EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF HUMAN INJURY PREDICTION SUBJECTED TO UNDERBELLY BLAST LOADING

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ABSTRACT

One of the lethal threats faced by an armoured vehicle comes from the explosion of a land mine. The blast wave from the explosion propagates to the vehicle structure, floor, seats and eventually to the occupants inside the vehicle. If the blast waves are not dissipated properly, it could bring harm to the occupants. In this study, the occupant response during mine blast was investigated using experimental test and numerical simulation. A mine blast capsule was fabricated and an instrumented dummy was utilized for the experiment. The numerical simulation was developed using LS-DYNA software. The finite element model was also optimized using LS-OPT so that comparable results from the experiment can be produced by the simulation. Next, the simulation was validated using CORA rating tools. CORA software rates the comparison of simulation and experimental results and produces rating numbers that indicate the feasibility of the simulation. The total CORA rating of the simulation yields a value of 0.577, which means that the simulation model is able to produce realistic results based on CORA analysis. After the validation process, LS-OPT were utilized once again to develop the meta-model of the injury probability against the mine charge weight. Three injury probability curves against charge weight were produced. The three curves were the head, DRI and tibia injury probability. The average mean absolute percentage error of the three curves produces a value of 30.71% error. The error value produces are common in mine blast field which indicates that more research needs to be done to improve its situation. Nonetheless, the meta-model produced is capable of simplifying the relationship between the injury probability against the land mine charge weights.

ABSTRAK

Di antara ancaman berbahaya terhadap kenderaan berperisai adalah dari letupan periuk api. Gelombang dari letupan periuk api tersebut akan tersebar merentasi struktur kenderaan, lantai, kerusi dan akhirnya ke penumpang dalam kenderaan tersebut. Jika gelombang ini tidak dibias dengan betul, ia boleh menyebabkan kecederaan atau kematian kepada penumpang. Di dalam kajian ini, tindak balas penumpang terhadap letupan di kaji dengan menggunakan kaedah eksperimen dan simulasi berangka. Di dalam kaedah eksperimen, satu kapsul letupan telah di fabrikasi dan di muatkan dengan satu patung ujian berperanti. Tindak balas penumpang juga di kaji dengan menggunakan kaedah simulasi berangka. Simulasi tersebut telah dibangunkan dengan menggunakan perisian LS-DYNA. Kemudian, simulasi tersebut telah di optimumkan dengan menggunakan LS-OPT. Model simulasi tersebut kemudiannya di sahkan dengan menggunakan perisian penarafan CORA. Penarafan CORA ini dilakukan dengan membezakan keputusan eksperimen dengan simulasi yang kemudiannya menghasilkan tahap yang menunjukkan skor kelayakan simulasi tersebut. Simulasi tersebut telah menghasilkan skor berjumlah 0.577 yang menunjukkan simulasi tersebut mampu menghasilkan keputusan yang realistik. Selepas disahkan, simulasi tersebut digunakan di dalam LS-OPT untuk membangunkan meta-model bagi kebarangkalian kecederaan terhadap berat caj bahan letupan periuk api. Tiga graf lengkungan kecederaan dihasilkan daripada meta-model tersebut. Tiga graf lengkungan tersebut adalah, kebarangkalian kecederaan bagi kepala, DRI dan tibia. Peratusan purata ralat mutlak yang dihasilkan oleh ketiga-tiga graf tersebut adalah sebanyak 30.71%. Nilai peratusan ini adalah aras nilai yang kebiasaan dalam bidang ini, ianya menunjukkan lebih banyak kajian yang perlu dilakukan untuk memperbaiki situasi ini. Walau bagaimanapun, meta-model yang dibangukan mampu memudahkan ramalan terhadap kebarangkalian kecederaan akibat berat letupan periuk api.

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APPROVAL

The Examination Committee has met on 21st August 2019 to conduct the final examination of Khalis Suhaimi on his degree thesis entitled 'Experimental and Finite Element Analysis of Human Injury Prediction Subjected to Underbelly Blast Loading'.

The committee recommends that the student be awarded the Doctor of Philosophy (Mechanical Engineering).

