Experimental Validation of a Finite Element Model for Lethality Prediction of Primary Blast Lung Injury Using an Additive Manufactured Anthropomorphic Test Device

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Abstract. The internal mechanical behaviour of a human thorax under loading from a blast wave (propagating wave of highly compressed air) is yet to be fully explored. Finite element (FE) simulations using tailored material models are used to predict internal stresses and strains to investigate lung injury biomechanics. To confirm the outputs of our computational model, we produced and blast tested an additive manufactured (AM) anthropomorphic test device (ATD). Validation allows the computational model to be used to: evaluate existing models of injury prediction which are based on external pressure loads; optimise designs of personal protection equipment to mitigate injuries; and provide a highly versatile platform for predicting primary blast lung injury (PBLI) outcomes with improved accuracy and specificity.

Introduction

Primary Blast Lung Injury. PBLI is a leading cause of mortality in explosive related accidents and attacks. It is present in around 6–11% of survivors of military blast scenarios but is seen in up to 80% of fatalities regardless of cause of mortality. Injury is evidenced by rupture of lung parenchyma, usually concentrated around the mediastinum, due to blast energy dissipation of shear and longitudinal stress waves [1]. This makes PBLI a wave propagation dominated phenomena.

Finite Element Simulations. Injury prediction through simulation requires accurate tissue models to replicate a thorax's dynamic response at high strain rates. However, acoustic properties are equally important to characterise the internal wave reflection/transmission behaviour at boundaries. This governs regions of stress concentration/mitigation. Current injury prediction methods are based on empirical data and measurement of external pressure loads [2]. FE simulations of internal loads are able to provide specificity (i.e. location) of the injury in the lungs and should improve accuracy in determining injury severity.

Methodology

Coupled Eulerian Lagrangian (CEL). Blast propagation and interaction with a target was simulated using a 3D CEL method in Abaqus CAE (Dassault Systemes) [3]. This method is selected as it: allows for any known static pressure history to be replicated and propagated; minimises the required domain size; accounts for the clearance phenomena which reduces impulse acting on small surfaces; is able to load all surfaces of a target; and permits modelling of external reflections from boundaries in the environment.

Material Modelling. Homogeneous elastic models were deemed suitable to describe materials under blast loads based on the success of other FE models [4,5] and two assumptions. The first is that high rate loading minimises the viscous response. The second is that rupture occurs at relatively low strains (based on max. strains observed in preliminary simulations of the approximate threshold for injury). Notably, this required modelling of the lungs using bubbly water theory to achieve wave speeds that would be expected in blast loading scenarios [4].

Additive Manufacturing. AM is used to produce an ATD of the human thorax with realistic geometry by matching the properties of available AM polymers to biological tissues. Blast testing of the ATD is used to validate the FE simulations. This establishes the effectiveness of the computational model in determining: blast wave propagation; deflection/velocity of the chest wall (an injury criterion [2]); internal stress wave reflections within the body; and the stress/strain distributions inside the lungs as indicators of injury [1,4].

Results & Discussion

Mechanical Testing. Compression and ultrasound testing was carried out on the AM materials to determine their elastic behaviour. An example of the validity of an elastic model at low strains for an AM material selected to mimic the behaviour of lung as an organ is shown in fig. 1. All materials used in the ATD were similarly tested.

Validation. To verify the CEL simulation is producing accurate propagating blast waves, the temporal and spatial decay of static pressure waves were compared to CONWEP, an accepted but limited approximation of blast loads [3,6]. Blast testing of the ATD will be carried out at the Indian Institute of Technology Madras using a shock tube. Loads investigated intend to cover all probabilities of lethality's predicted by Bowen/Bass/Axelsson [2,4] and includes an investigation of the effect of impulse. Fig. 2 shows examples of suitable agreement between CEL and CONWEP for pressure decay and a resulting prediction of strain distribution in the lungs.

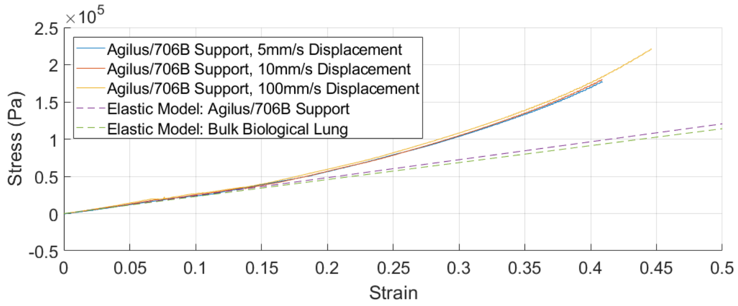

Figure 1 – Example Comparison of Elastic Models to Experimental Compressive Testing of an AM Material

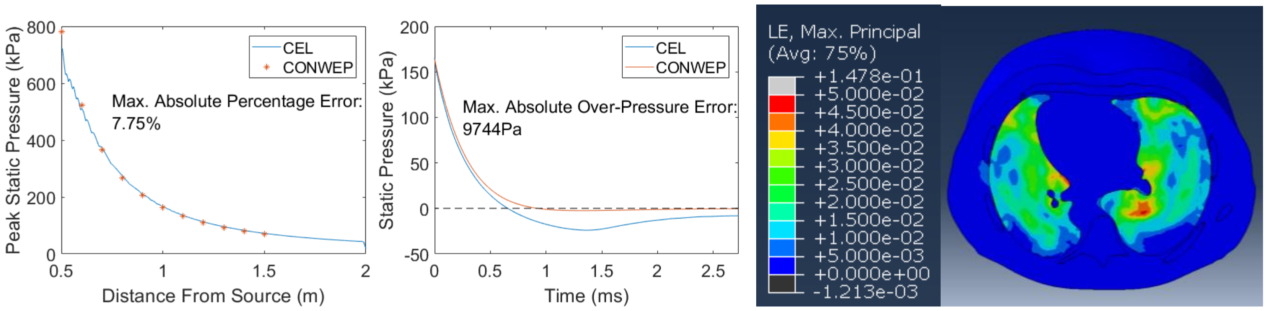

Figure 2 – Example comparison of CEL and CONWEP spatial (left) and temporal (middle) pressure decay. Resulting strain distribution in the lungs (right) shows concentration around the heart shortly after loading.

Conclusions

Blast Propagation. Blast simulations are capable of accurate spatial and temporal static pressure decay and application of reflected pressure loading to a target. This is all that is required for use of Axelsson's method of injury prediction which is compared to our model of injury prediction [2].

Tissue Modelling. High strain rate modelling of soft materials is a complicated challenge which contributed to difficulties in matching the properties of AM materials to real tissues. It was determined that approximations of the tissues would prove suitable to validate the mechanics of the model. Corrections to the computational material models (more accurate parameters, increased model complexity etc.) should allow for modelling of more precise realistic injuries.

Model Evaluation. Currently the model is capable of providing an approximation of PBLI based on the stresses and strains observed in the lungs and approximation of the chest wall velocity which can also be compared to Axelsson's numerical model. Several improvements can be made to improve the sophistication of the modelling procedure including: modelling of penetrative injuries (secondary injury); evaluation and optimisation of personal armour designs; and further development towards more precise biological microstructural modelling.

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