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Optimization of a Numerical Simulation Involving the Impact of an AP-T C44 12.7mm Projectile on a Semi-Infinite Monolithic 6061-T6 Aluminium Target

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Technical Memorandum

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Abstract

This memorandum details the creation of a numerical model to simulate the ballistic impact of an AP-T C44 12.7 mm round on a 152.4 mm diameter, 152.4 mm long cylindrical 6061-T6 aluminium target. Mesh sensitivity studies that examined the depth of penetration of the projectile for various mesh configurations were conducted. It was found that an optimum mesh density existed such that it would give results that were not significantly different from numerical simulations with higher density meshes. However, the numerical simulations with the optimum mesh density ran at greatly improved run times compared with the higher density meshes. On the contrary, if the mesh size became too coarse, the accuracy of the simulations suffered. A parameter study involving the erosion strain of the aluminium target was then conducted using the optimized mesh. Upon examining several values for erosion strain at various velocities, it was determined that a failure strain of 1.2 for the aluminium target yielded results that were the closest to the experimentally obtained values. The numerical model created as a result of this study will provide a foundation for ongoing numerical research into hybrid body armour systems for protection from high velocity large calibre small arms projectiles.

Résumé

Dans ce mémorandum, on décrit la création d'un modèle numérique pour simuler l'impact balistique d'une balle AP-T C44 de calibre 12,7 mm sur un cylindre d'aluminium de 152,4 mm de diamètre et de 152,4 mm de longueur. L'optimisation du modèle commence par une étude de l'effet du maillage sur la prédiction de la profondeur de pénétration de la balle dans la cible d'aluminium. Les résultats montrent qu'après une certaine densité optimale d'éléments finis, la précision des résultats des simulations numériques ne s'améliore pas, mais le temps de calcul augmente considérablement. Par contre, l'imprécision des résultats s'accroît si le nombre d'éléments dans la zone d'impact diminue en dessous de la densité optimale. La deuxième étape de la construction du modèle est l'étude de l'effet du paramètre d'érosion de la cible d'aluminium sur les résultats avec le maillage optimisé. L'étude montre qu'une valeur de 1,2 pour ce paramètre donne des résultats pour la profondeur de pénétration correspondant aux résultats expérimentaux. Le modèle optimisé durant l'étude décrit dans ce mémorandum servira de base pour un projet de recherche sur les systèmes de protection contre les projectiles de gros calibre à haute vitesse pour les armes légères.

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Executive summary

Given the vulnerability of peacekeeping personnel to large calibre small arms fire, new armour systems are being created. These armour systems consist of a composite/ceramic sandwich called hybrid armour that is capable of stopping heavy machine gun projectiles. Yet, at the same time, hybrid armour is light enough to be worn by a soldier for long periods of time.

However, hybrid armour systems consist of several constituent elements that must be optimized. Depth of Penetration (DOP) testing is an established means of evaluating ceramic materials. Live fire testing is the most realistic means of conducting these tests, but it is expensive. Hydrodynamic computer codes (hydrocodes) have been used to simulate high-speed impact events and requires only the use of a computer. However, great care must be taken in order to create numerical models that accurately reflect impact phenomena.

In this study a numerical model was created which accurately predicted the DOP of a 12.7 mm (0.50 Cal) AP-T C44 round into 152.4 mm diameter, 152.4 mm long 6061-T6 aluminium target. Simulations were performed on eight different density target meshes to determine which one exhibited the most advantageous combination of run time and accuracy. The optimized mesh was then selected for a parameter study of the erosion strain of the aluminium target in order to match the experimentally obtained DOP results.

The results of this study will be useful in providing a foundation for further numerical simulations which will be used to directly evaluate the ceramic component of hybrid armour.

Kaufmann, C. and Williams, K. 2004. Optimization of a Numerical Simulation Involving the Impact of an AP-T C44 12.7mm Projectile on a Semi-Infinite Monolithic 6061-T6 Aluminium Target. DRDC Valcartier TM 2002-015. DRDC Valcartier.

