Reduction of Acceleration Induced Injuries from Mine Blasts under Infantry Vehicles

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Abstract

Anti tank (AT) mines and improvised explosive devices (IED) pose a serious threat to the occupants of infantry vehicles. The use of an energy absorbing seat in conjunction with vehicle armor plating greatly improves occupant survivability during such an explosion. The dynamic axial crushing of aluminum tubes constitutes the principal energy absorption mechanism to reduce the blast pulse transmitted to the occupant in this investigation. The injury mechanisms of both vehicle-occupant contact interfaces are simulated viz. vehicle seat upon the occupant's torso and vehicle floor upon the occupant's feet. Data such as hip and knee moment, femoral force, and foot acceleration is collected from the numerical dummy which simulates the occupant's response. This data is then compared to injury threshold values from various references to assess survivability.

Keywords:

Energy Absorbing Seat, Mine Blast, LSDYNA, Occupant Protection, Survivability, Foot Impact, Energy Balance Formulation, Axial Crushing

Introduction

During the explosion of an AT (anti tank) mine or IED (improvised explosive device) under an armored vehicle, significant impulse loads are transmitted to the occupant through the vehicle-occupant interfaces such as the floor and seat. If these loads are not attenuated to survivable levels, it normally leads to fatality of the occupant. Armor plating a vehicle is not sufficient to protect the occupant against land mine explosions and thus further protective techniques need to be investigated.

One such concept is an Energy Absorbing Seat Mechanism (EASM) that cushions the occupant against these shock pulses by absorbing the kinetic energy of a mine blast through the elastic and/or plastic deformation of various energy absorbing elements thereby attenuating acceleration pulses transmitted from the vehicle structure to the occupant to survivable levels. There is currently no effective energy absorbing seat mechanism in use in US Army ground combat vehicles.

In 1996, Alem et al. [1] evaluated an energy absorbing truck seat to evaluate its effectiveness in protection against landmine blasts. In 1998, the Night Vision and Electronic Sensors Directorate published a report on Tactical Wheeled Vehicles and Crew Survivability in Landmine Explosions [2]. Concepts that are used in the crashworthiness analysis of aircraft seats are some what similar to those used in crew protection against mine blasts. This is because both events predominantly deal with the attenuation of very large vertical acceleration pulses. In 2002, Kellas [3] designed an energy absorbing seat for an agricultural aircraft using the axial crushing of aluminum tubes as the primary energy absorber, which forms the basis of our simulation.

The first part of this study focuses on the simulation of an EASM subjected to a mine blast. The mine blast is realistically numerically simulated by prescribing acceleration pulses to the structure that imparts the same response to the structure as would an actual land mine explosion directly underneath an infantry vehicle. The human occupant is simulated by a numerical 5^{th} percentile HYBRID III dummy. Data such as head and torso acceleration, and dummy-structure contact forces are collected during the simulation and analyzed for injury assessment. Only the contact interface of the occupant and seat is focused upon in the first part. New concepts to further minimize transmitted pulses are introduced, such as a foam and airbag cushion. The EASM design is then finalized.

Methodology

Energy Absorbing Seat Structure

Axial crushing of cylindrical tubes are a very popular choice as an impact energy absorber because it provides a reasonably constant operating force, has high energy absorption capacity and stroke length per unit mass. Further a tube subjected to axial crushing can ensure that all of its material participates in the absorption of energy by plastic work [9, 10]. The axial crushing can occur in two modes, concertina and diamond. It has been reported that the concertina mode of deformation results in a higher specific energy absorption than the diamond mode of deformation (high D/t ratios, non-axisymmetric) [11].

The EA seat structure with a Hybrid III dummy is displayed in Figure 1. The support structure rigidly supports two cylindrical steel rails inclined at a 20° angle to the vertical. In LS-DYNA, this rigid connection between the support structure and the two ends of the rails is accomplished by using the keyword *CONSTRAINED_NODAL_RIGID_BODY*. A set of upper and lower cylindrical steel brackets which slide along the rails are rigidly attached to the seat in the same manner. A steel collar is rigidly fixed to each rail. The cylindrical aluminum crush tubes are coaxial with the steel rails and are positioned between the upper brackets and collars.