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NOMENCLATURES

ρ	Density
3D	Three-dimensional
AFIS	Ankle and Foot Injury Scale
AIS	Abbreviated Injury Scale
APC	Armoured Personnel Carrier
AT	Anti-tank
ATD	Anthropometric Test Device
AV	Armoured vehicle
CAD	Computer Aided Design
cm	Centimeter
CPU	Central Processing Unit
DAQ	Data Acquisition
DOF	Degree Of Freedom
DRI	Dynamic Response Index
FE	Finite Element
FMVSS	Federal Motor Vehicle Safety and Standards
GPa	Giga Pascal
HIC	Head Injury Criteria
ICP	Integrated Circuit Piezoelectric
IED	Improvised explosive devices
JWL	Jones Wilkins Lee
K	Kelvin
kg	Kilogram

kPa	Kilo Pascal
LBE	Load Blast Enhanced
m	Meter
m/s	Meter per Second
mm	Millimeter
MM-ALE	Multi Material Arbitrary Lagangrian-Eularian
MPa	Mega Pascal
NATO	North Atlantic Treaty Organization
NHTSA	National Highway Traffic Safety Administration
NIC	Neck Injury Criterion
PE4	Plastic Explosive No.4
PMHS	Post Mortem Human Specimen
RS	Roadside
s	Seconds
t	Time
TCC	Thoracic Compression Criterion
TD	Test Dummy
TNT	Trinitrotoluene
UB	Underbelly
VC	Viscous Criterion

CHAPTER 1

INTRODUCTION

1.1 Background

Anti-tank (AT) and improvised explosive devices (IED) create severe threats to an armoured vehicle. A typical Anti-Tank mine contains 9.0 kg of high grade military explosive. The explosion generates impulse which yields an impact on the vehicle suspension and is then transferred through the suspension and the vehicle's body structures. The impulse loads are then transmitted to the occupants through vehicle-occupant contact interfaces such as the floor and seat. If the propagated shock loads and accelerations are not dissipated below the threshold limits of the occupant injury criteria, it may result in severe injury or even fatality to the crew of the vehicle (Nilakantan and Tabiei, 2009). Modern land mines with shaped charges are capable of producing impacts which can even penetrate 150 mm of armoured plate (Sliwinski, 2011). Conflicts in Iraq and Afghanistan show that AT mines and IEDs as one of the greatest source of threats to military and local security personnel (Camacho and Ortiz, 1996). Military operations in hostile areas result in the use different types of land vehicles. Fighting, armoured personnel carriers and mine clearing vehicles are examples of vehicles deployed in such missions. These vehicles are often deployed on tasks such as military combat support operations, patrol missions, convoys, mine-clearing and transport missions.

In Malaysia, there are several models of wheeled armoured vehicles which are used for training and military operations. For example, the Condor 4x4 Armoured Personnel Carrier, SIBMAS 6x6 Armoured Support Fighting Vehicle and the latest addition to the fleet, the AV8 Gempita and AV4 Lipan Bara as shown in Figure 1.1. The AV8 Gempita is an 8x8 wheeled armoured vehicle equipped with a composite aluminium hull and steel armour for protection against small arms fire. During the deployment of these armoured vehicles, the vehicles are driven on roads and also off roads in which the vehicles would face high possibility to encounter individual mines or IEDs (roads) and minefield sectors (in off-road setting) laid by the opposition. Based on this circumstance, in order to provide safety and ergonomical transport conditions for the military personnel, such vehicles are now required to have a high resistance towards mine and IED threats. Particularly, protection from the detonation of IEDs directly beneath the armoured vehicle where studies reveal that the critical acceleration towards the vehicle floor and seats causes severe damage to the occupant's legs, feet, head and spine (Ramasamy *et al.*, 2008). The impulse from a mine blast could throw the passengers from their seated positions and this may cause further serious injury to the passenger. The utmost challenge in evaluating a vehicle's underbelly mine blast effects is not only the structural behaviour of the vehicle but also the occupant's response and possible injuries sustained as a result of the blast impulse (Hryciów, 2012). Altogether, the vehicle's design should be detailed on every aspect of the vehicle hull construction, suspension systems, seat construction, and seating arrangement in the crews' compartment inside the vehicle and be linked together with the vehicle abilities to operate on and off the road.

