基于图像的有限元网格生成技术及其在开孔泡沫塑料大应变变形模拟中的应用

Image-Based Mesh Generation and its Application to Large Strain Deformation of Open Celled Foams

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摘要：开孔泡沫塑料因为其独特力学属性特别是轻质量、高吸能性而在工业界得到广泛应用，如座椅、头盔、空间飞行器等。但这种塑料的材料属性却是不同形式的微观结构和基体材料属性综合作用的结果。广泛的研究都已开展起来，包括分析法、试验法和计算模拟，这些研究增加了我们对开口泡沫材料物理行为的理解。计算模拟已逐渐被证实是一种非常有效、有价值的工具，它可以在微观水平调查研究材料行为并评估其在宏观水平的影响。计算模拟比试验测试能更深入理解变形机理，比分析法得到更真实的模型结果。但是，直到现在，开口泡沫塑料微观结构的复杂拓扑使划分网格的困难显而易见，这种困难为分析力学特性所采用的最流行的基于物理学的有限元方法之有效应用提供了障碍。

在本文中，一种新的基于图像的网格划分方法被第一次使用来分析复杂结构塑料的力学特性，这种分析是基于高精度的计算机断层扫描数据(微观 CT 或 X 波段微波发射机)。数据图像被导入到商用三维建模软件 ScanIP/$^+$ ScanFE (Simpleware Ltd.)生成几何形状和拓扑结构都很精确的三维有限元模型。这种技术将 CT 扫描数据直接自动转化成任意复杂域的六面体或六面体、四面体混合网格模型。网格模型的精度仅依赖于 CT 成像系统的精度。复杂单相或多相材料可被直接划分网格，从而解决了诸如多孔材料中流体引起的变形等流固耦合问题。

对于本文中选用的开孔泡沫塑料，建立了包含 1392751 个线性四面体单元和 360703 个节点的有限元模型，并用 LS-DYNA 显式模块(Livermore Software Technology Corp.)进行了准静态和动态应力-应变分析，考虑了不同加载速率和线弹性及弹塑性材料属性的影响。加载方式为两块刚性板从两侧压缩模型，并设定了刚性板和塑料模型之间的滑动接触关系。所有的求解都是在 LS-DYNA 中进行的。

本项研究的目的是介绍材料研究中的一种建模新方法，这种方法可以解决几何拓扑复杂的问题，精度很好，比其他方法节约了大量时间。此种复杂微细观结构的快速强健建模方法为材料科学家提供了强大的新工具，使他们能探索不同参数对新材料性能的影响，成为材料研究中的分析法和试验法的有益补充。上述的建模方法一定会逐渐成为复合材料研究中逆向建模方法的关键技术。

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Abstract: Open celled foams are used in an increasing number of industrial applications, (e. g. seating, helmets, space vehicles) due to their interesting mechanical properties, in particular their light weight and high energy absorption. However, the material properties of foams are a result of complex relationships involving different aspects of the micro-architecture and properties of the parent material. A wide range of studies have been carried out using analytical, experimental and computational approaches to increase our understanding of the physical behavior of foams. Computational simulation is increasingly proving to be a very effective and valuable tool in investigating materials behavior at the micro-scale level and in assessing its influence on the overall macro-scale properties. Computational modeling offers the prospect of providing a deeper understanding than experimental tests of the mechanisms at work during deformation, and more realistic model results can be achieved than via analytical approaches. However the difficulty of meshing the complex topologies of foam micro-architectures has proved, until recently, a barrier to effectively using the most popular of physics based simulation techniques for mechanical characterization: the finite element method (FEM).

In the present study, for the first time, a new image-based meshing approach is used for characterizing the mechanical properties of complex foams based on high resolution computed tomography data (MicroCT or XMT). The image was imported into the commercially available software program ScanIP/$^{+}$ScanFE (Simpleware Ltd.) which generates geometrically and topologically accurate finite element meshes of 3D imaging data. The technique converts CT scanner data directly into tetrahedral meshes (or mixed tetrahedral and hexahedral meshes) of arbitrarily complex domains robustly and automatically. The accuracy of the resultant mesh is contingent only on the accuracy of the imaging system. Complex single phase and multiphase materials can be meshed straightforwardly for solving coupled problems such as fluid flow induced deformation of porous materials.

