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EXPERIMENTAL AND NUMERICAL MODELLING OF A MANNEQUIN FOR THE ASSESSMENT OF BLAST INCAPACITATION AND LETHALITY UNDER BLAST LOADING

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There are multiple test methodologies currently in use to assess the performance of current and novel protective equipment and to investigate the thoracic injuries caused by blast overpressure. Among these methodologies, there is the Mannequin for the Assessment of Blast Incapacitation and Lethality (MABIL), an instrumented human upper body surrogate that can be used to assess the performance of personal protective equipment. The primary objective of this study was to develop and validate a simplified finite element model of MABIL for the purpose of investigating and predicting response to blast overpressure. The numerical model consists of a simplified three-dimensional slice of the MABIL mannequin, taken at the mid-sternum level, and subject to different blast. Experimental data captured during field trials were used to validate the numerical model. In general, the numerical chest wall acceleration and velocity were higher than the experimental ones. However, the ratio between the numerical and the experimental chest wall velocity was the same across the range of blast loads studied.

INTRODUCTION

Since World War I, primary blast injuries have been recognized as the most significant reported injury to the lungs [Ref. 1]. A simple definition of blast is an atmospheric overpressure wave, usually created by an explosive detonation, travelling in air at supersonic velocity. Blast waves are usually characterised by the peak overpressure and the positive pressure duration. Air containing organs such as the lungs, the auditory system, and the gastro-intestinal tract are the most susceptible to injuries induced by blast overpressure.

There are multiple test methods currently in use to assess the qualitative and quantitative performance of novel protective equipment against blast weapons. Each of these methods has its advantages and disadvantages. The surrogate used in the current study is the DRDC Mannequin of Assessment of Blast Incapacitation and Lethality (MABIL), which is being developed to assess primary blast injuries to the torso and head as well as burns [Ref. 2].

DRDC MANNEQUIN OF THE ASSESSMENT OF BLAST INCAPACITATION AND LETHALITY (DRDC MABIL)

The DRDC MABIL is a human surrogate that was designed to assess primary blast injuries and burns. The model incorporates an instrumented responding torso membrane and an instrumented head. The torso is instrumented with two single axis accelerometers. One accelerometer is located at the mid-sternum and the other is at the level of the belly button in the centre of the abdomen. In the experiments referenced in this article, the DRDC MABIL torso was placed facing the charge with the thelion (nipple) 1.27 m from the ground to represent a standing 50th percentile soldier. Figure 1 shows the complete DRDC MABIL mannequin prototype and its support.

A requirement for the DRDC MABIL was to have an external shape representative of the human body to ensure proper fit with personal protection equipment (e.g. a fragmentation vest). The anthropometry of the model is based on 1988 US Army anthropometric database [Ref. 2]. Overall, the MABIL model is considered approximately representative of the 50th percentile Canadian forces soldier.

Blast injuries are classified as primary, secondary, tertiary, and quaternary [Ref. 2]. Primary blast injuries are caused by the direct interaction between the blast wave and the body. Secondary injuries include those caused by environmental debris propelled by the blast and/or fragments from the warhead. Tertiary injuries are those injuries due to displacement of the body such as skull fracture caused by head impact on the ground. Finally, quaternary blast injuries include burns and injuries caused by detonation products and toxicity.

The current prototype of the DRDC MABIL torso surrogate membrane is made from Shore A 70 (PU70) polyurethane. This visco-elastic material has been used in the past to represent the behaviour of the human thorax under dynamic loading caused by behind armour blunt trauma [Ref. 3].

Figure 1. DRDC MABIL surrogate with its support

DRDC MABIL FE MODEL

The numerical model of the DRDC MABIL represents a quasi two-dimensional slice of the membrane as shown in Fig. 2. This simplified representation of the torso membrane was used in order to keep the computational times reasonable. The slice, 1.4 cm thick, is situated approximately at the mid-sternum of the torso where the accelerometer is located in the experimental rig.

