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Investigation of dynamic response of a mannequin in a vehicle exposed to land mine blast

Atıl Erdik*

Abstract

Explosive devices are serious threats for armored vehicles and occupants. Following detonation of a high explosive, blast loads, which are transferred through shock waves to the vehicle hull, might potentially cause severe injuries on the body parts. Anthropomorphic test devices (ATDs) allow for injury assessment of occupants in armored vehicles subjected to land mine explosion in accordance with injury criteria standards. This study examines the emerging role of numerical simulations in the context of survivability of combat vehicles in modern warfare. The objective of this paper is to contribute to the understanding of numerical simulation for dynamic response of human dummies seated in armored vehicles subjected to land mine by comparing the performance of Hybrid-III 50th percentile ATD in numerical simulation with that of full-scale blast testing. Therefore, force and acceleration data were collected from critical body parts; tibia, pelvis, lumber spine, upper neck, and head of the mannequin in blast testing. Those data were compared with numerical simulation results. The numerical simulations were performed in LS-DYNA using CONWEP blast loading method. It was found that the numerical simulation results are in accord with those obtained from blast testing.

Keywords: Land mine, Blast loading, Occupant Safety, Hybrid-III Anthropomorphic Test Device, LS-DYNA, CONWEP method

1. INTRODUCTION

Improvised explosive devices (IEDs) and land mines are typical explosive devices, which may cause severe damage on military vehicles and occupants during asymmetric combats. The US Department of State reported that the worldwide number of land mines in the ground is about 50 million and these land mines induce 10000 casualties in every year. Over 50% of army vehicles become incapable of working due to land mines [1].

In last two decades, with the increase of troop casualties and injuries stemming from asymmetric attacks in dangerous regions, armored vehicles offering high level of mine blast and ballistic protection became particularly significant. Advances in numerical techniques and computers enabled engineers to rapidly fulfill novel concepts for blast resistant systems [2]. Effectiveness of explosive devices was dramatically reduced after successfully deployment of new generation armored vehicles around the world. Lamb et al. [3] reported that the casualties and mortality rate of military personnel resulting from IEDs and land mines were sharply decreased after implementation of mine resistant systems into armored vehicles in US Army, as shown in Figure 1.

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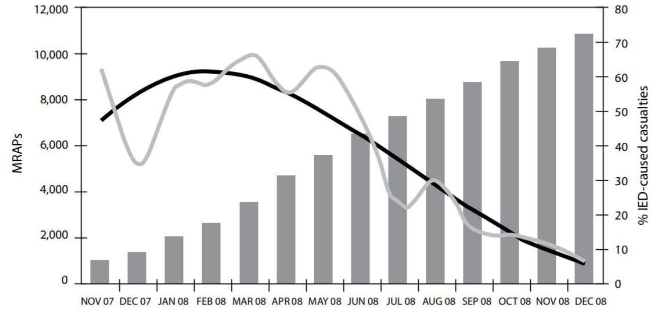

Figure 1 IED-caused fatalities and MRAP deployment [3]

During a land mine explosion, a certain amount of accumulated energy is dissipated by an explosive blast wave. The blast wave hits underneath the vehicle hull and causes dynamic deformation on the bottom plate while mechanical shock waves travel with the speed of 5000 m/s through the armor steel and those rapid induced oscillations result in potent vibrations and accelerations in vehicle. Vehicle acceleration caused by the detonation of land mine can have severe effects on occupants. The magnitude of blast loading acting on the occupants is directly related to ground clearance, geometry of vehicle, and seat mechanism. Hence, the design of armored vehicle is of great importance to minimize the risk posed by land mine explosions.

Mine blast testing of armored vehicles provides valuable insight into dynamic response of the body hull and makes possible to reveal weaknesses and strengths of the main structure under blast loading. According to NATO AEP-55 standardization agreement [4], vehicle integrity shall be protected and injury level of occupant inside the vehicle should be no more than the given values for specific points on human body in a blast test. For this purpose, mannequins are utilized to do the occupant safety evaluation in both blast testing and numerical simulations.

While some research has been carried out on the blast mitigating systems for armored vehicles, there is very little scientific understanding of responses of occupants in vehicles under blast loading. Collectively, the following studies provide significant knowledge about blast mitigating systems as well as the dynamic response of vehicle and crew members under blast loading using numerical simulation methods.

