IUTAM SYMPOSIUM

When topology optimization meets additive manufacturing – theory and methods

Oct. 7-12, 2018, Dalian, China

Program & Abstract Book

Sponsored by: International Union of Theoretical and Applied Mechanics
Chinese Society of Theoretical and Applied Mechanics
National Natural Science Foundation of China

Organizers: Dalian University of Technology
State Key Laboratory of Structural Analysis for Industrial Equipment
International Research Center for Computational Mechanics

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Preface

This IUTAM symposium on when topology optimization meets additive manufacturing – theory and methods is to be held during October 7-12, 2018 in Dalian, China. It aims to promote the interactions among top level researchers working in the area of topology optimization and AM. The central theme is to discuss the challenging issues and the corresponding solution approaches when topology optimization meets AM.

The topics of this symposium include but are not limited to

- New framework for AM oriented topology optimization
- Shape and topology optimization subjected to manufacturing constraints
- Effective material property prediction without separation of scales
- AM and Multi-physics/multi-scale topology optimization
- AM and meta-material design through topology optimization
- Integrate material and structure design through AM and topology optimization

Have a productive and enjoyable stay in Dalian, China!

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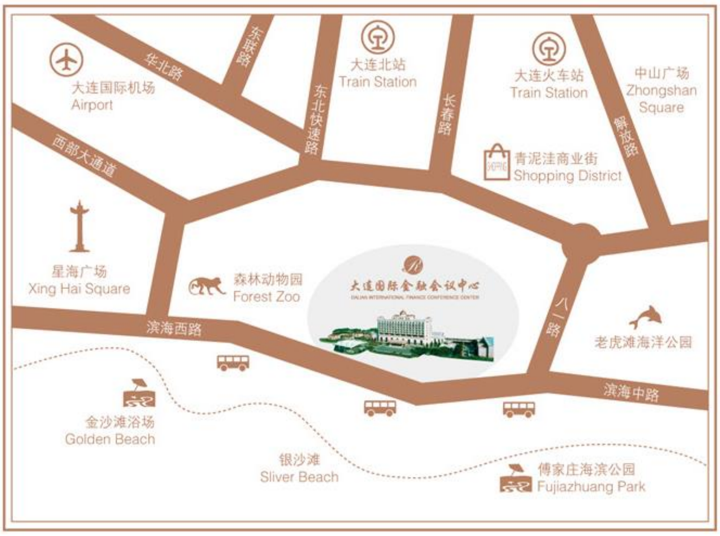
Contact:

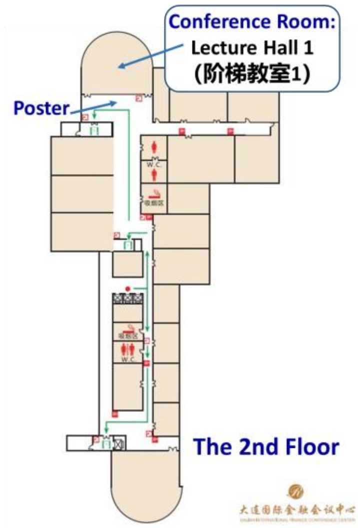
Prof. Jun Yan (Dalian University of Technology, China)
Email: yanjun@dlut.edu.cn, Tel: 86-13795146687
A/Prof. Bin Niu (Dalian University of Technology, China)
Email: niubin@dlut.edu.cn, Tel: 86-13842893083

Useful Information

Conference Place:

Dalian International Finance Conference Center (Hotel in Chinese: 大连国际金融会议中心，大连市西岗区滨海西路 68 号；about half an hour's drive) http://www.dlbankhotel.com/





Registration and Conference Rooms:

Registration:	Oct. 7, Lobby, 1st Floor
Conference:	Oct. 8-10, Lecture Hall 1 (阶梯教室 1), 2nd Floor

Lunch, dinner and banquet info:

Lunch & dinner place: Sea of Clouds Pavillion (海云轩), 1st Floor

Welcome Reception: 18:00 – 19:30 on 8 October 2018, Fontainebleau (枫丹白露厅), 9th Floor