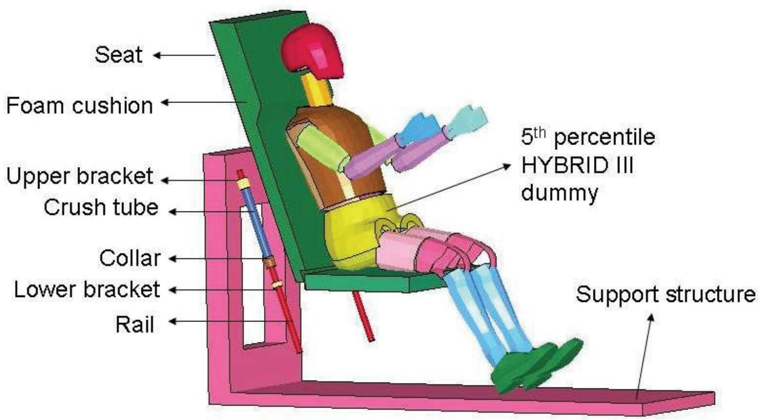

Fig. 1. Energy absorbing seat structure with Hybrid III dummy

Table 1 lists a few geometrical and material properties of the aluminum tubes used in the EA seat structure. Upon impact during a vertical drop test, the upper brackets move downward along with the seat and crush the aluminum tubes against the fixed collar. This constitutes the primary energy absorption principal used in this study. During a mine blast, the collars move upward along with the support structure and crush the aluminum tubes against the upper brackets which are attached to the seat. The occupant is modelled using a 5^{th} percentile HYBRID III dummy. An initial time delay of 50 ms is provided in all simulations to allow for gravity settling of the dummy against the seat which ensures proper contact. In addition to the aluminum crush tubes, further energy absorbing elements are added to the design.

Table 1: Dimensions and properties of the cylindrical aluminium tubes

Inner diameter (Di)	26.437 mm
Outer diameter (Do)	28.215 mm
Mean diameter (D)	27.326 mm
Thickness (t)	0.889 mm
Yield Strength (Y)	145 MPa
Length (L)	228.6 mm
Density (ρ)	2.610E-09 ton/mm^3
Young's modulus of Elasticity	68948.000 N/mm^2
Poisson's ratio	0.33
LS-DYNA Material model	Piecewise Linear Plasticity
Material model number	24

A foam cushion provides additional cushioning to the occupant. The part of the cushion behind the dummy's neck and head is made thicker than the rest of the cushion so as to follow the contour of the rear part of the head and neck. This is seen in Figure 1. This will minimize the head recoil distance before contact with the cushion which will reduce acceleration induced injuries of the head and neck that are characterized by parameters such as Head Injury Criteria (HIC) and Neck Injury Criteria (NIC). More details about HIC and NIC can be obtained from [4] and [27] respectively. The material model used in LS-DYNA for the foam cushion is *MAT_LOW_DENSITY_FOAM* [12]. The material properties are as follows, modulus of elasticity (E) is 0.794 N/mm^2, density (ρ) is 1.22E-7 kg/mm^3, hysteretic unloading factor (Hu) is 0.7, decay constant (β) is 0.0, and tension cut off stress (Tc) is 1 MPa. Figure 2 displays the nominal stress strain plot of the foam material. The attachment of the foam cushion to the seat and specification of contact between them is accomplished using the LS-DYNA keyword *CONTACT_TIED_NODES_TO_SURFACE*.

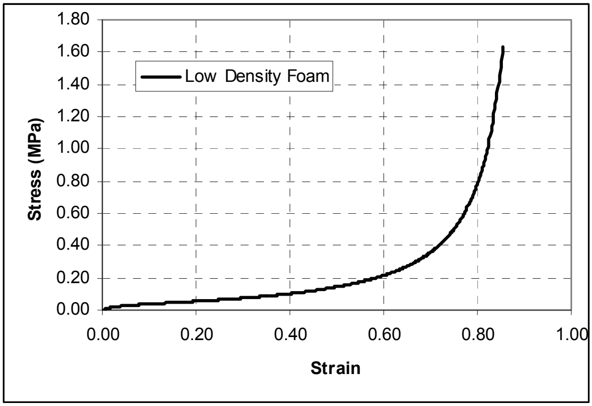

Fig. 2. Nominal stress strain plot of the low density foam used

An airbag cushion whose inflation is controlled by a sensor that triggers at a user defined acceleration level provides additional cushioning, especially during vehicle slam down after a mine blast. The inflation of the airbag is controlled in LS-DYNA using a user defined load curve. The *SIMPLE_AIRBAG* model [12] in LS-DYNA has been used. The initial filled shape of the airbag cushion is identical to the foam cushion.