Wei et al. [5] offered an interesting study of blast mitigation systems that involves multilayer honeycomb sandwich structure which is mounted on the bottom of the vehicle. Numerical simulation of dynamic responses of both vehicle and Hybrid III dummy were validated through physical experimentation of buried mine blast. They reported that simulation results are promising. Suhaimi et al. [6] performed a numerical simulation of a vehicle and occupant dummy exposed to mine explosion in order to study the effect of blast loading on the dummy. They revealed that shock response of the dummy model is mostly affected by the seat height and charge position. Wang et al. [7] investigated head injury of occupants in a tracked vehicle exposed to land mine explosion using finite element method. They examined head responses to the input accelerations according to various injury criteria. It has been concluded that head injury might be evaluated by utilizing input accelerations and by analyzing head responses to impact. Baker et al. [8] studied on characterization of behavior of polymeric materials frequently used in human dummy models for underbody blast loading and implementation of those materials in finite element model of ATD. They stated a good agreement was achieved between material model simulations and related experiments and they also expressed that polymers with higher modulus shows rate dependent and strain hardening behaviors.

Comparative study of Ramasamy et al. [9] found that vehicle modifications decrease the ratio of kill to unharmed and similarly, elevated ground clearance, blast mitigating and deflecting systems, and V-shaped hull undoubtedly reduce the ratio of kill to injured resulting from Anti-vehicle mine blast. Cheng et al [10] investigated numerical and experimental interpretations for thoraco-lumbar spine injury hinged on pelvis acceleration, dynamic response index (DRI), and lumbar spine axial force. They found that numerical models cannot instutite appropriate forces compared to the experimental tests with the physical ATD. Denefeld et al. [11] carried out several blast tests with different ground clearances and vehicle geometries. They validated numerical simulation parameters for the investigation of IED effects on vehicles and crew members. They demonstrated that global acceleration acting on vehicle and crewmembers can be reduced through optimized vehicle geometries. Babu et al. [12] examined and compared that energy response, structural response and occupant behavior of a generic military vehicle hull subjected to land mine blast for two numerical solution technique, namely S-ALE and ALE. They concluded that performance of those techniques are similar and S-ALE and ALE methods can be used interchangeably.

Bonsmann and Fourney [13] studied the effects of different mitigation methods on blast-loaded vehicles.

They demonstrated that global acceleration of vehicle could be decreased from 150 G to about 10 G by utilizing thin-walled cylinders. Cheng et al. [14] prepared analytical models to find differences between drop tower test results and blast test results for the assessment of blast mitigation seats. They pointed out that this approach has some limits and it should be given special care while predicting the test results since drop tower technique mostly overestimates the performance of blast mitigation seats. Tabiei and Nilakantan [15] developed a numerical formulation calculating energy transformations, velocities, accelerations, and crushing loads for specific circular tubes as the energy absorbing part of a seat structure in occupant survivability applications. This formulation represents a response history of impactor and energy absorbing seat through crushable aluminum tubes. They reported that test measurements, simulation, and formulation give similar results.

The principal aim of this paper is to contribute to the understanding of numerical simulation for dynamic response of human dummies seated in armored vehicles subjected to land mine. The remaining part of the study proceeds as follows: The first part explains numerical simulation methodology. The second part describes experimental approach and instrumentation utilized in blast test. The third part draws a comparison between numerical model and experiments. The final part summarizes the principal findings of both experiment and numerical simulations and provides a discussion of the implication of the findings to future research into blast simulation.

2. NUMERICAL SIMULATION METHODOLOGY

Blast Loading Method

The detonation of an explosive charge releases blast energy resulting in disturbances in the surrounding air, which grows into a blast wave system led by a shockfront. This physical phenomenon can be simulated through two essential techniques in the commercial finite element method, LS-DYNA; CONWEP and Arbitrary Langrangian-Eulerian (ALE). The first method calculates conventional blast loading effects on structures from the equations and curves of TM 5-855-1 [16]. The latter offers explicit modeling of explosive and air using equation of states. The Lagrangian structure is loaded through Fluid Structure Interaction (FSI) algorithm.

The CONWEP method was implemented in LS-DYNA hydrocode with the use of the *LOAD_BLAST keyword function by Randers-Pehrson and Bannister [17, 18]. *LOAD_BLAST function provides a simplified and proven analysis approach with less computational cost and decent accuracy at certain conditions [19] over the computationally expensive ALE Method [20].

To adequately collect force and acceleration data from body members of the Hybrid III dummy inside the vehicle subjected to land mine explosion, the calculation should continue at least 200 milliseconds. The fact that, calculation of such a physical event with a long duration in LS-DYNA employing the ALE method can takes up to four or five weeks of compute times on the workstation with 36 CPUs might not be practicable for an engineering problem. Hence, *LOAD_BLAST function was selected to induce blast loading acting on underbelly of the hull.