Banquet: 18:00 – 19:30 on 9 October 2018. Coach pick up at the outside of the lobby (all delegates must assemble at the lobby at 17:55)

Program at a Glance

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10:00-10:30		Photo / Morning Break/ Poster Viewing	Morning Break/ Poster Viewing	Morning Break/ Poster Viewing		
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14:00-15:30		Session 3	Session 7	Panel Discussion		
15:30-16:00		Afternoon Break/ Poster Viewing	Afternoon Break/ Poster Viewing	Afternoon Break/ Poster Viewing		
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	15:00－15:30	**Ming Zhou** (Altair Engineering), Fabian Fuerle, Raphael Fleury, Martin Solina, *Design for Additive Manufacturing – Comprehensive Software Solutions*
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	16:00－16:30	**Weihong Zhang** (Northwestern Polytechnical University), Jihong Zhu, *Topology Optimization of Structures for Additive Manufacturing with Considerations of Manufacturing constraints and Material Properties*
	16:30－17:00	**Liang Gao** (Huazhong University of Science and Technology), Junjian Fu, Hao Li, Mi Xiao, *Multiscale Topology Optimization of Shell-infill Structures Using a Distance Regularized Parametric Level-set Method*
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	9:30—10:00	Fabio Conde, Pedro Coelho, Rodrigo Tavares, Jose M Guedes, Pedro P. Camanho, **Helder C. Rodrigues** (Laeta- Associated Laboratory for Energy, Transports and Aeronautics), *Optimization of Pseudo-Ductile Behavior of Hybrid Composites Under Uniaxial Traction*
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	14:30—15:00	**Jun Wu** (Delft University of Technology), *Topology Optimization of Adaptively Refined Infill Structures for Additive Manufacturing*
	15:00—15:30	Haihui Liu, Lyu Zhang, **Jiyuan Ye** (EOS Electro Optical Systems (Shanghai) Co., Ltd), *The Opportunities and Challenges Brought by Additive Manufacturing to Topology Optimization*
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	16:00—16:30	**Xianghai Chai** (AVIC Commercial Aircraft Engine Co., LTD), Tongcheng Shi, *Scratch Analysis and Optimization Design for Fan Blade and Case of Aero Engine*

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	9:00－ 9:30	Gregoire Allaire, **Lukas Jakabcin** (Ecole Polytechnique), *Thermal Constraints in Topology Optimization of Structures Built by Additive Manufacturing*
	9:30－10:00	Reza Behrou, Mikhail Osanov, **James K. Guest** (Johns Hopkins University), *Improvements to Projection-based Topology Optimization for Overhang Constraints*
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	11:00－11:30	**Shikui Chen** (State University of New York at Stony Brook), Xianfeng David Gu, *Design for Discovery: Generative Design of Conformal Structures using Level-Set-Based Topology Optimization and Conformal Geometry Theory*

	11:30—12:00	**<u>Linwei He</u>** (University of Sheffield), Matthew Gilbert, Hongjia Lu, Thomas Johnson, Tom Pritchard, *Interactive Conceptual Design of AM Components using Layout & Geometry Optimization*
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- **Yingjun Wang** (South China University of Technology)

  "*Graded Cellular Hip Implant Design through Topology Optimization and Additive Manufacturing*"

- **Zhao Zhang** (Dalian University of Technology), Z. J. Tan, J. Y. Li, X. X. Bai

  "*Integrated Modelling of Process-Property-Structure in Friction Stir Additive Manufacturing and the Data-driven Design*"

- **Qi Xia** (Huazhong University of Science and Technology), Tielin Shi

  "*A Poor Man's Topological Derivative Based on BESO for Stable Hole Nucleation in Level Set Optimization*"

- **Mingdong Zhou** (Shanghai Jiao Tong University), Yichang Liu

  "*Structural Topology Optimization for Thermal Stress Control in Laser Additive Manufacturing*"