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La vulnérabilité du soldat, dans le rôle de maintien de la paix en particulier, face à la menace d'armes légères de calibre de plus en plus gros pousse la recherche dans le domaine de la protection du personnel. Les plaques de protection du torse sont composées d'une plaque laminée de composite et de céramique appelée blindage hybride. Les plaques hybrides sont capables d'arrêter des balles de mitrailleuse et en même temps offrent une plus faible surcharge de poids.

Un blindage hybride est constitué de plusieurs matériaux dont la composition doit être optimisée. Le test de profondeur de pénétration (*Depth of Penetration – DOP*) est une méthode établie pour évaluer la performance des matériaux céramiques. Normalement, les résultats sont obtenus au moyen d'une série d'essais qui nécessitent beaucoup de temps et d'équipements spécialisés, ce qui par conséquent coûte très cher. La modélisation numérique hydrodynamique est une option moins dispendieuse. Les codes hydrodynamiques sont conçus pour modéliser des événements balistiques à taux élevé de déformation. Par contre, la modélisation numérique doit être utilisée avec soin afin de s'assurer que le modèle reflète les mécanismes de fracture et de pénétration réels.

L'étude décrite dans ce mémorandum présente, un modèle numérique mis au point pour prédire la profondeur de pénétration (*Depth of Penetration – DOP*) d'une balle AP-T C44 de calibre 12,7 mm (0,50 cal). Des simulations ont été effectuées avec huit différentes densités du maillage de la cible pour optimiser le temps de calcul et la précision de la prédiction. Par la suite, on a utilisé le maillage optimal pour étudier l'effet du paramètre d'érosion du modèle de la cible. Des résultats expérimentaux ont été utilisés pour valider les simulations et par la suite choisir une valeur finale du paramètre d'érosion qui donne un *DOP* égal à ce qui a été mesuré.

Les résultats de cette étude serviront de base à d'autres simulations numériques qui auront comme but l'évaluation de plaques céramiques pour un système hybride de blindage personnel .

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1. Introduction

Advancements in armour materials have resulted in personal and vehicle armour systems that are lightweight and yet can still protect the user from most small-arms rounds. In response to improved armour protection, ammunition that is capable of penetrating personal armour has been developed.

Existing body armour could be increased in thickness to the point where an AP round would be defeated. However, the increase in the weight of the armour vest would severely impair the mobility of the wearer. In the past, conventional Kevlar fabric armour vests are occasionally supplemented with ceramic ballistic plates in order to provide enhanced levels of protection. A proposed type of armour for defeating AP rounds consists of a ceramic/composite "sandwich" known as hybrid armour.

The performance of each of the individual constituents of a hybrid armour system influences the overall performance of the armour. Depth of Penetration (DOP) testing is a well-established means of evaluating the ceramic component of armour systems. The most realistic means to determine the effectiveness of amour materials is to conduct live fire tests. However, experimental testing is both costly and time consuming. Numerical simulation of impact events is a cost-effective alternative to actual experimentation, but requires not only accurate simulation of the ceramic, but the projectile and backing material as well. In addition, numerical simulations must be validated by experimentation in order to verify that the simulation is producing results that are accurate.

Numerical simulations involve considerable user input. Values such as material properties and parameters such as mesh size, mesh density and erosion criteria must be entered. Various material models, which predict the behaviour of a material, are implemented within the numerical software. However, the failure of the material requires a model as well. A popular means of representing elements that have failed is through the use of erosion strain. This parameter is responsible for the deletion of elements that have strained beyond a user-specified plastic limit. Because element deletion is dependent upon strain, element deletion is also dependent upon the size of the elements used to descretize the model of the impact event. In addition, the size of the elements will affect the run time and accuracy of a numerical simulation [1].

