

DEVELOPMENT OF HETEROGENEOUS LUNG MODEL FOR BLUNT IMPACT LOADS

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**Development of heterogeneous lung model
for blunt impact loads**

by

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CERTIFICATE

This is to certify that the thesis entitled ‘**Development of heterogeneous lung model for blunt impact loads**’ being submitted by **Pydi Yeswanth Sai** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a bonafide record of original research work carried out by him under our supervision in conformity with rules and regulations of the institute.

The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

Automobile crashes and blunt trauma often lead to life-threatening thoracic injuries, especially to the lung tissues. Finite element (FE) human body models are used to simulate and predict these resulting injuries. However, these models rely on an accurate estimation of the material properties to simulate crash and trauma scenarios. Moreover, the existing finite element models of lung tissue are considered as homogeneous, which may be computationally efficient but fail to capture the true dynamics of lung tissue.

To model the heterogeneous lung model, it is important to ascertain the material properties of individual lung tissue (i.e. parenchyma and bronchi). These tissues are strain-rate-dependent and their material properties corresponding to blunt impact loading need to be determined. The aim of this study is to develop a heterogeneous lung model with the strain-rate-dependent material parameters of parenchyma and bronchi.

Quasi-static and dynamic compression studies were performed on the human and porcine parenchyma tissue to determine its strain-rate-dependent material properties. A UMAT bilinear material model was utilized to model the strain stiffening and strain rate behaviour of the tissue. The FE model of the parenchyma sample was modelled in LS Dyna, using its average sample dimensions from the experimental tests. The bilinear material properties were then optimized by integrating the inverse FE and genetic algorithm (GA). The normalized root mean square error between the experimental and the FE load time responses were minimized. The quasi static and dynamic tensile experimental studies were performed on the porcine bronchi tissue and using the similar optimization methodology the tensile material properties were optimized. Strain and strain

rate variation in both parenchyma and bronchi samples were analyzed to understand the attainment of dynamic equilibrium in the sample.

For human parenchyma, with an increase in loading rate from 1 mm/s to 5 m/s, the maximum engineering stress (for 50% strain) increases from 1.27 to 141 kPa. With the strain rate varying from 0.1 to 500 s⁻¹, the elastic modulus increases from 11.6 to 158.8 kPa, and the toe strain decreases from 0.4 to 0.31. For porcine bronchi, as test speed increases from 0.5 to 2 m/s, the maximum tensile stress increases from 1.26 to 2.39 MPa and the failure strain decreases from 0.66 to 0.54. The optimized bilinear properties of bronchi show that the elastic modulus of the bronchi tissue increases from 6.2 to 3960 MPa, and the toe strain decreases from 0.19 to 0.11.

A heterogeneous lung tissue, with both parenchyma and bronchi, was tested using the dynamic compression setup. Before testing, the heterogeneous lung sample was scanned using the micro-CT machine to generate the exact CAD model of the test sample. Later the CAD model was used to generate the corresponding FE model using HyperMesh. The optimized bilinear material properties of parenchyma and bronchi were then incorporated to the generated heterogeneous FE model. The developed heterogeneous model was then validated by the comparing the experimental and the simulated load time responses.

Finally, the full organ lung model was then simulated for the frontal and side impact loading condition. The strain and strain rate variation in the full organ lung model was analyzed, since these parameters are considered as the injury metrics in the soft tissue. The strain and strain rate variation in the heterogeneous lung was compared with the homogeneous lung model (model with pure parenchyma) and identified the stress wave amplification at the vicinity close to bronchi. This enhances the probability of injury in the parenchymal tissue, which signifies the need and necessity of heterogeneous lung model during impact loads.

सार

ऑटोमोबाइल दुर्घटनाएँ और कुचलन के कारण अक्सर जीवनसंदर्भी थोरेसिक चोट जैसे कि फेफड़े के ऊतकों में होती हैं। फाइनाइट एलिमेंट (एफई) मानव शरीर मॉडल का उपयोग इन चोटों को नकल और पूर्वानुमान करने के लिए किया जाता है। हालांकि, इन मॉडल्स में चोट और चोट के स्थितियों की नकल के लिए सामग्री की सटीक अनुमान पर निर्भरता होती है। इसके अतिरिक्त, फेफड़ों के ऊतकों के मौजूदा फाइनाइट एलिमेंट मॉडल को घनी माना जाता है, जिससे गणनात्मक रूप से अच्छा परिणाम मिल सकता है लेकिन फेफड़ों के वास्तविक गतिविधि को नहीं पकड़ सकता है।

विभिन्नतापूर्ण फेफड़ों का मॉडल बनाने के लिए, व्यक्तिगत फेफड़ा ऊतकों (यानी पेरेंकाइमा और ब्रॉन्काई) की सामग्री के निर्धारण में महत्वपूर्ण होता है। ये ऊतक तनाव-दर-निर्भर होते हैं और चोट स्थितियों में उनकी सामग्री की गुणवत्ता को निर्धारित करने की आवश्यकता होती है। इस अध्ययन का उद्देश्य पेरेंकाइमा और ब्रॉन्काई के तनाव-दर-निर्भर सामग्री पैरामीटर्स के साथ विभिन्नतापूर्ण फेफड़े का निर्माण करना है।