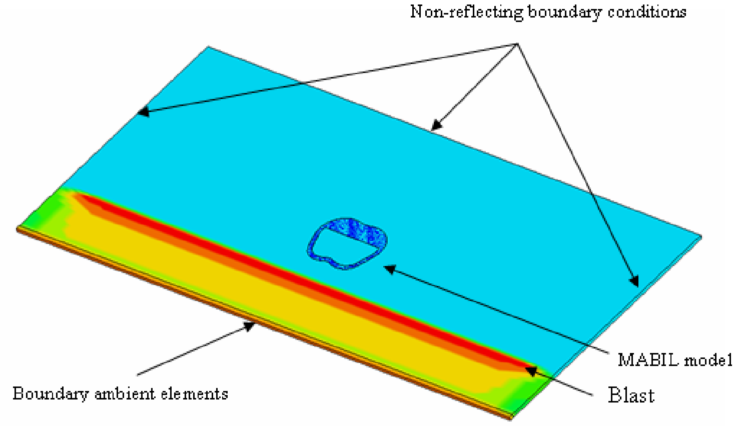

Figure 2. DRDC MABIL finite element model

The model is composed of 436 hexagonal solid elements with an average dimension of 4.5 mm. As shown in Fig. 2, the DRDC MABIL front chest wall is thinner than the back. This geometry has been designed to approximate the rigidity of the spine while modelling the dynamic response of the chest wall.

The LS-DYNA constitutive model used to simulate the behaviour of the PU 70 was *MAT_QUASILINEAR_VISCOELASTIC. This material model represents a quasi-linear isotropic viscoelastic material and was introduced by Fung in 1993 [Ref. 5]. The model is often used to represent viscous biological materials and soft tissues such as brain, skin, kidney, and spleen. Only common quasi-static mechanical properties (density and hardness) of the PU70 were provided by the supplier [Ref. 4]. The high strain rate experimental tests performed by Doman [Ref. 6] on the PU 70 were used to define the other material properties used throughout the numerical study.

Experimental and numerical loading conditions

In the experiments that have been conducted using the DRDC MABIL, the surrogate was placed at different distances from bare explosive charges in order to reproduce loading conditions that are associated with varying probabilities of lung primary blast injury. The blast was usually produced by a 5 kg C4 charge suspended at a 1.5 m height of burst with the mannequins located between 2 m to 5 m from the charges. Several lollipop pressure transducers and pitot tubes were used to record the static and the dynamic blast overpressure histories.

The current study was performed using an Arbitrary Lagrange Eulerian (ALE) formulation to capture the interaction of the blast overpressure in the air and the DRDC MABIL membrane. The blast loading is modeled as a material flowing through a fixed finite element mesh (Eularian representation) while the DRDC MABIL was modeled using a Lagrangian approach where the elements are deformable. The two models were coupled using a penalty-based method, with the interaction force between the fluid/solid interface determined by the distance of separation and the contacting material properties [Ref. 5]. The blast was created by inducing a time-pressure dynamic curve in the boundary ambient elements. Applying a pressure history to a series of ambient elements along the boundary of the Eularian mesh results in a more or less planar blast wave propagating through the mesh towards the DRDC MABIL model at supersonic speed as shown in Fig. 2. The complete numerical model contains approximately 150,000 nodes and 100,000 elements.

Scenarios considered during the numerical simulations

Three experimental scenarios were reproduced in order to compare the response of the numerical model of the DRDC MABIL with experimental measurements. These three configurations correspond to the DRDC MABIL placed at 2, 2.5, and 3.5 m from a 5 kg C4 explosive charge. Figure 3 shows a comparison between the measured blast overpressure histories and the loading replicated in the numerical model. The height of burst used in the experimental results in the shock wave being reflected from the ground, which in turn creates a complex blast wave with two peaks. Even if these experimental blasts cannot be considered to be ideal Frielander waves it is possible to use the peak overpressure and an estimate of the positive phase duration to obtain a rough estimate of the expected lethality using the Bowen curves [Ref. 7]. Based on these curves, the pressure histories from the 2, 2.5, and 3 m tests correspond approximately to 50% survivability (LD50), 99% survivability (LD1) and threshold lung injury (LTH).

