Numerical Simulation of Light Armoured Vehicle Occupant Vulnerability to Anti-Vehicle Mine Blast

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Abbreviations:

ATD	Anthropomorphic Test Device
DOB	Depth of Burial
DRDC	Defence R&D Canada
LAV	Light Armoured Vehicle
RHA	Rolled Homogeneous Armour

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Anti-vehicular Mine, Armoured Vehicle, Blast Loading, Occupant Injury

ABSTRACT

An ongoing program at Defence R&D Canada to reduce the vulnerability of Light Armoured Vehicle (LAVs) to anti-vehicular blast mines is relying heavily on numerical simulation to help design and optimize add-on armour systems. One of the greatest challenges faced during the evaluation of the vulnerability of a given vehicle to blast mines is not only assessing the structural response of the vehicle but also evaluating the injuries sustained by the vehicle occupants due to the accelerations induced by the blast. Anthropomorphic test devices (ATDs such as the Hybrid III) are used in the experimental program but these human surrogates were developed specifically for automotive crash tests. The loading conditions observed during a mine detonation, particularly where there is a breach in the hull of the vehicle, are such that extensive damage can be caused to the ATD. In addition, placing more than 2 or 3 ATDs in a vehicle is prohibitively expensive. As a result, the use of ATDs is somewhat limited. Numerical techniques allow any number of vehicle occupants to be simulated even in scenarios where there is potentially catastrophic failure of the hull.

This paper presents the results of a series of simulations performed with LS-DYNA. A finite element model of the Canadian Cougar AVGP LAV, previously validated against experimental data for mine blast, was modified to include details of the rear crew compartment. The vehicle occupants were modelled using the GEBOD simplified ATD model incorporated in LS-DYNA. A simulated blast from a 6-kg C-4 mine surrogate was used to load the vehicle model. The predicated accelerations and velocities for various parts of the GEBOD dummies were compared to injury threshold criteria.

INTRODUCTION

The vulnerability of light armoured and soft skinned vehicles to anti-vehicular blast mines is well known and Defence R&D Canada – Valcartier (DRDC - Valcartier) has been involved in the development of protection systems for a range of vehicles for over 8 years. Recently, numerical modeling with LS-DYNA (Hallquist, 2001) has begun to play a very significant role in the design and validation of these systems (Williams, 1999 and Williams and Poon, 2000).

The current test program at DRDC – Valcartier is using decommissioned Canadian Cougar 6x6 LAVs as platforms for developing advanced mine protection systems. A number of scenarios are being investigated including wheel and under belly detonations of mine surrogates ranging from 6 to 8 kg of C-4. One of the tests that is to be performed during the summer of 2002 is a stowage test which is designed to verify the effectiveness of the equipment stowage systems in the LAV-III, the newest addition to the Canadian fleet. The rear crew compartment of a Cougar vehicle has been modified to represent the larger LAV-III crew compartment. During the tests Hybrid III ATDs will be positioned in the rear of the vehicle to assess occupant injuries.

A numerical model of the Cougar has been developed and validated for wheel and underbelly detonations of 6-kg C-4 mine surrogates. In the current study, this model has been modified to represent the enlarged crew compartment and a crew of GEBOD simplified ATD models have been added. The simulation undertaken is a mine blast under the left centre wheel of the modified Cougar. The analysis was used to look at injury assessments based on the acceleration of the head and pelvis as well as the velocity of the floor impacting the feet during the first few milliseconds of the event. DRDC – Valcartier uses other analytical codes to predict the rigid body response of the vehicle (e.g. roll over) and vulnerability of the crew to the accelerations and displacements of the vehicle on a longer time scale.

APPROACH

Model Geometry

The model used in the present analysis is a modified version of the Canadian Cougar AVGP LAV (see Figure 1). This model has been previously validated against experimental data for mine blasts and has shown to be a good representation of the real vehicle. The hull geometry is an accurate representation of the Cougar. The turret, hatches, and interior bulkheads have been removed as they have a negligible effect on the response of the vehicle hull in the first few milliseconds of the event which is the duration of interest here. The wheels and drive shafts have also been removed to simplify the model. These components play a much more important role in the response of the vehicle and in the local deformation of the hull (e.g. the wheels can absorb and deflect a significant amount of the blast) but the loading model used in the analysis is incapable of explicitly modelling their effect on the blast. The engine and transmission block along with their attachment points were preserved. Although these components see little deformation, they are bolted to the floor of the vehicle and contribute to the overall stiffness and inertia of the lower hull.

