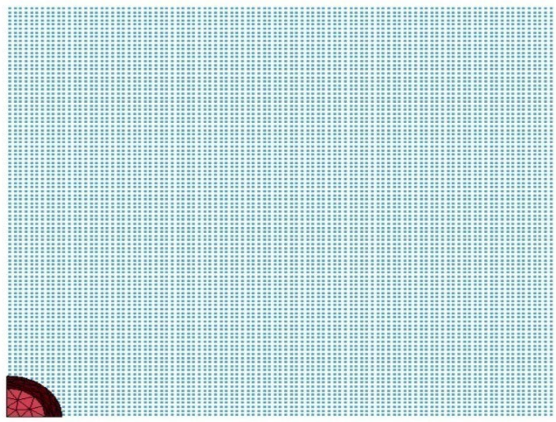

Figure 10: Finite Element and Free Particle (SPH) Model - View 2

The plate modeling was done with 112211 particles, and the internodal distance in all directions is 1 mm.

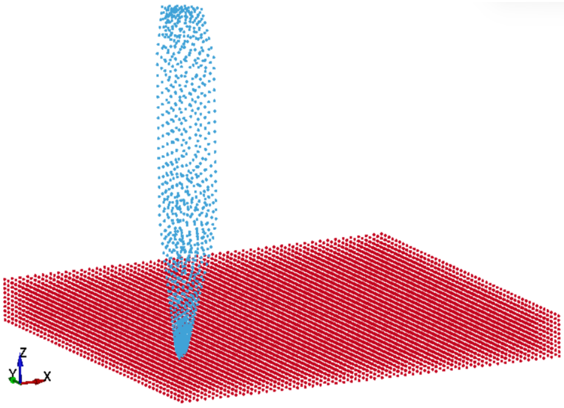

Figure 11: Free Particle (SPH) Model

For the model in Figure 11, the uniform internodal distance for the plate is 2 mm, while for the projectile, the distribution is non-uniform, resulting from discretization with finite elements with an average size of 2 mm. The use of the SPH method was carried out while adhering to certain recommendations - such as uniformity of particle distribution - and specific parameter values, for which there are no clear criteria (the type of weighting function, the size of the support domain).

3. Comparative Analysis of the Results

The assessment of projectile-target impact effects is succinctly presented by determining the projectile displacement during impact, the perforation/penetration velocity, and the evolution of the projectile's kinetic energy during perforation or penetration. These parameters essentially characterize the target's resistance characteristics to impact. The results of numerical simulation of the impact, under the described conditions, with the presented calculation models, are succinctly summarized in Tables 4 and 5.

Table 4 Simulation Results of Impact Using the Axial-Symmetric Plane Model

Model no.	**Measure units**	**Analyzed Parameters**	**Analyzed Parameter Values**	**Error [%]**
1	[m]	UY	-0,119	0,85
	[m/s]	VY	-789	0,25
	[Nm]	KE	6870	0,09
2	[m]	UY	-0,119	0,85
	[m/s]	VY	-789	0,25
	[Nm]	KE	6870	0,09
3	[m]	UY	-0,119	0,85
	[m/s]	VY	-791	0,51
	[Nm]	KE	6900	0,54

Table 5 Simulation Results of Impact Using 3D Models

Model no.	Measure units	**Analyzed Parameters**	**Analyzed Parameter Values**	***Error [%]***	**Model Type**
4	[m]	UY	-0,118	-	ENTIRE
	[m/s]	VY	-787	-	
	[Nm]	KE	43100	-	
5	[m]	UY	-0,118	***0,00***	
	[m/s]	VY	-787	***0,00***	
	[Nm]	KE	42900	***-0,46***	
6	[m]	UY	-0,118	***0,00***	
	[m/s]	VY	-787	***0,00***	
	[Nm]	KE	42900	***-0,46***	
7	[m]	UY	-0,118	***0,00***	HALF
	[m/s]	VY	-787	***0,00***	
	[Nm]	KE	21500	***-0,23***	
8	[m]	UY	-0,118	***0,00***	
	[m/s]	VY	-785	***-0,25***	
	[Nm]	KE	21400	***-0,70***	
9	[m]	UY	-0,119	***0,85***	QUARTER
	[m/s]	VY	-789	***0,25***	
	[Nm]	KE	10800	***0,23***	
10	[m]	UY	-0,118	***0,00***	
	[m/s]	VY	-786	***-0,13***	
	[Nm]	KE	10700	***-0,70***	