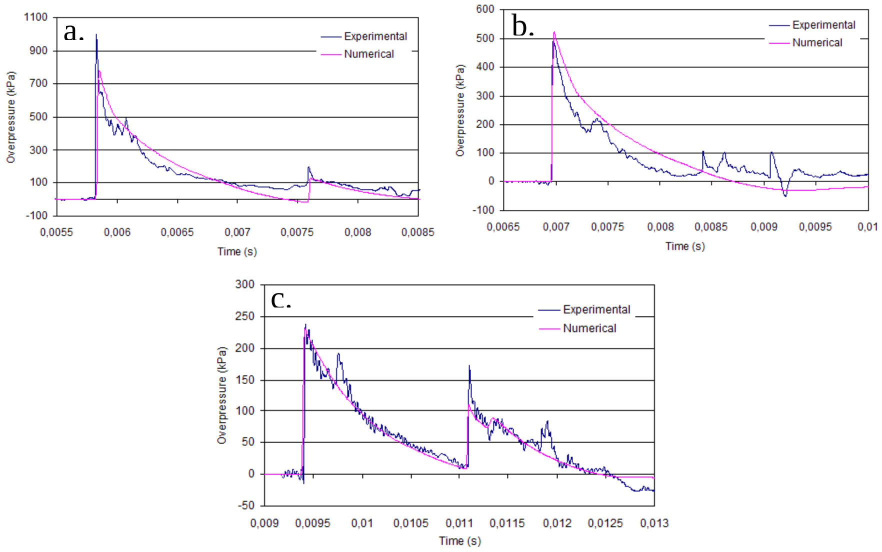

Figure 3. Experimental and numerical blast overpressure curves for 5 kg C4 at 2 m (a), 2.5 m (b) and 3.5 m (c).

NUMERICAL RESULTS

Validation the FE model with the experimental data

The comparison of the experimental and numerical results for the DRDC MABIL response to blast loading was based on the mid-sternum acceleration and velocity. The acceleration signal was computed numerically at an equivalent 200 kHz sampling rate and filtered with a 40 kHz cut-off frequency, which is the same as the anti-aliasing filter applied to the experimental signals. The velocity and displacement were then computed from these acceleration histories. In general, the experimental and numerical MABIL mid-sternum acceleration histories for the three selected scenarios (2, 2.5 and 3.5 m) were the same. Figures 4 and 5 show a comparison between the experimental and the numerical results for the maximum mid-sternum wall acceleration and velocity, respectively. In general, the predicted peak acceleration and velocity of the FE MABIL model were higher than those measured experimentally. However, the ratio between the mid-sternum wall experimental and numerical acceleration and velocity remains reasonably constant across the range of loading investigated.

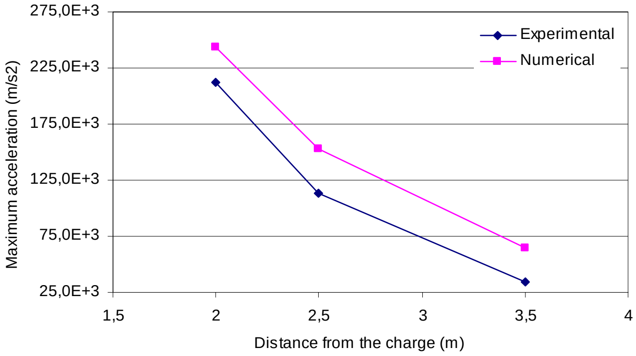

Figure 4. The experimental and the numerical MABIL maximum mid-sternum wall acceleration.