Finite Element Modeling

Finite element model involves vehicle body, tires axes, chassis, and powerpack components as well as structural parts and seat mechanism. Hull plates, chassis subsystem parts, and tires were modeled using Belytscho-Tsay shell elements with two integration points. Seat mechanism consists of seat frame, seat belts, cushion, and main plate tension apparatus. Seat frame, belts and tension apparatus were modeled with shell formulation, while cushion was generated using hexahedral solid elements. Bolts and welds were prepared using beam elements. The entire model consists of 339,638 shell elements, 62,178 solid elements, and 1,340 beam elements. LSTC's rigid Hybrid-III 50th percentile dummy was preferred as a mannequin [21] due to its compatibility with blast simulation models. Figure 2 illustrates finite element modeling details of the entire vehicle and Hybrid III test dummy as well as detonation point.

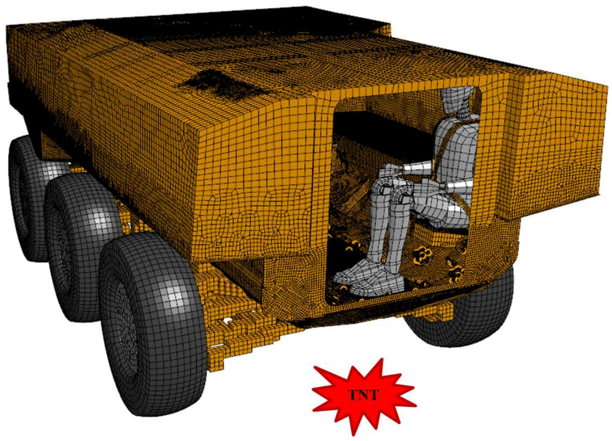

Figure 2 Finite element modeling details and detonation location

Material Models

The Johnson-Cook (J-C) constitutive model is one of the widely used material models, which was primarily developed for computational hydrocodes, focusing on high-speed impact and penetration problems at high rates of strain. The model having a viscoplastic formulation capability for ductile metallic materials considers strain hardening, strain rate hardening, and thermal softening effects on material behavior and fracture.

Johnson and Cook [22] expresses the equivalent stress as a function of plastic strain, strain rate and temperature with an empirical relationship for the flow stress, which is represented as:

$$\sigma_Y = \left[A + B{\varepsilon_p}^n\right]\left[1 + Cln{\dot{\varepsilon}_p}^*\right]\left[1 - {T_H}^m\right] \qquad (1)$$

where ε_p is the equivalent plastic strain, ${\dot{\varepsilon}_p}^*$ is the dimensionless plastic strain rate for $\dot{\varepsilon}_0$, and T_H is normalized temperature for $T_H = (T - T_{room}/T_{melting} - T_{room})$. The five material constants are A, B, C, n and m. The expression in the first set of brackets gives the stress as a function of ${\dot{\varepsilon}_p}^* = 1$ and $T_H = 0$. The expressions in the second and third sets of brackets represent the effects of strain rate and thermal softening, respectively. For strain hardening, strain rate hardening, and temperature phenomena, an independent term is generated. By multiplying these three independent terms, a flow stress as a function of effective plastic strain, plastic strain rate, and temperature is obtained. The calibration of material model parameters is relatively easy because the model allows isolation of various effects. J-C material model was used for the armor and mild steel structures in the vehicle model by activating *MAT_JOHNSON_COOK material function [23].

Energy absorbing capability is a fundamental property of a cushion material. The fact that cushion could absorb respectable shock energy, which is transmitted from structural parts of vehicle to the seat mechanism during mine blast has a direct impact on the magnitudes of the acceleration and force acting on the human body. For this purpose, energy dissipation of cushion material was determined by conducting a simple mechanized experiment so as to gather material model parameters of cushion. In the experiment, the ability of cushion in absorbing energy is obtained by measuring hystererisis, which is demonstrated by the area between load-deformation curves for loading and unloading conditions through MAT_FOAM keyword function.

Contact Algorithms

*CONTACT_AUTOMATIC_SINGLE_SURFACE function was assigned for the contact between structural parts. The mesh resolution of LSTC's rigid hybrid dummy is quite coarser than vehicle mesh. This difference may emerge numerical issues for the contact algorithm in constituting a reliable contact between dummy and seat parts. *CONTACT_AUTOMATIC_GENERAL function was thus selected for the contact between seat components and human dummy. *CONTACT_INTERIOR function was designated for solving the possible source of numerical errors, which could be encountered during the calculation of contact algorithm for the interior elements of seat elements. Another possible contact interference might take place between seat frame and cushion. To prevent this, *CONTACT_NODES_TO_SURFACE keyword function was adopted.