The primary objective of this work is to provide a numerical model which will accurately predict the DOP of a 12.7 mm (50 Cal) AP-T C44 round into 152.4 mm diameter X 152.4 mm long 6061-T6 aluminium target. This will be accomplished by first evaluating several different target meshes in order to create a mesh that gives reasonably accurate results with the lowest CPU cost. Simulations of the optimum mesh will then be performed with several different values for the parameters responsible for the erosion of the target. The finished model will ideally have accurate parameters and an optimized mesh size in order to reduce CPU cost to a minimum.

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2. Numerical Simulations

The geometry and the finite element mesh for this impact scenario were created in LS-MAZE [2]. LS-DYNA2D [3] was used to perform the finite element analysis. LS-DYNA2D is a hydrodynamic finite element code which can be used to model high rate events including ballistic impacts [4]. It uses a Lagrangian mesh and calculations to determine the deformation of objects undergoing impact.

2.1 Projectile and Target Descriptions

A cross section of the AP-T C44 is shown in Figure 1. The projectile consists of a tungsten carbide core, lead-antimony point filler and is enclosed by a gilding metal jacket. All of these components were modeled for the purposes of the numerical simulation.

The target consisted of a 152.4 mm diameter, 152.4 mm long 6061-T6 aluminium cylinder.

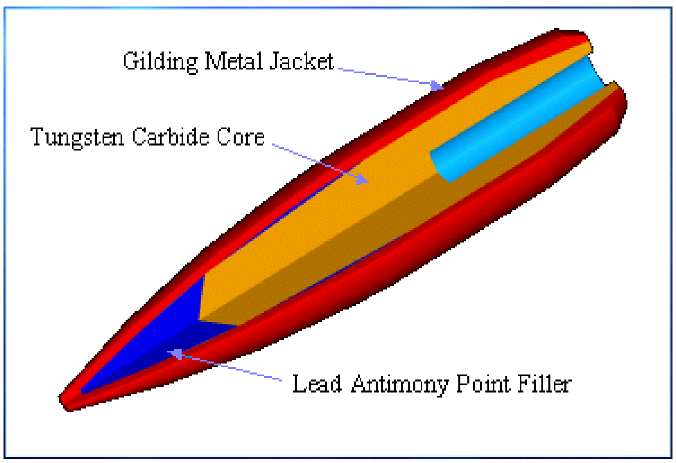

Figure 1. *Sectioned AP T-C44 projectile*

All simulations used a Kinematic/Isotropic Elastic/Plastic model for the tungsten carbide core, the lead-antimony point filler and 6061-T1 aluminium backing cylinder. Nandlall and Wong [1,4] have had success using this particular model to investigate armour design and other projectile impact scenarios. A Johnson-Cook material model was used for the gilding metal jacket. The parameters used for both the projectile and the target are given in Table 1.

Table 1. Material Properties

PARAMETERS	TARGET	PROJECTILE		
	AL6061-T6	JACKET	LEAD	TUNGSTEN
Density, ρ (kg/mm^3)	2768	8858	11350	14027
Yield Strength, σ_Y (MPa)	335.0	344.7	11.0	38000.0
Elastic Modulus, E (MPa)	73100	117200	13800	545000
Poisson's Ratio, ν	0.34	0.40	0.42	0.303
Tangent Modulus, E_t (MPa)	645.7	0.0	0.0	0.0

It should be noted that all strain failure criteria were set to 1 for the determination of the optimum mesh size. After the optimum mesh size was determined, several models were implemented with a varying erosion strain for the aluminium target and the same (optimum) mesh size.

Frictional forces between the materials involved in the projectile impact were not modeled since the frictional forces involved are relatively small compared to the hydrodynamic pressures present during the impact.

2.2 Numerical Mesh Selection

Because of the axisymmetric nature of this impact scenario, only one half of the projectile and target was modeled in a two dimensional frame. Quadrilateral elements consisting of four nodes were used for all numerical meshes.