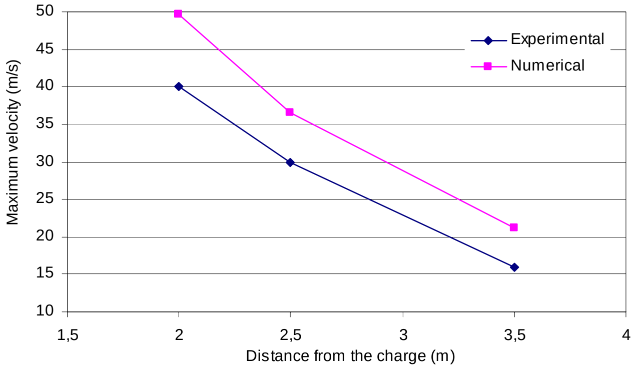

Figure 5. The experimental and the numerical MABIL maximum mid-sternum wall velocity.

New blast loading

A parametric study was performed to predict MABIL responses to different blast intensities. Loading curves that represented lung threshold (LTH), 1% (LD1) and 50% (LD50) probability of lethality, based on the Bowen curves [Ref. 7], for durations equal to 1 ms and 5 ms were selected. The two parameters that typically describe a Frielander curve, the peak overpressure and duration, are listed in Table 1.

Table 2 shows the MABIL numerical results for short (1 ms) and longer (5 ms) duration Frielander type blast overpressure histories. Based on the Bowen curves, the level of injury for the 1 ms and 5 ms durations should be the same for each of the lung threshold (LTH), LD1 and LD50 cases. However, the mid-sternum acceleration and mid-sternum velocity are not the same for the same level of injury.

Table 1: The numerical test matrix

Bowen injury level	1 ms	5 ms
Lung Threshold (LTH)	210 kPa	130 kPa
1% Lung damage (LD1)	560 kPa	350 kPa
50% lung damage (LD50)	770 kPa	500 kPa

Table 2: Blast duration response

	Short blast duration		Long blast duration	
Blast	Acceleration (m/s^2)	Velocity (m/s)	Acceleration (m/s^2)	Velocity (m/s)
TH	56000	10	32000	17
LD1	152000	28	105000	44
LD50	239000	35	158000	56

In all the injury levels (LTH, LD1 and LD50), the maximum mid-sternum acceleration is higher for blasts with short duration than for the longer duration loading histories. In experimental tests performed by Cooper on pigs [Ref. 8], the lung injury was found to be proportional to the peak acceleration of the lateral thoracic wall. Using the data from Table 2 and the Cooper results, blast with short duration will induce more injuries than a one with long duration.

To predict non-auditory blast injury from complex waves, Axelsson et al [Ref. 9] use their own experimental data to correlate values from a mathematical model. In this mathematical model, the Adjusted Severity of Injury Index (ASII) is proportional to the model chest wall velocity. Applying the Axelsson conclusions to the numerical results (Table 2), blasts with long duration will induce more injuries than blasts with short duration. From these two conclusions, which are contradictory, it is difficult to state which one is correct. Chest wall acceleration, velocity and blast impulse are used currently to design protection systems. More experimental and theoretical studies have to be done in order to find the right injury predictor to be used during design process.

CONCLUSION

The aim of the present study was to validate the mechanical response of the MABIL FE model, subjected to different blast loadings, using experimental results from the DRDC MABIL membrane. The comparison was based on the maximum mid-sternum acceleration, and maximum velocity. Even if the numerical results were different from the experimental ones, the ratio between the experimental and the numerical results for the different blast scenarios was constant suggesting that the constitutive model used under predicts the stiffness of the polyurethane used to construct the surrogate. Frielander type blast overpressure histories that represent a lung threshold injury, 1%, and 50% probabilities of lethality for both short (1 ms) and long (5 ms) durations were used to perform a parametric study on the FE model. Through the numerical simulations, some contradictions were found for the same level of injury on the Bowen curves. In fact, blast with a short duration generated higher mid-sternum acceleration than a blast with long duration, even though the Bowen curves would suggest that the injuries should be similar. On the other hand, blast with a long duration induced higher mid-sternum velocity than blast than those with a short duration. These two contradictory conclusions illustrate the need to more experimental and theoretical studies.

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