For the open celled foam, a finite element model consisting of 1,392,751 linear tetrahedral elements and 360,703 nodes was generated. Computer simulations were carried out using explicit code LS-DYNA (Livermore Software Technology Corp.) to characterize the quasi-static through to dynamic stress-strain behavior of the materials for various compression velocities and for both linear elastic and elasto-plastic material properties from small strains right through to strains well into the compaction regime. The foam models were compressed between two rigid platens with the bottom platen fixed and a displacement time history applied to the top platen. Sliding contact was assumed between the bottom platen and the foam and the top platen and the foam, allowing for frictionless sliding in the in-plane direction (except where noted differently). For foam-to-foam contact modeling, a sliding self-contact algorithm with zero friction was used. All the solutions were run through LS-DYNA for the maximum compression until the solution failed to converge.

The aim of this study was to illustrate the ability to simulate topologically complex problems with a high degree of accuracy but in a fraction of the time taken by other approximate methods. The ability to straightforwardly and robustly model the response of complex micro-architectures provides powerful new tools for the material scientist to easily explore the influence of various parameters on the performance of novel complex material systems, which will be increasingly used in addition to and in combination with analytical modeling and experimental tests. These computational techniques will also be pivotal to the development of tools for material characterization of complex composites using inverse modeling techniques.

Key words: foam; image based meshing; finite element; stress-strain behavior; elasto-plastic material properties

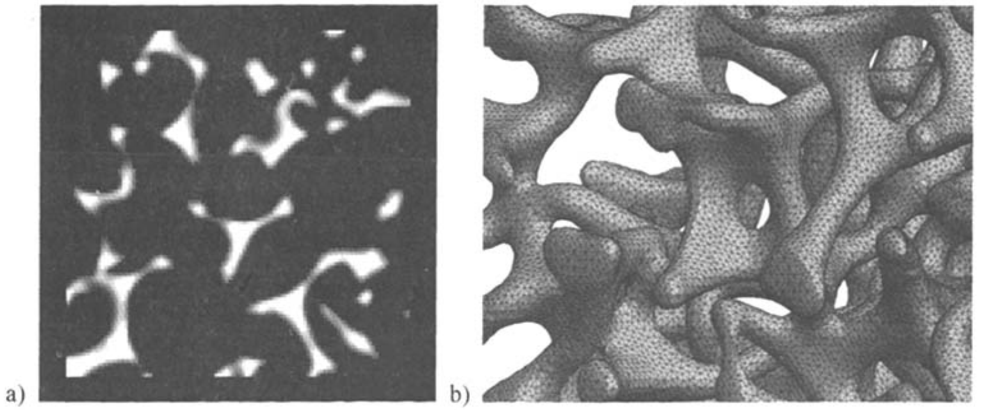

Fig. 1 a) CT image of foam; and b) zoomed in view of the meshed foam

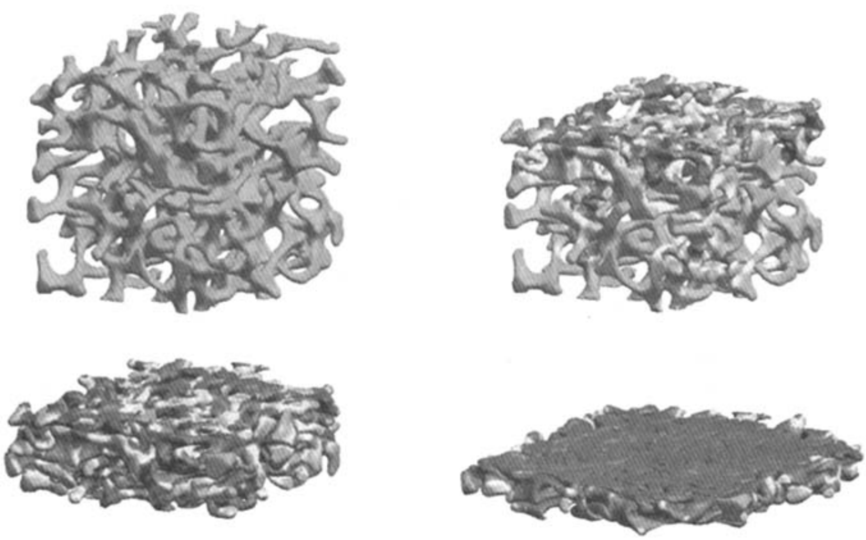

Fig. 2 Large strain deformation of foam at different stages of compression

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3 结论

(1)Pin 的植入显著增加了夹层结构的压缩性能。同普通泡沫相比，X-cor 夹层结构的压缩强度提高 9.7 倍，压缩模量提高 17.9 倍。

(2)随着植入角度的增加，X-cor 夹层结构的强度和模量均增加，且在 90°附件模量增加显著。

(3)不同 Pin 直径对 X-cor 夹层结构的影响不同，相同体积分数 Pin，大直径的 Pin 对 X-cor 夹层结构的压缩强度增强效率较高；小直径的 Pin 对 X-cor 夹层结构的压缩模量增强效率较高。

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