- **Eduardo Fernandez-Sanchez** (University of Liege), Pierre Duysinx

  "*Imposing the Distance between Solid Members Generated by Maximum Size Constraints in Topology Optimization*"

- **Niklas Ivarsson** (Lund University), Mathias Wallin, Daniel Tortorelli

  "*Topology Optimization for Designing Periodic Microstructures based on Finite Strain Visco-plasticity*"

- **Shengyu Duan** (Central South University), Weibin Wen, Daining Fang

  "*Mechanical Performance of Additively-Manufactured Three-Dimensional Lattice Meta-materials Designed via Topological Optimization*"

- Lei Zhang, **Bo Song** (Huazhong University of Science and Technology), Yusheng Shi

  "*Evaluation of Topology-Optimized Metallic Pentamode Material Manufactured by Selective Laser Melting*"

- Qi Chen, Xianmin Zhang, **Benliang Zhu** (South China University of Technology)

  "*Topology Optimization and Experimental Study on Buckling-induced Mechanical Metamaterials*"

- ✧ **<u>Dongliang Quan</u>** (Beijing Aerospace Technology Institute), Guanghui Shi, Chengqi Guan

  "*Bracket Design by Topology Optimization and Manufactured by Additive Manufacturing*"

- ✧ **<u>Xiaoyu Zhang</u>** (China Academy of Space Technology), Hao Zhou, Huizhong Zeng

  "*Additive Manufacturing Spacecraft Structure: Design and Evaluation*"

- ✧ **<u>Wenjiong Chen</u>** (Dalian University of Technology), Xiaonan Zheng, Shutian Liu

  "*Finite-Element-Mesh Based Method for Modeling and Optimization of Lattice Structures for Additive Manufacturing*"

- ✧ **<u>Yichao Zhu</u>** (Dalian University of Technology), Shaoshuai Li, Zongliang Du, Chang Liu, Xu Guo, Weisheng Zhang

  "*A Novel Asymptotic-Analysis-Based Homgenisation Approach towards Fast Design of In-Fill Graded Microstructures*"

Addictive Manufacturing: From 3D to 4D Printing

Daining Fang
Beijing Institute of Technology, Beijing, China.

With progressive advancements in various cutting-edge technologies, lightweight structures with both robust mechanical stability and multi-functions are highly pursued to meet the critical requirements in the complicated environments. Currently, development of addictive manufacturing (AM) technology has fundamentally exhibited great advantages, which provides an exclusive platform for manufacturing lightweight multi-function materials and structures. Based on 3D and 4D printing, in the present talk, I would initially analyze the critical challenges in the current advanced lightweight multi-function materials and structures via AM technology, aiming to further discussing the essential scientific and technical issues in AM design, AM processing and R&D of AM apparatus. Accordingly, a variety of design methods are presented for achieving advanced structures, including lattice structures, smart lattices, origami and kirigami, chiral structures, etc. Also, novel technologies and processes are developed to construct large-scale multi-material structures, advanced ceramic/composite structures, 4D printed smart structures. Additionally, we have developed advanced AM apparatus for metals, ceramics and composites, with capability in precisely manipulating both structure shapes and functions. The technologies are expected to open up novel routes for substantially manufacturing and promoting the lightweight multi-function materials and structures in advanced industrial devices and equipments.

Data-driven Microstructure and Mechanical Property Design in Additive Manufacturing using Self-Organizing Map

Wing Kam Liu
Northwestern University
Email: w-liu@northwestern.edu

The transport phenomenon of molten pool model includes heat transfer, liquid metal flow, mass transfer; liquid-gas interface capture for direct metal deposition (LENS) is first presented. The model is utilized to simulate multi-track and multi-layer LENS additive manufacturing processes. The effect of scanning path and process parameters on transport phenomena and solidification behavior will be examined and discussed. Process design for the prediction of microstructure and mechanical properties in additive manufacturing (AM) of Ni-based Superalloy motivates us to develop a novel data-driven approach, which combines physics-based models, experimental measurements and data mining methods. The simulation is based on computational thermal-fluid dynamics (CtFD) model, which can obtain thermal behavior, solidification parameters such as cooling rate, and dilution of solidified clad. Based on the computed thermal information, dendrite arm spacing, microhardness, and other mechanical properties are estimated by using well-tested mechanistic models. Experimental microstructure and microhardness are obtained for validation. To visualize process-structure-properties linkages, simulation and experimental datasets are the input to a data-mining model, the Self-Organizing Map (SOM). The design windows of process parameters under multiple objectives can be obtained from the visualized maps.