It is known that mesh-free/meshless methods, using a weighting function that depends on certain parameters that can strongly influence

the results, by appropriately choosing their values (there are no precise rules), can lead to higher accuracy of results compared to the finite element method.
For this reason, models with a coarser discretization, such as models 3, 6, 8, and 10, were chosen for comparing the results.
Table 7 presents a comparative overview of the calculation results using the ELG method and FEM.

Table 7 Comparative Results ELG-FEM Method

Model no.	**Unit of measurement**	**Analyzed Parameters**	**Analyzed Parameter Values**		**Error [%]**
			FEM	**EFGM**	
1	[m]	UY	-0,118	-0,119	0,85
	[m/s]	VY	-787	-793	0,76
	[Nm]	KE	43100	43520	0,97
5	[m]	UY	-0,118	-0,119	0,85
	[m/s]	VY	-787	-789	0,25
	[Nm]	KE	42900	43200	0,69
7	[m]	UY	-0,118	-0,119	0,85
	[m/s]	VY	-787	-790	0,38
	[Nm]	KE	42900	21600	0,70
9	[m]	UY	-0,118	-0,119	0,85
	[m/s]	VY	-787	-790	0,38
	[Nm]	KE	43000	10800	0,46

The analysis of the results in Table 7 shows a very good agreement between the two methods. The choice between using one or the other method will be determined based on other criteria, such as the description of fracture and, especially, the degree of distortion of finite elements.

Table 8 Comparative Numerical Results Regarding Normal Impact

Parameters	**Numerical calculation methods**				
	FEM	**EFG**	***Erorr [%]***	**SPH**	***Erorr [%]***
UY [m]	-0,118	-0,119	***0,85***	-0,119	***0,85***
VY [m/s]	-787	-793	***0,76***	-794	***0,89***
KE [Nm]	43100	43520	***0,97***	43600	***1,16***

The comparative analysis of the results (Table 8) shows that, for the study of normal impact, practically any of the three methods can be used. Analyzing the results of normal impact simulations using modern numerical methods and the LS-DYNA program yields the following:

- All calculation errors, compared to the reference model (Model 3), are less than 1%; this means that, practically, for ordinary engineering calculations, any model is valid;
- The most efficient model, in terms of calculation time, is the axial-symmetric plane model, which, even with a coarser discretization, leads to errors below 1%;
- When choosing the calculation model, the intended purpose, the capabilities, and the calculation accuracy of the finite elements used must be taken into account; for example, if the consideration of the vibration phenomenon arising from the impact is desired, the axial-symmetric plane model is not the most suitable, as it cannot describe all vibration modes.

4. Conclusions

Knowledge of both the theoretical foundations of numerical calculation methods and the projectile-armor impact phenomenon has enabled the development of calculation models based on a well-established methodology capable of yielding accurate results. The similar results obtained with different models, where the error is below 1%, typically below 0.5%, are evidence of the accurate modeling of the utilized models. In the models created, the projectile was designed using the rigid material model because the primary objective was to determine the effects on the target, not the projectile's damage. On the other hand, this modeling also led to a reduction in computer working time. Since the numerical simulations were not specific to any particular experiment, the errors and efficiency of the simulations were evaluated in relation to a model called the reference model. This was the complete model with the finest discretization, which, according to the general theory of FEM analysis, ensures the best accuracy.

Regarding modeling with the SPH method, it is notable that if both the projectile and the plate are modeled using free particles, contact no longer needs to be modeled through any procedure. In contrast, for example, in modeling with finite elements, contact was modeled through the procedure offered by the program in the variant called ESTS (eroding surface to surface).

In modeling with the Galerkin Free Element Method, the results were very good, even when using the largest grid sizes (finite elements), but choosing a higher-order weighting function and a large number of integration points on the support domain (coinciding with the finite element).

The results obtained with each of the three calculation methods constitute a guarantee for the use of any of the methods.

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