The application of the real effects of the vertical drop and mine blast tests are through applied pulses that prescribe structural accelerations in LS-DYNA. This is accomplished using the LS-DYNA keywords *DEFINE_CURVE* to specify the prescribed acceleration history and *BOUNDARY_PRESCRIBED_MOTION* to apply the pulse to the support structure. Figure 3(a) displays the deceleration pulse that represents vertical impact after freefall, based on data from [3]. Figure 3(b) displays the acceleration pulse that represents a mine blast under an armored vehicle. Both pulses act along the vertical direction. The mine blast pulse includes a peak acceleration of 180 G for a duration of 5 ms. This is followed by a 85 ms duration of negative acceleration to put the final velocity at zero and final displacement at its maximum vertical position. After that the acceleration stabilizes at -1 G (freefall) until the displacement is zero [13].

A series of vertical drop test simulations are run using LS-DYNA. Numerical data such as seat and torso accelerations are compared to experimental data from [3]. Once the finite element model is validated, a series of mine blast simulations are run using LS-DYNA. Occupant data such as head and neck accelerations, neck flexion-extension moments, seat and torso accelerations, are collected and examined to assess occupant injury and survivability.

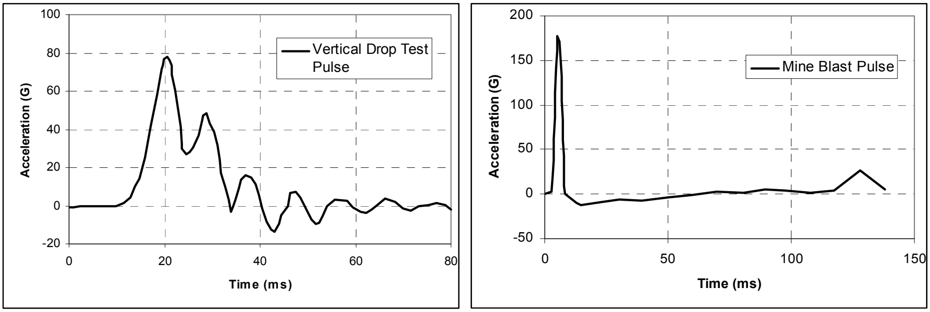

Fig. 3. Applied pulse simulating (a) impact after free fall (b) mine blast under armored vehicle

Numerical Results and Discussion

Numerical results from the Energy Absorbing Seat simulations have been compared with experimental observations and data from [3]. The results from our simulations are in very good agreement with the experimental data as can be seen from Figure 4.

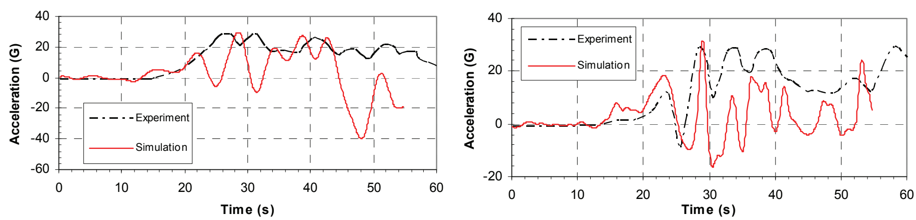

Fig. 4. Comparison of experimental and simulation results (a) seat pulse (b) occupant pulse

It is important to note the scarcity of further available experimental data for such vertical drop testing of energy absorbing seats with a dummy occupant. Numerous simulations were run using both the seat foam cushion and airbag cushion designs. It was found that both designs proved equally effective in reducing the maximum load transmitted to the occupant. However the foam cushion design proves to be more economically viable. The crushing of the aluminum tubes proved effective in reducing the maximum acceleration pulse transmitted to the occupant. However, the compressive lumbar load also needs to be considered. The peak dynamic crushing load of the aluminum tubes is much larger than the maximum allowable compressive lumbar load. Without a device to limit this compressive load, the lumbar column will get crushed before the aluminum tubes begin to crush leading to instant fatality. This is where the foam cushion and airbag cushion designs play an important role by reducing the vertical contact force between the occupant and seat system, thereby reducing the compressive lumbar load, supporting the head and neck, and generally providing additional cushioning and comfort to the occupant. Large amounts of data have been extracted from the numerical dummy during the simulations, however only the most significant data have been graphically presented due to space limitations.