For the purposes of the current study, the baseline Cougar geometry was modified to represent the enlarged crew compartment. The rear compartment was widened and the roof was raised to match the LAV-III dimensions. Benches were also added on either side of the rear compartment as shown in Figure 1.

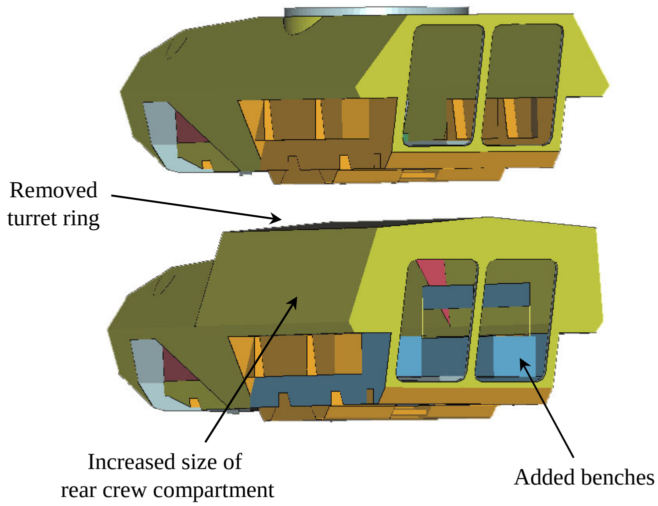

Figure 1. Modification of baseline Cougar model to include rear crew compartment of the LAV-III and seating.

A protection system was added under the floor of the model (refer to Figure 2). It consists of a stiffened steel plate that prevents perforation of the floor by the blast, thereby reducing the risk of damage to the Hyrbid III ATDs from blast pressure and fragment intrusion into the crew compartment. The plate was developed, optimized numerically, and successfully tested in the fall of 2002. It is important to note that this protection system was developed strictly for the purposes of protecting the mannequins during the experimental trials and not as an actual mine protection system concept. This plate will be used in the trials on the modified vehicle during the summer of 2002 and, as a result, was included in the numerical model.

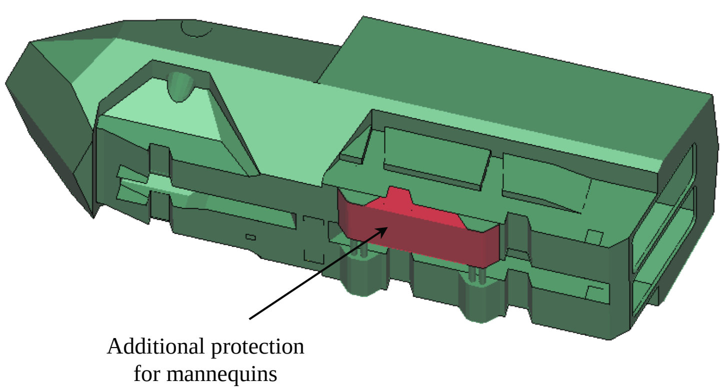

Figure 2. Protection added to baseline vehicle to prevent damage to Hybrid IIIs caused by hull rupture during tests.

The vehicle occupants were modelled using the GEBOD dummy model incorporated in LS-DYNA. In all, six GEBODs were placed in a staggered sitting position on the benches, three on each side. This is a typical seating configuration for the vehicle. In the numerical model, the crew were not restrained.

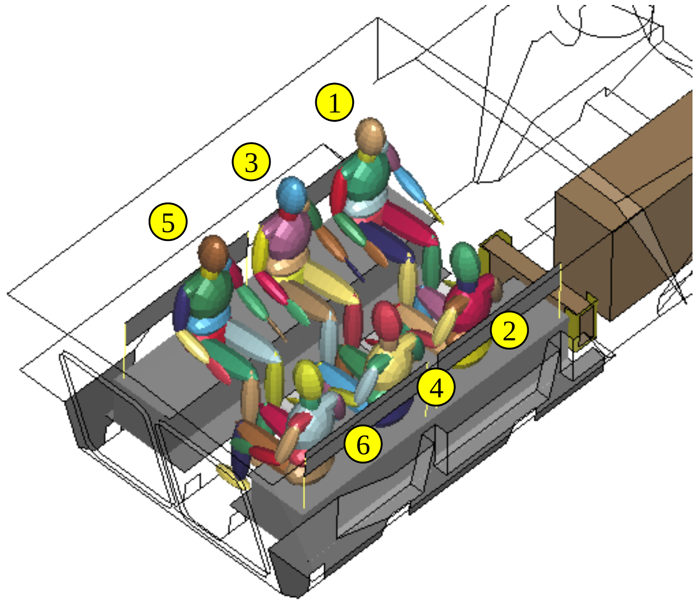

Figure 3. Position of GEBOD dummies inside the vehicle model.