3. BLAST TEST

NATO AEP-55 standardization agreement [4] describes mine blast testing conditions for wheeled armored vehicles for NATO member countries. In this study, 6 kg of cylindrical TNT charge was placed in a steel pot, which is made of 42CrMo4 alloy underneath the hull of the armored vehicle. Figure 3 gives the dimensions of the steel pot and the TNT charge used in the full-scale blast test.

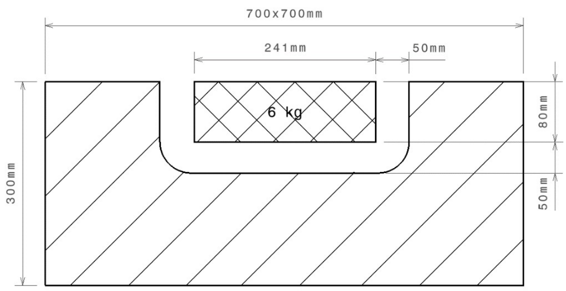

Figure 3 Dimensions of steel pot and TNT

Hybrid III 50th percentile dummy was seated with five-point seat belt in the cabinet where the maximum deformation occurs during land mine blast. Five point seat belts prevent the the dummy from flying any direction during explosion. Force and acceleration data were collected from the tibia, pelvis, lumber spine, neck, and head on Hybrid III in blast experiment. The test results were utilized to draw a comparison with numerical simulation methodology. Figure 4 shows the position of the dummy in the vehicle prepared for the blast test.

Figure 4 Hybrid-III dummy positioned for a mine blast test

Hybrid III 50th percentile dummy was used to record the blast effects felt by occupant inside the crew compartment as a consequence of a mine blast and the resulting the vehicle movement. Accelerometers measured head, chest, and pelvic acceleration, while load cells measured forces from the neck, lumber spine, and lower leg. A descriptive illustration of the transducer locations in the Hybrid III dummy model is given in Figure 5. Blast injury takes place as a shock wave directly loads the occupant body. Overpressure measurements were done outside the vehicle to determine the magnitude of the explosion at a certain distance. Aside from measuring the blast loads on the target structure, these data might assist to institute the consistency of the energy output from the explosive charge.

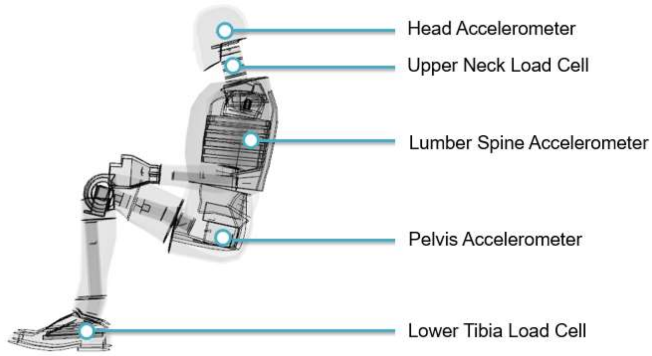

Figure 5 Sensor positions of the Hybrid-III

4. RESULTS

Mine Blast Simulation

Numerical simulations were performed in LS-DYNA MPP R6.1.0 version on a high performance compute cluster with 36 CPUs and 216 GB RAM. It took 6h, 23 minutes to reach the termination time of 200 milliseconds, which was considered the minimum duration for attaining purposeful data from measurement points of ATD.

Kinematic responses of critical members of ATD has been instrumental in our understanding of injury mechanism for human body. Figure 6 could provide insight into prominent factors influencing the movement of the Hybrid III ATD seated with five-point seat belt at the instances of 50, 100, 150 and 200 milliseconds, respectively. Figure 6 (a) illustrates the initial movement of the dummy. Figure 6 (b) shows the advance of the blast loading while it is transferred to the body by legs. Hybrid-III inclines its head and neck forward. Figure 6 (c) and (d) presents that the motion of the legs upward while the back of the Hybrid III ATD compresses the seat cushion and the movement of the head goes backward. It can be seen in Figure 6 that the five-point seat belt operates properly to keep the dummy on the seat as well as pre-tensioning the seatbelt prior to explosion influences the kinematic responses of occupant.