Mine Blast Tests with the EA Seat and HYBRID III Dummy

The peak deceleration pulse has been attenuated from 171 G to 11 G at the lower torso, as displayed in Figure 5. According to [4] the vertical acceleration of the lower pelvis over a 7 ms interval must not exceed 23 G. The peak dynamic crushing force of both aluminum tubes is 14640 N. However the compressive lumbar load experienced by the dummy is just 3160 N which is well below the lumbar load criterion. The compressive femur force is 11434 N which is above the maximum allowable limit of 10000 N at any instant.

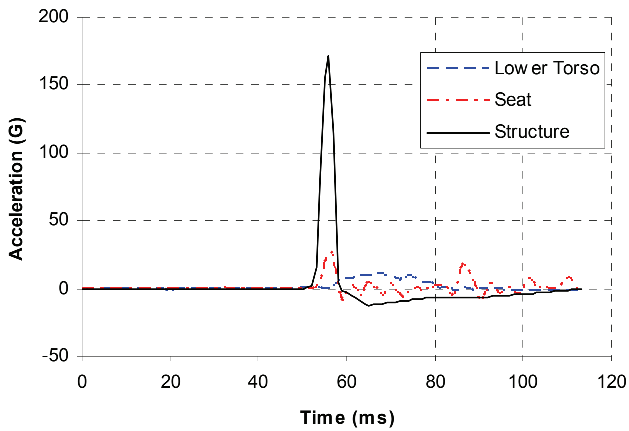

Fig. 5. Mine blast test simulation results: acceleration

Lower Leg Impact with HYBRID III Dummy

The data from the numerical simulations are compared against experimental data from [16]. It is important to note the scarcity of available data due to limited research conducted, especially on human cadavers, and the classified nature of such work. Data such as foot acceleration and tibia axial compressive force have injury criteria [2, 4, 5, 7, 17] associated with them and are therefore used for validation. Figure 6 compares the tibia axial compressive force between our numerical simulation and test *db3* from [16]. Figure 7 compares the foot acceleration. As can be seen, the data from our numerical simulations is in very good agreement with the experimental data.

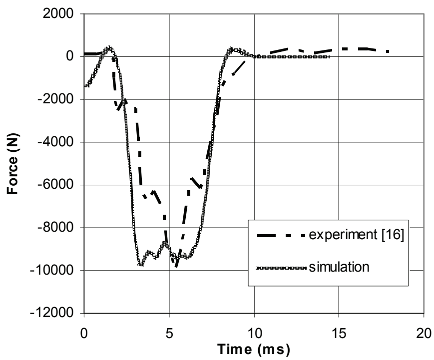

Fig. 6. Validation of tibia axial compressive force with test db3a

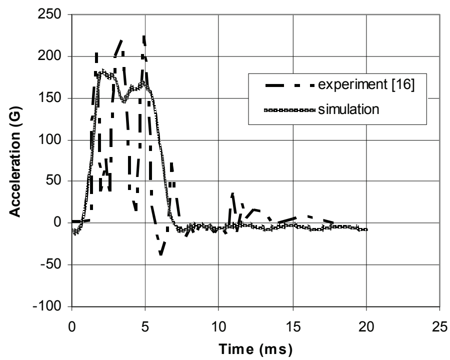

Fig. 7. Validation of foot acceleration with test db3a

Data such as knee, hip and ankle moments do not have associated injury criteria yet and further research needs to be conducted into this. This data has still been investigated in our study as it is important and can serve as a reference in the future. Figure 8 displays the hip and knee moments in the driving position for varying peak wall speeds where the knee flexion angle is 55 degrees, compared to the sitting straight case where it is 90 degrees.