Finite Element Model

The FEMAP CAD/CAE software package (SDRC, 2000) was used as a pre-processor to build the solid model and finite element mesh of the vehicle. The vehicle hull, benches, and interior structure were meshed using Belytschko-Tsay shell elements. The supports for the bench backrests were modelled with beam elements with appropriate cross section definitions. The engine block and transmission were represented by simplified block structures meshed with constant stress solid elements. The model mesh consists of 37607 nodes, 34891 shell, 64 beam, and 2706 solid elements.

The structure of the vehicle is RHA steel and the add-on protection system is manufactured from mild steel. The simplified benches were modelled as sheet steel. In all cases a bilinear elastic plastic material model (Material type 3 - *MAT_PLASTIC_KINEMATIC) was used.

A *CONTACT_AUTOMATIC_SINGLE_SURFACE definition with the default parameters was used to ensure contact between the various components.

The default properties for the 50th percentile male GEBOD were used for the vehicle occupants.

Loading Model

The mine impulse loading model developed by Westine *et al.* (1985) for the U.S. Army TACOM was used to simulate the blast loading from the mine surrogate. The model is based on a series of tests that were conducted to measure the impulse at various locations above a land mine explosion. The data gathered from these tests was used to develop an empirical model which accounts for effects such as mine depth of burial (DOB), charge size, target height, and soil density. A pre-processor for LS-DYNA has been written by DRDC – Valcartier (Dumas and Williams, 2002) that implements the empirical equations from the impulse model. The pre-processor uses material data and element thicknesses already in the LS-DYNA input deck to generate an updated LS-DYNA input file with appropriate initial nodal velocities based on the Westine *et al.* model.

The baseline mine and soil conditions used for the analytical model are presented in Table 1.

Table 1. Baseline mine and soil conditions.

Property	Value
Mine Mass	6 kg
Mine Diameter	25.4 cm
Mine Thickness	7.62 cm
Depth of Burial	8.81 cm
Soil Density	2301 kg/m^3
Correction Factor	0.66

The mine DOB, diameter, and mass are all representative of the mine surrogate that will be employed in the trials. Note that the depth of burial used by the model is measured from the surface of the soil to the centre of the mine. This is in contrast to the more usual definition of the depth relative to the top surface of the mine (i.e. the overburden). The soil density was measured at the test site. Finally, a correction factor was applied to the calculated impulse. This correction factor (0.66) has been shown to give good agreement between predicted and measured results for a variety of simplified geometries tested at the DRDC- Valcartier test site (Williams, 1999, Williams and Poon, 2000 and Williams *et al.*, 2002). The confinement offered by different types of soil and different soil conditions have a significant effect on the energy directed to a target from a mine. It is hypothesised that this scaling factor accounts for differences between the soil at the DRDC- Valcartier test site and the test site used by Westine *et al.* to develop the empirical impulse model. The mine was aligned with the location of the centre of the left inside edge of the middle wheel (refer to Figure 4) which is below and to the back of the position of GEBOD #3.

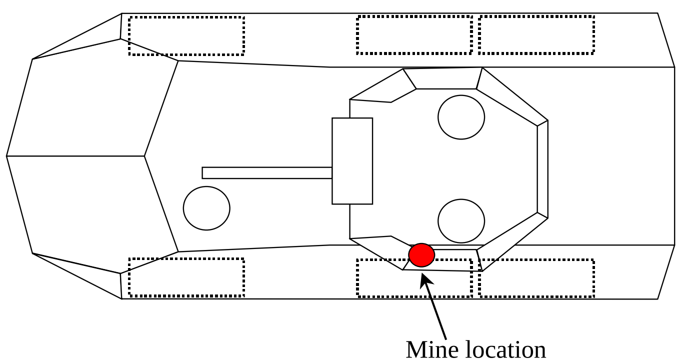

Figure 4. Position of mine relative to vehicle.

RESULTS

Figure 5 shows the predicted motion of the GEBOD dummies during the mine blast event.