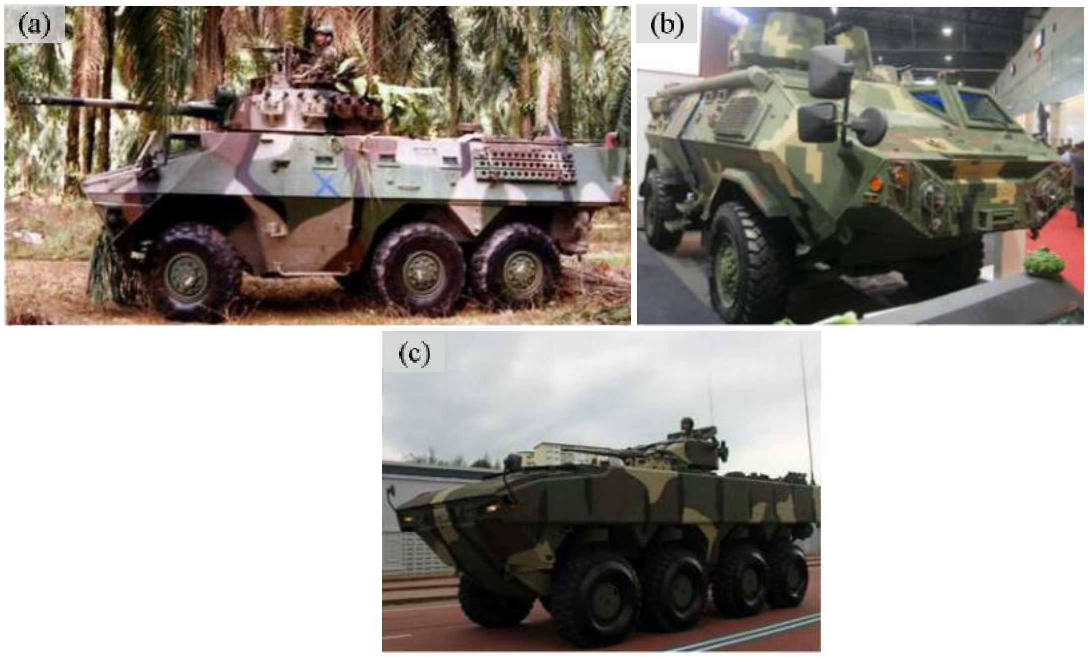

Figure 1.1: Type of armoured vehicles (a) 6x6 SIBMAS (Kanavakis (Kanavakis *et al*., 2009). (b) 4x4 Condor (Abas, 2017). (c) AV8 Gempita (Kanavakis, *et al.*, 2016).

The STANAG 4569 AEP 55 standard by NATO sets the level of protection for armoured vehicles. There are four levels of the protection described based on the mine's explosive charge weight in which Level 2, 3 and 4 corresponds to 6 kg, 8 kg and 10 kg of charge mass respectively. Figure 1.2 shows an example of anti-tank mine that commonly falls into the category of STANAG level 4 threat category. Whereas STANAG Level 1, protection only corresponds to blast of hand grenades, artillery fragmenting sub-munitions and small anti- personnel devices. STANAG Level 2, 3, and 4 are then further divided into two categories as shown in Table 1.1. While Table 1.2 depicts the pass fail reference value of the mine blast test.

Figure 1.2: Examples of an Anti-tank mine (Barry, 2017).

Table 1.1: Protection levels for occupants of armoured vehicles for grenade and blast mine threats, STANAG 4569 (NATO, 2011).

Level		**Grenade and Blast Mine threat**	
4	**4b**	Mine Explosion under belly	10 kg (explosive mass) Blast AT Mine
	4a	Mine Explosion pressure activated under any wheel or track location	
3	**3b**	Mine Explosion under belly	8 kg (explosive mass) Blast AT Mine
	3a	Mine Explosion pressure activated under any wheel or track location	
2	**2b**	Mine Explosion under belly	6 kg (explosive mass) Blast AT Mine
	2a	Mine Explosion pressure activated under any wheel or track location	
1	Hand grenades, unexploded artillery fragmenting sub-munitions, and other small anti-personnel explosive devices detonated anywhere under the vehicle		0.5 to 1 kg(explosive mass)