The target mesh was divided into two areas: A and B (See Figure 2). Area A, aligned with the axis of the incoming projectile, was meshed with a relatively fine mesh in order to accurately capture the large plastic deformations of the target material in the vicinity of the projectile impact. Area B, which would not experience large plastic deformations, was meshed coarsely in order to optimize processor time. Discretization of the target was carried out using several different approaches. The element size was biased such that horizontal dimension of the element increased as one travels from the centre of the target towards the outer edges. A summary of the different meshes used for the aluminium backing cylinder used in this study are presented in Table 2.

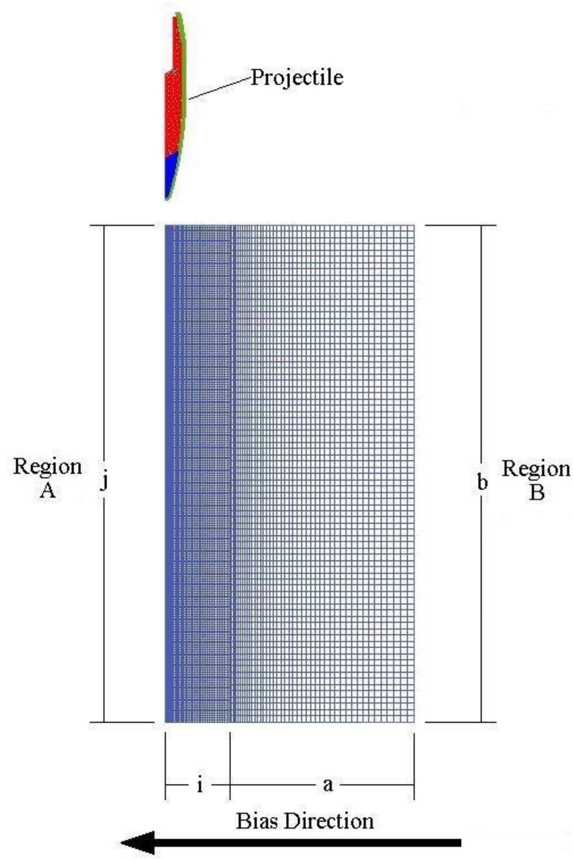

Figure 2. *Mesh parameters*

Table 2. *Mesh Parameters*

MESH NUMBER	NUMBER OF ELEMENTS				BIAS		NUMBER OF ELEMENTS		
	i	j	a	b	REGION A	REGION B	PROJECTILE	TARGET	TOTAL
1	36	120	45	40	3:1	2:1	1944	6120	8064
2	36	240	45	80	3:1	2:1	1944	12240	14184
3	36	480	45	160	3:1	2:1	1944	24480	26424
4	18	240	45	80	3:1	2:1	1944	7920	9864
6	46	720	45	240	3:1	2:1	1944	43920	45864
7	23	720	45	240	3:1	2:1	1944	27360	29304
8	69	720	45	240	3:1	2:1	1944	60480	62424

2.3 Depth of Penetration Testing

In this study, Depth of Penetration (DOP) was used to evaluate the performance of the meshes involved. A DOP value is obtained by measuring the depth of the impact crater that is left in the backing material of protected and unprotected targets. By comparing the residual penetration of a projectile into ceramic protected media and unprotected targets, a ceramic's ballistic performance may be determined. It should be noted that only numerical simulations of monolithic aluminium blocks are studied in this report. Figure 3 displays an example of how DOP measurements are obtained from a specimen.