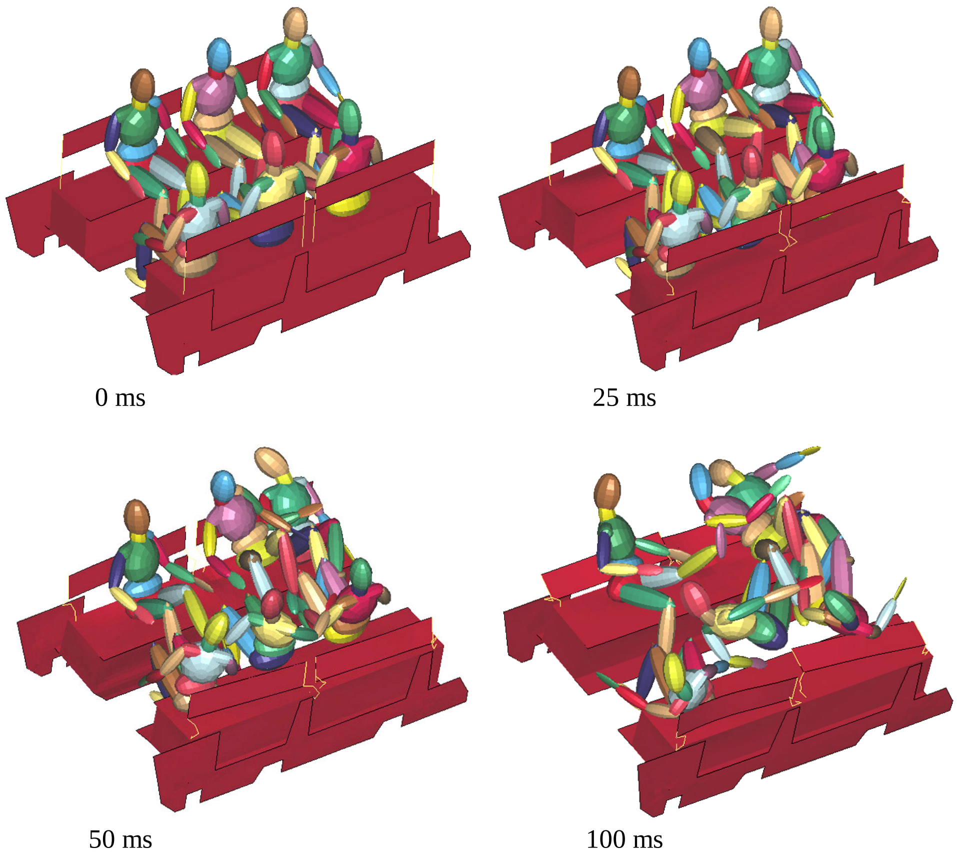

Figure 5. Sequence of GEBOD reactions to the detonation of a 6-kg C-4 mine surrogate under the left centre wheel viewed from the side opposite the mine location (vehicle faces to the right). The vehicle hull has been removed for clarity.

Figure 6 shows an example of the predicted rigid body acceleration history for the pelvis and the head. In this case it is for the crewmember at the rear of the left side of the vehicle (GEBOD #5 as indicated in Figure 3).

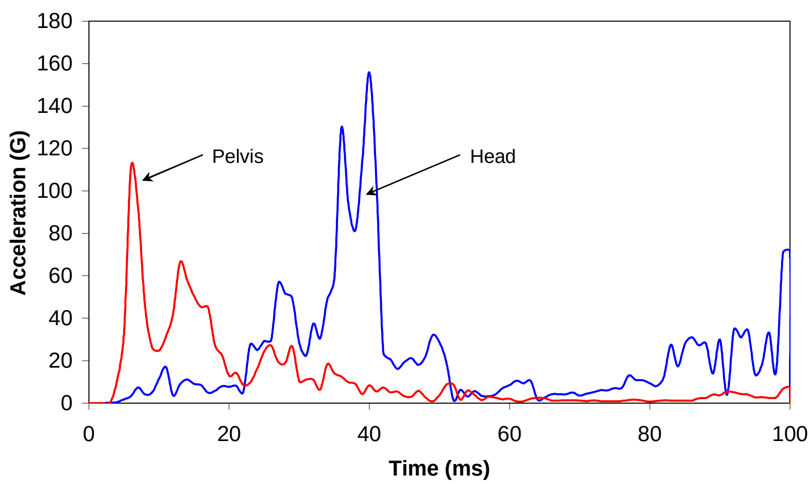

Figure 6. Predicted acceleration history of the head and pelvis of GEBOD #5.

The injury assessment for the feet is based on velocity rather than the acceleration. Figure 7 shows the predicted velocity history of the floor directly under the feet of GEBOD #5.