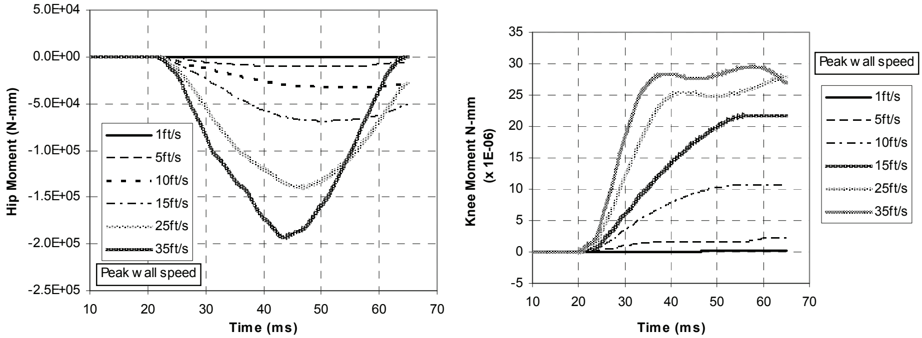

Fig. 8. Driving position data (a) Hip moment (b) Knee flexion-extension moment

Figure 9 displays the effect of an initial gap between the feet and the floor. A 3 mm gap leads to a peak acceleration magnitude of 383 G and a 5 mm gap leads to 590 G. This widely differs from the case with no gap present where the peak is at 199 G. To ensure proper contact between the feet and floor in the simulations, an initial gravity settling period is included. The tibia axial compressive force is far higher in the case of sitting straight position than the driving position. In the former case the entire compressive load is directly transmitted to the tibia bone since its axis is parallel to the direction of the applied load. In the latter case the tibia is inclined at an angle to the direction of the applied load and only a smaller component of the load is transferred to the tibia via the ankle joint. A trend can be observed in the plots of the compressive axial tibia load versus the angle of inclination with the floor.

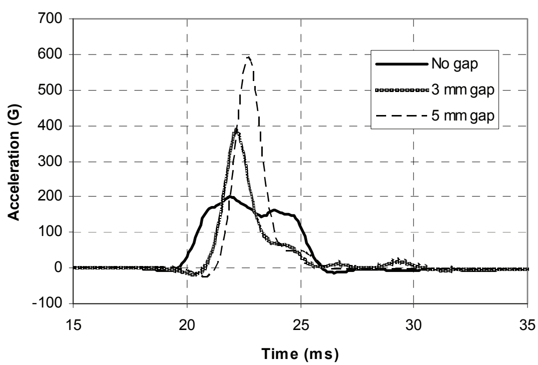

Fig. 9. Effect of initial gap between the feet and floor

The ankle moments are significantly higher for the upper range of wall impact speeds in the driving position, compare to the sitting straight position where the complete lower surface of the foot maintains its flat contact with the wall throughout the simulation leading to negligible ankle moments. Thus occupant position plays an important role in the magnitude of loads transmitted and injury severity. Further data extracted such as hip, knee and ankle moments can therefore be used now for accurate injury assessment. It has been reported in automobile crash testing that the HYBRID III legs are too stiff which may lead to an underestimation of injury. The accuracy of results can be optimized by using more advanced dummies that better model the human body such as the Thor-Lx and Hybrid Denton leg [5, 16]. However our simulations have demonstrated the use of the HYBRID III dummy for occupant safety assessment during a mine blast application with satisfactory results. There is a scarcity of available data pertaining to lower leg impact during a mine blast under infantry vehicles and extensive research needs to be conducted, especially testing on human cadavers in order to better understand the injury assessment and establish a reliable and extensive source of data. Further, new injury criteria for the foot need to be developed.

Conclusions

The presented energy absorbing seat design proves to be effective in occupant survivability during vertical drop and mine blast scenarios. Numerical simulations of the energy absorbing seat subject to vertical drop tests and mine blast tests with a dummy occupant prove to be reliable and a far less expensive alternative to conducting destructive tests. From the numerical results of the simulations, it is evident that the crushing of aluminum tubes provides a controlled, acceptable means of attenuating deceleration pulses to survivable values. The use of a contoured foam cushion helps in additionally attenuating the peak deceleration pulse at the occupant's lower torso, and the compressive lumbar load. The contoured headrest ensures a minimal gap between the head and seat thereby minimizing head rearward accelerations. In a future study, the authors will examine the feasibility of using a honeycomb structure as an efficient energy absorbing member.

The use of the HYBRID III dummy for occupant simulation during mine blast testing has been satisfactorily validated, after comparison of foot acceleration and tibia axial compressive load, with experimental data. The transmitted compressive tibia loads are much higher in the case where the tibia bone is perpendicular to the floor, compared to the inclined position.

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