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Bostanabad, R., Zhang, Y., Li, X., Kearney, T., CL. Brinson, Apley, DW., Liu, W.K., Chen, W., Computational Microstructure Characterization and Reconstruction: Review of the State-of-the-art Techniques, *Progress in Materials Science*, 95, 1–41 (2018). doi: https://doi.org/10.1016/j.pmatsci.2018.01.005.

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Topology Optimization of Structures and Infill for Additive Manufacturing

Ole Sigmund[1*], Jeroen P. Groen[1], Jun Wu[2]

[1]*Department of Mechanical Engineering, Technical University of Denmark, 28200 Lyngby, Denmark,*
Corresponding author: sigmund@mek.dtu.dk

[2]*Department of Design Engineering, Delft University of Technology, Delft, The Netherlands*

Topology optimization (TO) [1] is a widely used tool for generating optimal structures for subsequent realization by additive manufacturing (AM) methods. TO delivers optimal but often rather complex topologies. As such, TO can take full advantage of the large design freedom offered by AM technologies. Much recent effort in the TO community has been devoted to the development of algorithms that take manufacturing constraints into account, such as overhang angles, printing directions and minimization of support material. In this talk we will discuss recent developments in simultaneous design of structures and their infill.

Infill is often used to save material consumption and weight in AM structures. Infill is also used as a design gimmick to illustrate the capabilities of AM to mimic natural creations like honeycombs and bone structure. Partly for manufacturing reasons, infill microstructure is often built as open-walled foam structures. However, it is not generally acknowledged that open-walled microstructures are not optimal with respect to stiffness [2]. Even if one builds structures with uniform and stiffer closed-walled infill, it does not beat simple solid structures with regards to stiffness. On the other hand, porous infill structures may posses advantages with regards to buckling stability compared to their solid counterparts [3].

The talk will discuss above issues in more detail and present recent developments of topology optimization with uniform and isotropic infill [3, 4, 5], anisotropic infill for fixed outer geometries [6], simultaneous anisotropic infill and structural design [7], buckling strength optimization of periodic structures [8], as well as recent multiscale topology optimization approaches that may speed up the previously mentioned approaches [9].

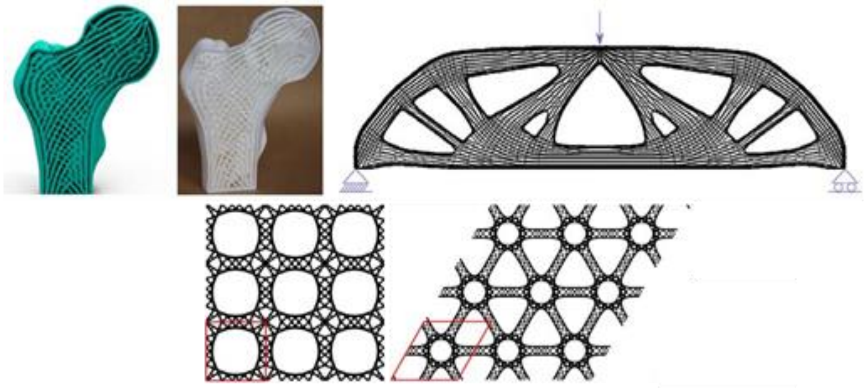

Figure 1: Top row: examples of topology optimization of structures with infill. From [6] (left) and [7] (right). Bottom row: examples of periodic microstructures optimized for buckling strength (from [8]).