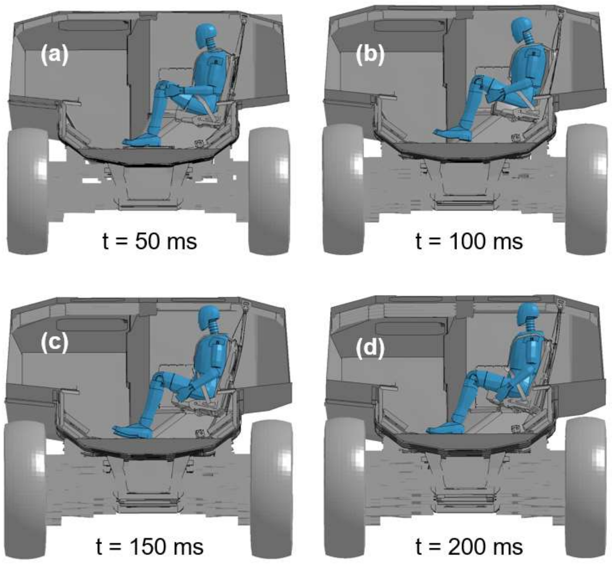

Figure 6 Illustration of kinematic responses of Hybrid-III dummy influenced by blast loads at various instances of numerical simulation

When an explosive charge is detonated, a certain amount of energy is released in a direction perpendicular to the surface of the explosive. In particular, during a land mine blast, the blast waves are focused to produce a greater local effect on the underbelly of the vehicle. Amount of energy transferred from the vehicle hull to the seat could deliver a proof on injury level of occupant. For this purpose, the ratio of kinetic energy of TNT material at the initial moment to transmitted energy to the occupant was determined. 0.343 percent of 26.7 kJ energy released by 6 kg of TNT charge at the detonation moment was accumulated by seat structure during explosion event. This result indicates that only a small fraction of kinetic energy released by explosive charge transferred to the seat.

Comparison of Results

Force and acceleration data are collected from the lower leg, pelvis, lumbar spine, upper neck, and head of the Hybrid-III in both the test and numerical simulation to predict injury levels of the occupant. A comparison is provided for the peak values of those quantities given in Table 1.

Table 1 Comparison of force and acceleration

Body Member	Analysis	Test	Deviation (%)
Left Tibia (F_z) (N)	3563	3716	4
Right Tibia (F_z) (N)	3276	3483	6
Pelvis (A_z) (G)	11.99	12.96	8
Lumber Spine (F_z) (N)	2278	1949	17
Upper Neck (F_z) (N)	388	499	22
Head (A_z) (G)	9.9	11.89	17

When overall results are considered, a good approximation is provided since the highest deviation percentage is lower than 23 for the upper neck. Similarly, the second highest deviation is measured on the head sensor. It is deduced from results that upper body part of numerical model of ATD needs further calibration.

5. CONCLUSION

This study set out to determine the role of numerical simulation in assessing the injury level of occupant inside armored vehicles subjected to land mine explosion. The first step in this process was to conduct full-scale blast test of armored vehicle in order to validate numerical simulation results. Forces and acceleration data were collected from tibia, pelvis, lumber spine, neck, and head on the Hybrid III ATD in blast testing. The measured results were then compared with the peak values of those data determined in the numerical simulation. Table 1 demonstrated that numerical simulation results are in line with blast testing measurements.

The research has also shown that CONWEP blast loading method is feasible to examine the response of mannequin inside vehicle when high computational resources are not available for performing numerical simulation through more complicated blast loading methods. In this present case, a correlation factor could be adapted to CONWEP method to obtain better accuracy of results on sensor points in numerical model of ATD.

The investigation of energy balance reported here suggests that the preliminary assessment about the injury level of occupant in accordance with NATO AEP-55 standard might be done by investigating amount of energy transfer from vehicle to seat structure to some degree.

One interesting finding to emerge from the analysis is that the experimental measurements give greater values than numerical calculations for each sensor except the lumber spine. A possible explanation for the result calculated on the lumber spine could be the use of the rigid ATD instead of the deformable model. Characterization and validation of material modeling of mannequin are crucial factors in the determination of the quantity of structural load transmitted to the hip joint from the seat frame. In the light of this deduction, LSTC's rigid Hybrid III 50 percentile male ATD must be used with caution. A further study might be fulfilled to check which issue result in that peculiarity.

This study provides a comparison table that can be used for fine-tuning and validation of LSTC's Hybrid III 50 percentile rigid ATD. In addition, this work has increased knowledge about the responses of occupant in an armored vehicle under blast loads. The data presented here support the advancement of current and future numerical models of ATD, which will contribute to the development of improved seat mechanism in armored vehicles that reduce the number of troop casualities and injuries in land mine blasts.

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