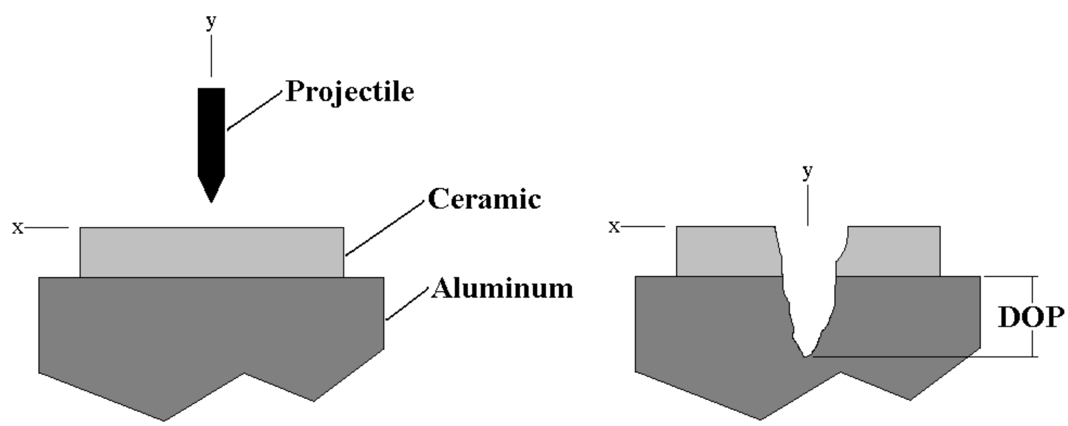

Figure 3. *Depth of penetration testing*

3. Mesh Study

Before actual DOP results are gathered from numerical simulations, it is beneficial to have a mesh that will accurately predict the penetration of a projectile with a minimum of CPU run time. This is accomplished by performing a mesh study.

The mesh study in this memorandum involved holding all parameters constant and varying the size of the target mesh. Although a fine mesh may result in a more accurate reading, a mesh that is coarser may be almost as accurate and yet run in a fraction of the time. It should be noted that the ceramic block was omitted from the target for the purposes of the mesh study.

Figure 4 shows the DOP versus mesh number. Note that the value predicted by the relatively fine mesh (mesh 7) is within 5.5% of the value predicted by meshes 1, 2, 3 and 5. However, mesh 7 requires ten times more CPU time to run compared with mesh 1. Figure 5 shows the CPU time for each mesh to run normalized to the fastest mesh time (mesh 1) versus mesh number.