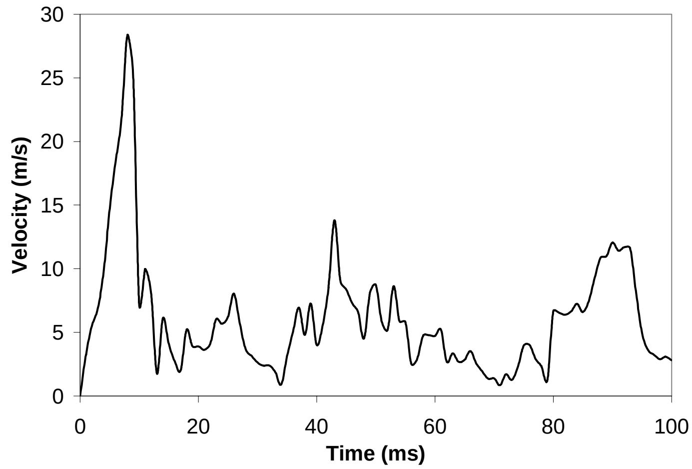

Figure 7. Predicted velocity history of the floor under the feet of GEBOD #5.

Injury Assessment
Table 2 gives a comparison between the predicted accelerations and the injury criteria. The injury criterions used for the head and pelvis were developed using the Hybrid III ATD (Alem, 1996). In our case, the acceleration is measured on the GEBOD. Therefore, the comparison between the preceding results and the injury criterions is an approximation. However, the response seems to be representative of the real situation and as a result the assumption is made that the criteria are valid. For the feet, the criterion is based on experimentation with cadavers (Black *et al*., 1945 and Draeger *et al.*, 1945). Again, the assumption is made that the GEBOD is representative of the real human body so that the criterion can be used for comparison. In most cases, the loading rates and event durations involved with mine blast loading fall well outside those used to develop the injury criteria available.

Table 2. Comparison with injury criterion

Part	Predicted Loads	Injury Criteria	
Head	a > 80 g for 6 ms a_{peak} = 155 g	a = 150 g for 2 ms	High risk of brain damage
Pelvis	a > 40 g for 5 and 3 ms a_{peak} = 110 g	a = 40 g for 7 ms	High risk of spinal cord damage
Feet	v_{peak} = 27 m/s	v = 3,5 to 5,0 m/s	Apparition of lower leg fracture

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Before reviewing the injury criteria in detail, it is important to note that these results are valid for this specific case (i.e. a 6-kg charge ideally buried under the inside edge of the middle wheel of a vehicle with no protection) which is being used as a worst-case scenario for the development of protection systems. Anti-vehicular mines that peacekeepers come across in the field, for example, are buried in an adhoc fashion. Even the difference between a detonation directly under the wheel or just outside the centre line of the wheel can lead to a significantly better outcome.

Head. The head of GEBOD #5 is subjected to an acceleration of over 80 G for a period of 6 ms and reach a peak value of 155 G. In fact, for two of the GEBOD positions, the heads are observed to impact the roof of the vehicle. The injury criterion for the head gives a high risk of brain injuries for an acceleration of 150 G for 2 ms. As a result, we can conclude that there is a high risk of brain injuries predicted for the members of the crew sitting near the detonation of the mine.

Pelvis. In the simulation, the pelvis of GEBOD #5 reaches an acceleration of 110 G and stayed above 40 G for periods of 5 and 3 ms. This is higher than the injury criterion for the spine which predict spinal cord damage for an acceleration of 40 G during 7 ms.

Feet. Based on a study performed on real legs, bone fractures are caused in the lower leg when a steel plate impacts at greater than 3.5 to 5.0 m/s. In the simulation, the floor under the feet of GEBOD #5 reaches a velocity of 27 m/s, which is much higher than the injury threshold thereby indicating a high risk of lower leg injury. The legs are one of the most vulnerable parts of the body because of their proximity to the blast.

SUMMARY

The results presented in this paper show the application of numerical modelling to the prediction of the vulnerability of armoured vehicle crews to anti-vehicular blast mines. The work builds on a development program for mine protection systems at DRDC – Valcartier that includes numerical modelling for the development and optimization. The application of FEM to predict the structural response of the protected vehicle has proven to be highly successful. The study also represents the next step in increasing the detail included in the models, namely the inclusion of the occupants. The results are providing insight into methods that can be used to limit the vulnerability of LAV crews to the effects of anti-vehicular blast mines. However, the preliminary injury assessments made here are relatively crude and there is clearly much more work needed on appropriate injury criteria for high acceleration short duration events such as this.

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