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<tr>
<td><strong>Publication date</strong></td>
<td>2009-07-01</td>
</tr>
<tr>
<td><strong>Conference details</strong></td>
<td>1st International Conference on Computational and Mathematical Biomedical Engineering (CMBE09), Swansea, UK, June 29 - July 1, 2009</td>
</tr>
<tr>
<td><strong>Publisher</strong></td>
<td>Computational &amp; Mathematical Biomedical Engineering (CMBE)</td>
</tr>
<tr>
<td><strong>Item record/more information</strong></td>
<td><a href="http://hdl.handle.net/10197/4742">http://hdl.handle.net/10197/4742</a></td>
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CHARACTERISATION OF A SURROGATE LUNG MATERIAL MADE OF POLYURETHANE FOAM AND FLUID-FILLED GELATINE MICROCAPSULES

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ABSTRACT

In this study, a surrogate lung material, developed to mimic the lungs behaviour in low and high rate impact tests in order to better understand the damage mechanism in the lungs resulting from car crashes, collisions and explosion [1], is tested and characterised. This aims to eliminate the practice of live animal testing. The surrogate lung consists of polyurethane foam mixed with gelatine microcapsules filled with Barium Sulphate solution. Thus, both the foam and microcapsules must be individually characterised in addition to the surrogate lung itself when treated as a continuum material. For this, a number of compression tests were carried out on each material to ascertain their mechanical properties. On the other hand, the damage to the surrogate lung specimens as represented by burst microcapsules was analysed by carrying out CT scans before and after testing. The results show that the modulus of elasticity increases with the test speed. CT scan results clearly demonstrated the magnitude and distribution of damage within the specimen.

Key Words: Surrogate lung, polyurethane foam, microcapsule, CT scan, damage analysis.

1. INTRODUCTION

The exposure of the human thorax to external loads can cause severe injuries to internal organs, particularly to lungs, and can cause death. Most critical are rapidly changing loads caused by impacts and blasts, resulting from car crashes, collisions and explosion. Over 1.2 million people are killed in road crashes every year according to the World Report on Road Traffic Injury Prevention 2004. Most common lungs injuries are oedema and haemorrhage [2-4]. These injuries impair oxygen transport mechanism and cause secondary injuries to the brain. This is due to the fact that the lungs are more susceptible to damage than the other organs in the human thoracic region.

Presently the damage mechanisms in lungs are not fully understood. The current methods of modelling blunt impact on the thorax include the use of a combination of lungs from mammals and artificial models. In order to eliminate the practice of live animal testing, this research which is a continuation of previous research [5,6], aims to develop a surrogate lung material that will reproduce the dynamic response of a human lung under various loading conditions. It is also aimed to develop a numerical model of the surrogate lung to simulate and predict damage to the lungs. The outcome of this work will provide necessary input data for subsequent numerical and experimental analysis of the blast impact and predicting primary blast injuries to human lungs.
2. MATERIALS AND METHODS

There are two main criteria that the surrogate lung material must fulfil: (a) Its stress wave speed should be similar to that of a real lung (more than 30 m/s); (b) It must be able to reproduce the extent and the distribution of damage resulting from impact at appropriate pressures similar to the lung overpressure at injury level (above 4 bars) [7]. A closed-cell polyurethane foam with a theoretical wave speed of 39.15 m/s was used to mimic the spongy material of the lungs. Gelatine microcapsules filled with Barium Sulphate solution were used to simulate the damage of alveoli in blast tests in terms of haemorrhage and bursting pressure while the Barium Sulphate solution is detectable under X-rays for easy scanning and analysis of the damage distribution. Hence, the surrogate lung was manufactured by mixing the polyurethane foam and gelatine microcapsules.

For characterisation of the microcapsules, initially, the diameter of each microcapsule was measured using an optical microscope. In this research, a number of low rate compression tests were carried out on individual microcapsules of diameter of 750 µm to investigate their mechanical properties and bursting pressure. Each microcapsule was compressed between two parallel plates made of steel at constant rate of 200 µm/min until bursting occurred. The load-displacement curve was obtained using a 10 N load cell (Tinius Olsen Ltd, UK) and the profile of the deforming microcapsule was recorded by a Nikon digital camera attached to an optical microscope. An analytical model derived by Feng and Yang [8] was employed and solved numerically using a MathCAD application, developed for this purpose. The model considers the deformation of a hyperelastic spherical membrane, filled with an incompressible fluid. In principal, fluid was not modelled in the analysis, but the incompressibility was achieved by pertaining the contact volume occupied by microcapsule membrane. Two material models were used to represent the rubber-like behaviour of the microcapsule: neo-Hookean and 2-term Mooney-Rivlin [9,10]. The material model parameters were iterated until the prediction for both the load-displacement and the profile of the deforming microcapsule were in good agreement with experimental data, particularly in terms of bursting pressure.