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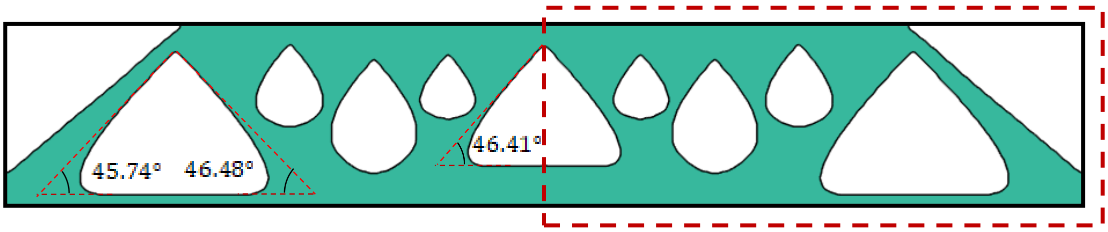
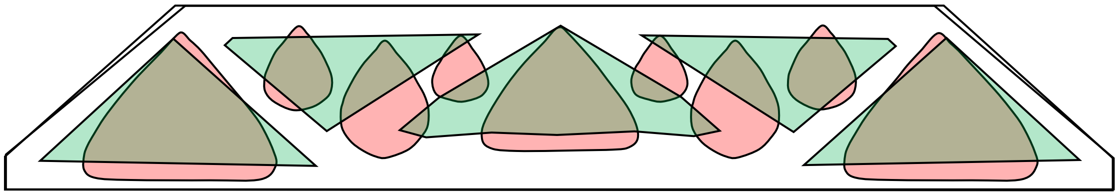
Additive Manufacture Oriented Topology Optimization Based on Approaches with Explicit Geometry Description

Xu Guo
State Key Laboratory of Structural Analysis for Industrial Equipment,
Department of Engineering Mechanics,
International Research Center for Computational Mechanics,
Dalian University of Technology, Dalian, 116023, P.R. China

Topology optimization (TopOpt) which aims at distributing a certain amount of material in a prescribed design domain in order to achieve some exception properties has received ever-increasing attention due to the fast development of additive manufacture (AM). It is, however, worth noting that on the one hand, the advent of AM provides the unprecedented possibilities making the optimized results obtained from TopOpt manufacturable. On the other hand, AM also poses some challenging problems to the development of theory, method or even solution framework associated with AM oriented TopOpt. In the represent lecture, I will talk about how to resolve some challenging issues in TopOpt considering AM related design constraints (e.g., controlling of overhang angles, restricting minimum length scale, designing infill structures with well-connected graded microstructures) with use of the newly developed Moving Morphable Component/ Moving Morphable Void (MMC/MMV)-based explicit TopOpt approaches. Some representative examples will also be presented to illustrate the effectiveness of the proposed approaches.



(a). Optimized solution considering self-supporting constraint.



(b). A comparison with the unconstrained optimized solution.
Fig. 1 The optimized structure obtained with the MMV-based approach.