मानव और सुअर के पेरेंकाइमा ऊतक पर क्वासी-स्थैतिक और गतिशील दबाव अध्ययन किए गए थे ताकि इसकी तनाव-दर-निर्भर सामग्री के गुणवत्ता पैरामीटर्स को निर्धारित किया जा सके। यूएमएट बायलिनियर सामग्री मॉडल का उपयोग ऊतक की तनाव वृद्धि और तनाव दर के व्यवहार के मॉडल करने के लिए किया गया था। पेरेंकाइमा नमूने का एफई मॉडल एलएस डाइना में मॉडल किया गया था, जिसमें अपने प्रयोगात्मक परीक्षण से औसत नमूने के आयाम का उपयोग किया गया। फिर उम्पन एफई और जेनेटिक एल्गोरिदम (जीए) का उपयोग करके बायलिनियर सामग्री गुणकों को अनुकूलित किया गया। प्रयोगात्मक और एफई लोड समय प्रतिक्रियाओं के बीच औसत मूल वर्ग त्रुटि को कम से कम किया गया। सुअर ब्रॉन्काई ऊतक पर क्वासी-स्थैतिक और गतिशील कशोर प्रयोगात्मक अध्ययन किए गए और इसी समान अनुकूलन पद्धति का

उपयोग करके तनावीय सामग्री गुणवत्ता को अनुकूलित किया गया। पेरेंकाइमा और ब्रॉन्काई नमूनों में तनाव और तनाव दर की विभिन्नता का अध्ययन किया गया था ताकि नमूने में गतिशील संतुलन को समझा जा सके।

मानव पेरेंकाइमा के लिए, लोडिंग दर को 1 मिमी/ सेकंड से 5 मीटर/सेकंड तक बढ़ाते हुए, इंजीनियरिंग तनाव (50% तनाव के लिए) 1.27 से 141 किलोपास्कल तक बढ़ जाता है। जबकि तनाव दर 0.1 से 500/सेकंड तक बदलती है, तो इलास्टिक मॉड्यूलस 11.6 से 158.8 किलोपास्कल बढ़ता है, और टो तनाव 0.4 से 0.31 कम हो जाता है। सुअर ब्रॉन्काई के लिए, जब परीक्षण की गति 0.5 से 2 मीटर/सेकंड बढ़ती है, तो अधिकतम कशोर तनाव 1.26 से 2.39 मेगापास्कल बढ़ता है और विफलता तनाव 0.66 से 0.54 कम हो जाता है। ब्रॉन्काई की अनुकूलित बायलिनियर गुणस्तरों में ब्रॉन्काई ऊतक का इलास्टिक मॉड्यूलस 6.2 से 3960 मेगापास्कल बढ़ता है, और टो तनाव 0.19 से 0.11 कम हो जाता है।

एक विभिन्नतापूर्ण फेफड़ा ऊतक, जिसमें पेरेंकाइमा और ब्रॉन्काई दोनों शामिल हैं, गतिशील दबाव सेटअप का उपयोग करके परीक्षण किया गया था। परीक्षण से पहले, विभिन्नतापूर्ण फेफड़ा नमूना को माइक्रो सीटी मशीन का उपयोग करके स्कैन किया गया था ताकि परीक्षण नमूने का ठीक से CAD मॉडल उत्पन्न हो सके। बाद में CAD मॉडल का उपयोग HyperMesh का उपयोग करके उसके अनुरूप एफई मॉडल उत्पन्न करने के लिए किया गया। पेरेंकाइमा और ब्रॉन्काई की अनुकूलित बायलिनियर सामग्री गुणस्तरों को फिर उत्पन्न विभिन्नतापूर्ण एफई मॉडल में शामिल किया गया। विकसित विभिन्नतापूर्ण मॉडल को अंतिम रूप दिया गया था और प्रयोगात्मक और नकली भार समय प्रतिक्रियाओं की तुलना करके मान्यता प्राप्त की गई।

अंत में, पूर्ण अंग फेफड़ा मॉडल फ्रंटल और साइड प्रभाव लोडिंग अवस्थिति के लिए नकली गया। पूर्ण अंग फेफड़ा मॉडल में तनाव और तनाव दर की विभिन्नता का अध्ययन किया गया था, क्योंकि ये पृष्ठ ऊतक में चोट के मापक के रूप में माना जाता है। विभिन्नतापूर्ण फेफड़ा में तनाव और तनाव दर की विभिन्नता को समान फेफड़ा मॉडल (केवल पुरे परेंकाइमा के साथ मॉडल) के साथ तुलना की गई और ब्रॉन्काई के करीबी क्षेत्र में तनाव तरंगों के वृद्धि को पहचाना गया। इससे परेंकाइमा ऊतक में चोट के संभावना को बढ़ावा मिलता है, जो संकेत करता है कि प्रभाव लोडों के दौरान विभिन्नतापूर्ण फेफड़ा मॉडल की आवश्यकता और आवश्यकता को सूचित करता है।

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List of abbreviations

E_{toe}	=	Toe modulus
$E_{elastic}$	=	Elastic modulus
ε_{toe}	=	Toe strain
ε_{toe}	=	Elastic strain
UMAT	=	User defined material model
ε_e	=	Effective strain
$(\dot{\varepsilon}_e)$	=	Effective strain rate
ε_{ij}^d	=	Deviatoric strain component
t	=	Time step
$t + 1$	=	Subsequent time step to (t)
Δt	=	time increment between the time steps t and $t + 1$
ω	=	correction factor
E	=	modulus
σ_{ij}^t	=	Total stress at (t)
$\Delta \varepsilon_{ij}^{t+1}$	=	incremental strain
μ	=	Poisson's ratio
C_{ijkl}	=	stiffness matrix
ε_{xx}	=	True strain along X direction
RMS	=	Root mean square
NRMS	=	Normalized root mean square
$F_i^{exp,j}$	=	experimental force values
$F_i^{sim,j}$	=	simulated force values
n^j	=	number of data points
SD	=	Standard deviation
ROI	=	Region of interest
DIC	=	Digital image correlation