A number of compression tests were carried out on the cylindrical specimens (diameter of 51mm and height of 30mm) including foam and surrogate lung material, using the Hounsfield machine with a 100N load cell to ascertain their mechanical properties. Two parallel plates were used for this purpose and they were both lubricated by PTFE/Silicone lubricant to minimise friction and ensure uniaxial compression during the test. The tests were performed at various rates between 5 and 500mm/min and they were repeated to ensure accuracy. The load-displacement curve was obtained and then converted to an engineering stress-strain curve.

Some preliminary high rate tests were done and the damage to the surrogate specimens as represented by burst microcapsules was analysed by carrying out CT scans on the specimens before and after testing using the CT scanner available at St. Vincent’s University Hospital in Dublin. Firstly a virgin sample was scanned which was later completely crushed, inducing near 100% damage. This sample was then rescanned to compare the difference between two specimens.

3. RESULTS

Figure 1a shows the comparison between the different material models and the experimental data on the microcapsules. The results show that both Mooney-Rivlin and neo-Hookean material with modulus of elasticity of 180 MPa and 198 MPa, respectively, and wall thickness of 4 µm agree well with experimental results. A bursting pressure of 5 bar was calculated at 45.5% deformation which is comparable to the lung overpressure at injury level. The simulated deformed profile of the compressive microcapsule at various deformation stages i.e. undeformed, 19.2% and 45.5% is shown in Figure 1b. A comparison between the experimental recorded deformation and the numerical simulated profile of the compressive microcapsule shows that they are in excellent agreement.
Figure 1: (a) Comparison of the numerical simulation of microcapsule compression tests with the experimental data, (b) the simulated deformed profile of the compressive microcapsule at various deformation stages.

Figure 2 demonstrates the stress-strain curve of both the foam and surrogate lungs at various rates of compression. The results show that the modulus of elasticity increases with the test rate. The measured values for modulus of elasticity (E) were 42 kPa and 70 kPa for the foam and surrogate lung specimens, respectively. Now, using the density of material, one can calculate the stress wave velocity through $c = \sqrt{\frac{E}{\rho}}$; values of 18 and 20 m/s for foam and surrogate lungs, respectively, are obtained.

Figure 2: Stress-strain curves of foam and surrogate lung specimens.

Regarding the damage analysis, Figure 3 illustrates the difference between the virgin and tested surrogate lung specimen. The white shiny spots in the virgin specimen are the microcapsules. In each CT slice of the virgin surrogate lung (1mm), the average number of microcapsules was approximately 47. This was assigned as a number of microcapsules in any undamaged plane and was compared with the planes of the impacted samples by counting the remaining microcapsules after impact. The ratio of damaged to undamaged microcapsules was used to define the percentage of damage occurring in the specimen. This was then graphed as a function of location from the anterior to posterior of the impact site. Figure 4 shows the statistical distribution of the burst microcapsules through the sample before and after damage (0% and 100% damage).

Figure 3: Comparison of a surrogate lung before and after test.
4. CONCLUSIONS AND FUTURE WORK

In conclusions, a numerical model of the uniaxial compression of a single fluid-filled gelatine microcapsule has been developed. Experimental results agree well with numerical simulations in terms of the deformed shape and bursting pressure. Based on the experimental data and numerical simulations a microcapsule bursting pressure of 5 bar was obtained which is comparable to the reported lung overpressure at which injury occurs. Thus, it may be concluded that these microcapsules can be effectively utilised in the surrogate lung specimens for the detection of damage in impact experiments. Furthermore, compression tests combined with the numerical simulation have proven to be an efficient and accurate tool for the determination of the material properties of microcapsules. It is also concluded that the surrogate lung specimens developed in this work exhibit similar stress wave speeds to those of real lungs while CT scan results clearly demonstrate the magnitude and distribution of damage within the specimen as represented by burst microcapsules. These results can be used as a quantitative measure of the damage by comparing the state of the microcapsules between virgin and tested specimens.

High rate compression tests on microcapsules are currently in progress. Here, drop-weight tests are conducted on stationary microcapsules, and the loading rate is varied by varying the drop height. Further high rate impact tests will be carried out on the surrogate lung material containing smaller microcapsules similar in size to alveoli (350µm) using a drop weight tower.

REFERENCES