Investigation of Lung Response Resulting from Behind Armour Blunt Trauma Impact Scenarios

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I. INTRODUCTION

Blunt trauma may result from the dynamic deformation of personal protective body armour into the thorax following a high energy projectile impact, where the maximum deformation is known as the Back Face Signature (BFS) [1]. Dynamic armour deformation can result in rapid focal loading to the thorax and potential damage to the internal organs and thoracic cage [2]. Animal [3] and post-mortem human subject tests [4] have identified injuries including pulmonary contusion, rib fracture and sternum fracture. A common test method to evaluate armour uses a conditioned clay backing to measure the BFS, with an acceptance value of 44mm for soft (layered ballistic fabric) body armour also known as a bullet resistant vest. Hard body armour, comprising a ballistic plate (ceramic with a laminated composite backing), is worn in conjunction with a bullet resistant vest. Some jurisdictions use a value of 44mm BFS [5], while others use smaller values (e.g. 25mm in the UK) [1]. The severity of loading and potential for injury depends on the projectile and amour, as well as materials that may provide stand-off between the armour and wearer (e.g. clothing) [6], and the incorporation of energy absorbing foam layers. The strong dependence on the impact conditions and variability in the tests make experimental determination of BABT effects challenging. BABT impacts occur over a small contact area with initial velocities in the order of 50 to 150 m/s and impact durations in the order of 1-2ms [1,2,3,6,7]. However, it has been noted that the impact conditions can vary greatly depending on armour standoff from the wearer or the inclusion layers of fabric [6] or foam between the armour and wearer. BABT impact velocity has been found to decrease exponentially up to the maximum deformation, known as the back face signature (BFS) of the armour [8]. The aim of this study was to investigate lung response for varying BFS using finite element thorax models and representative armour loading.

II. METHODS

Two previously developed thorax models were used in this study, including a three-dimensional torso model (3DTM) (Fig. 1) developed for automotive and blunt impact [9], and a transverse plane model (TPM) (Fig. 2) developed for blast response and injury prediction [10]. Mesh refinement and convergence has been investigated for the 3DTM (300,000 elements, 0.16 µs time step) [11] for high velocity impact and the TPM (100,000 elements, 0.28 µs time step) [10] for blast loading. The 3DTM in this study was a refined version of the model developed by Yuen [11] to address the focal nature of the BABT impact and was previously shown to predict sternum fracture for BABT impacts [12].

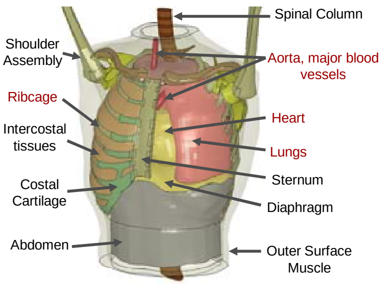

Fig. 1: 3D Torso Model (3DTM)

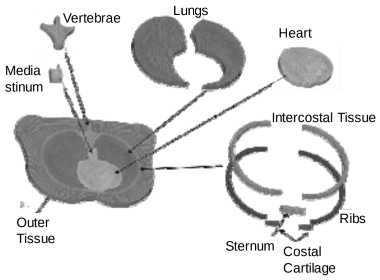

Fig. 2: Tranverse Plane Model (TPM)

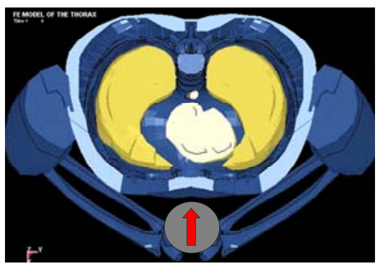

Fig. 3: Simplified BABT impact

BABT impact scenarios were investigated using a spherical impactor with boundary conditions applied to reproduce BABT (e.g 50 mm spherical impactor, 40 mm maximum deformation, 1.4 ms duration) (Fig. 3) determined from experimental studies and reported in [12]. The spherical impactor was located on the sagittal plane, impacting the anterior of the thorax at the fourth rib. The potential for lung injury was determined using

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the maximum dynamic pressure predicted in the lung tissue [10,11]. Previous studies have shown that there is a high risk of developing acute respiratory distress syndrome (ARDS) when the lung contusion cumulative volume exceeds 18-24% [10,11,13,14]

III. INITIAL FINDINGS

The models predicted increasing impact force for increasing impact severity, with significant deformation to the lungs and heart during the impact. In general, the predicted BABT force and force required to fracture the sternum was in good agreement with published values for post-mortem human subject tests [4,12].