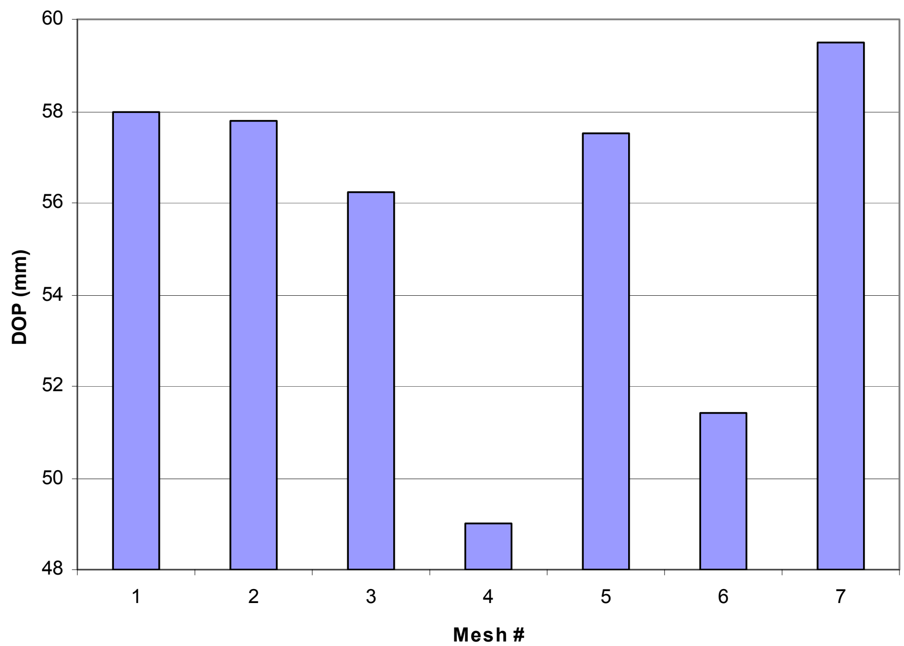

Figure 4. *DOP versus mesh number*

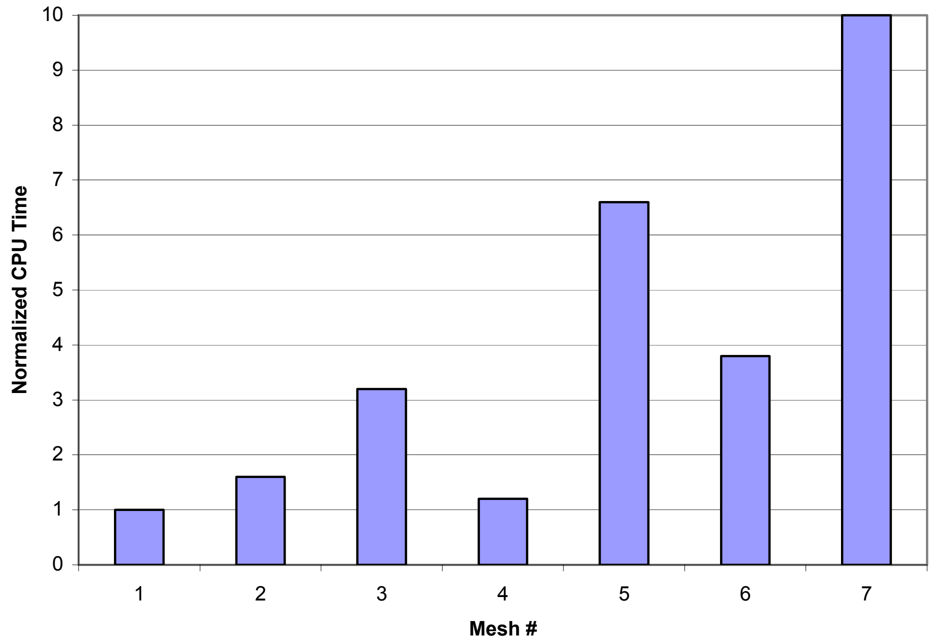

Figure 5. *Normalized CPU time versus mesh number*

Mesh 2 was selected for the remainder of the parameter study. Mesh 2 provided a DOP reading within 3% of mesh 7's reading with the third lowest processor time. Although mesh 1 provided a slightly better DOP reading with less processor time, it was felt that the larger element size of mesh 1 could lead to contact problems such as interpenetration of the projectile and target meshes.

4. Parameter Study

In order for the numerical model of the projectile impact to be accurate, parameters must be selected such that the materials involved behave realistically. One of these parameters is erosion strain. Erosion strain is the parameter responsible for deletion of target elements that have plastically strained beyond a user-defined limit. The time step used in an explicit FEM calculation is based on the size of the smallest element in the problem. Large plastic deformations, particularly crushing of elements, can drive the run time of a problem up by orders of magnitude even though the element that is driving the time step is contributing little to the problem (i.e. the element has failed). The erosion strain provides a mechanism to delete these elements thereby improving the efficiency of the problem.

By holding all other material parameters constant with the exception of the erosion strain for the aluminium target, the results of the numerical model can be fit to the experimentally obtained DOP data. This fitting exercise is necessary because the erosion strain is an artificial parameter that cannot be directly measured experimentally. However, once the erosion strain of a particular material has been identified, it can generally be used for different types of projectiles and impact velocities.

Erosion strain, f_s, for the aluminium target was varied from 0.7 to 1.5 (Figure 6). An impact velocity of 556 m/s was used for the erosion strain parameter study. This impact velocity was chosen because it is the same as the velocity used in an identical impact scenario in a separate experiment.