Lung response was measured using a dynamic pressure criterion proposed by [10] and [11]. The volume of lung tissue exceeding the criterion was calculated for the BABT impact conditions. The predicted lung contusion volumes (Fig. 4) demonstrated a dependence on both BABT impact diameter and BFS. There was no significant injury predicted for a 20mm BFS, while significant levels of contusion were identified for larger BFS. The predicted contusion levels increased with increasing BFS (Fig. 6). The TPM predicted the same trends as the 3DTM model, but generally predicted higher values of lung contusion, owing to the planar assumption of the model. The exception was the 3DTM and the 50mm diameter impactor, where sternum fracture occurred for the larger BFS leading to an increased level of lung contusion.

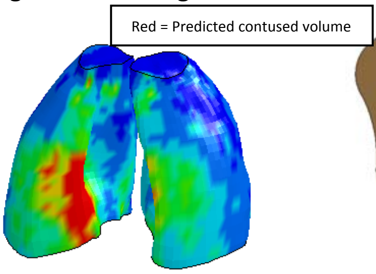

Fig. 4: 3DTM lung response

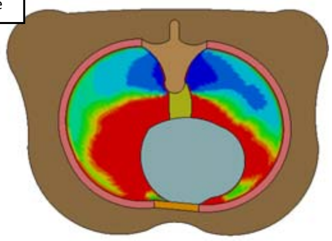

Fig. 5: TPM lung response

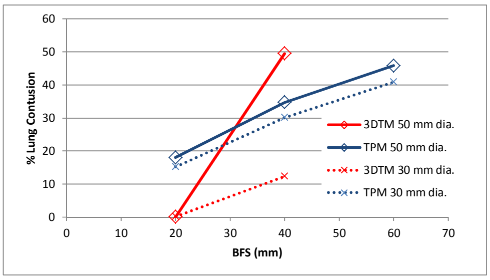

Fig. 6: Predicted lung response

IV. DISCUSSION

Both the TPM and 3DTM predicted localized transient response at the impact location; however, it was noted that the amount and extent of deformation depended on the impactor diameter (e.g. 30mm versus 50mm). The potential for lung contusion was predicted using a dynamic (transient) pressure criterion. Although other metrics have been proposed in the literature (e.g. various measures of strain, stress), the dynamic pressure criterion has been found to provide predictions across a range of loading rates, including automotive and blast [10], that are consistent with experimental test data. The volume of lung contusion, expressed as a percent of the total lung volume, increased with increasing BFS (Fig. 6) and was larger for the larger diameter impactor. The 3DTM and TPM trends differed for the 50mm diameter impactor and 40 mm BFS (Fig 6) due to fracture of the sternum, resulting in increased load transmission to the lungs and a larger predicted contusion volume. Aggressive BABT loading (e.g. 60mm BFS) often resulted in early termination of the 3DTM due to excessive local deformation of the thorax; however, in the 50 mm diameter case the predicted lung contusion level had already exceeded levels expected to result in ARDS. The TPM included a refined mesh; however, one limitation was the transverse slice assumption, which overestimated the total percent lung injury for the impact cases.

It should be emphasized that the thorax response is known to be highly sensitive to stand-off distance for BABT impact conditions [6] and the current study did not consider variations in the velocity-time curve or impact location. The actual back face velocity and BFS will depend on the specific combination of armour, projectile, and projectile impact velocity. Future research will include evaluation of alternate impact locations, varying the velocity-time curve, and coupling of protective body armour models to the thorax models.

V. REFERENCES

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