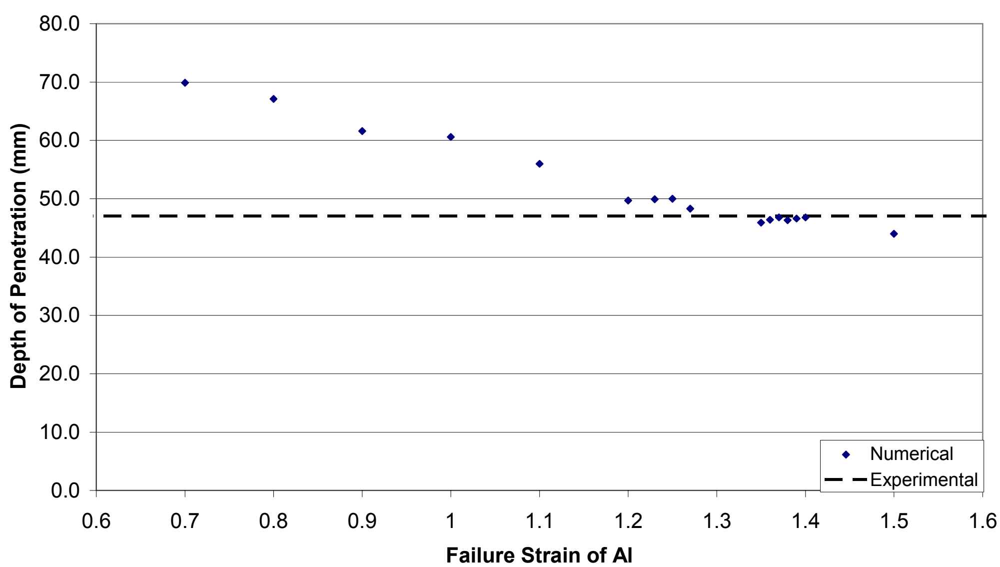

Figure 6. *DOP versus failure strain of aluminium target @ 556 m/s*

It was found that values of f_s between 1.2 and 1.4 resulted in simulations that gave the most realistic DOP values (see Figure 6). It was found that DOP increased as failure strain decreased. It appears that the model is more sensitive to values of erosion strain below $f_s = 1.2$.

Three failure strains ($f_s = 1.2, 1.27, 1.37$) were evaluated at the initial velocities used in the experimental DOP tests (see Figure 7). A failure strain for the aluminium backing of 1.2 was selected due to the accurate prediction of DOP over the expected velocity range.

It is interesting to note the deviation of the predicted DOP for an impact velocity of 750 m/s. This may be due to a numerical instability affecting the accuracy of the model at that particular velocity. It is not uncommon to encounter these numerical instabilities at particular velocities. An impact velocity slightly higher or lower will usually give a good result.

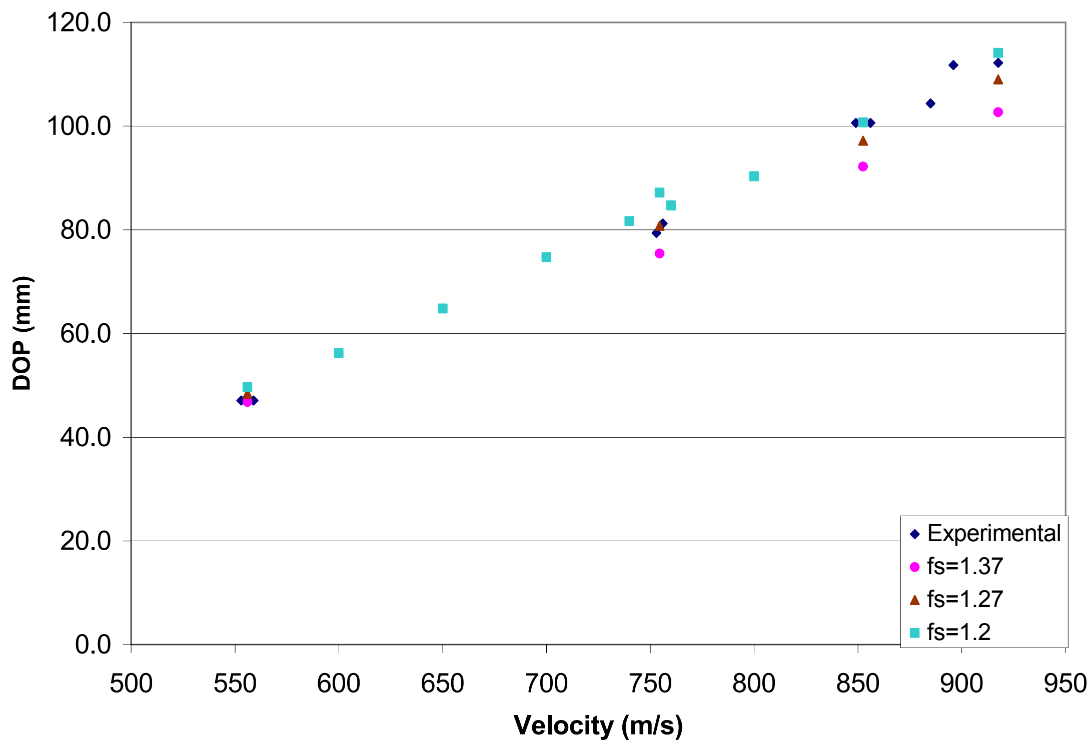

Figure 7. *DOP versus velocity*

5. Conclusion

This study consisted of a mesh sensitivity study as well as a study of the erosion strain of the target on the depth of penetration results obtained from the simulation of the impact of an AP-T C44 12.7 mm projectile on a semi-infinite 152.4 mm diameter, 152.4 mm long 6061-T6 aluminium cylinder. Several numerical simulations were conducted to determine the optimum mesh density that allowed simulations to run efficiently while producing accurate results. The refined mesh was then used to conduct numerous numerical simulations in order to determine the value for erosion strain of the aluminium target.

First, depth of penetration results were obtained from several different mesh configurations. It was found that there was an optimum mesh density which gave accurate results with a reasonable run time. Results from higher density meshes (i.e. longer run times) did not significantly improve the predicted DOP, while the accuracy of simulations with meshes suffered.

A parameter study investigating the erosion strain of the aluminium target was then conducted based on the optimized mesh and a fixed impact velocity of 556 m/s. It was found that values of erosion strain between 1.2 and 1.4 resulted in DOP predictions that were comparable to those obtained experimentally. A finer variation of erosion strain between 1.2 and 1.4 was then performed for a range of impact velocities. It was determined that a failure strain of 1.2 gave results that were the closest to the experimentally obtained values.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
DOP	Depth of penetration
ρ	Density
σ_Y	Yield strength
E	Elastic modulus
ν	Poisson's ratio
E_t	Tangent modulus

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This memorandum details the creation of a numerical model to simulate the ballistic impact of an AP-T C44 12.7mm round on a 152.4mm diameter, 152.4mm long cylindrical 6061-T6 aluminium target. Mesh sensitivity studies were conducted which examined the depth of penetration of the projectile for various mesh configurations. It was found that an optimum mesh density existed such that it would give results that were not significantly different from numerical simulations with higher density meshes. However, the numerical simulations with the optimum mesh density ran at greatly improved run times compared to the higher density meshes. On the contrary, if the mesh size became too coarse, the accuracy of the simulations suffered. A parameter study involving the erosion strain of the aluminium target was then conducted using the optimized mesh. Upon examining several values for erosion strain at various velocities, it was determined that a failure strain of 1.2 for the aluminium target yielded results that were the closest to the experimentally obtained values. The numerical model created as a result of this study will provide a foundation for ongoing numerical research into hybrid body armour systems for protection from high velocity large calibre projectiles.

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