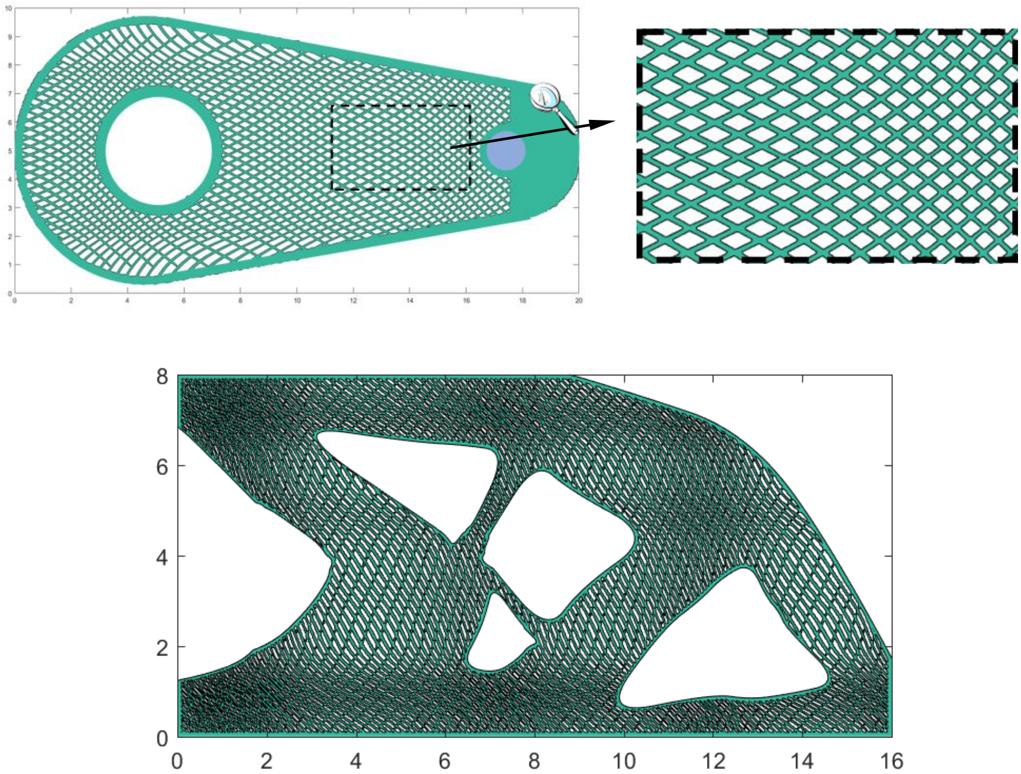


Fig. 2 The optimized graded lattice structure obtained with
the MMC and MMV-based approach respectively.

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A Virtual-Temperature-Method for Topology Optimization Design Considering Manufacturing Constraints

Shutian Liu[1*], Quhao Li[2,1*], and Wenjiong Chen[1,*]
[1]*State Key Laboratory of Structural Analysis for Industrial Equipment,*
Dalian University of Technology, 116023, Dalian, China
* Corresponding author: stliu@dlut.edu.cn
[2]*School of Mechanical Engineering, Shandong University, Jinan 250061, China*

Topology optimization has been regarded as a powerful design approach for determining optimal topology of a structure to obtain desired functional performances within a defined design domain. While a topology optimum design may offer an optimal performance in computational setting, it should be pointed out that the results are often complicated, impractical or unrealizable and may not be optimal from fabrication viewpoint. In order to address this question, considering manufacturing constraints in topology optimization becomes increasingly important. The authors [1,2] have proposed a topology optimization model, labeled as virtual temperature method (VTM), for describing and enforcing the desired connectivity constraint in Additive manufacturing. In this paper, this method is introduced and modified to handle the molding constraint in order to guarantee the cast-ability of topologically designed structures. In the modified method, a new virtual thermal diffusion problem is defined and the molding constraint is set to a maximum temperature constraint. The parting directions, unidirectional or multi-directional, are modeled by modifying the heat dissipation boundaries and the material properties. This method does not require an optimization process to start from a feasible initialization and can be applied almost in any topology optimization problems. Based on the proposed method, a new mirror configuration of a large-aperture space telescope is obtained and numerical analysis shows the superiority of the new mirror configuration compared to two classical mirrors.

Key Words: Topology optimization, Additive Manufacturing, Manufacturing constraints, Connectivity constraint, Virtual temperature method

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Additive Manufacturing Opportunities: Multiscale Topology Optimization and Related Topics

Narasimha Boddeti[1], Oliver Weeger[1], Sang-In Park[1], Yeming Xian[2], Martin Dunn[3], David Rosen[1,2]

[1]*Digital Manufacturing and Design Centre, Singapore University of Technology and Design*
[2]*School of Mechanical Engineering, Georgia Institute of Technology*
[3]*College of Engineering, University of Colorado, Denver*

Keywords: additive manufacturing, topology optimization, multiscale modeling, integrated material- structure design

This presentation discusses design opportunities afforded by additive manufacturing (AM) in the context of topology optimization (TO). Design for manufacturing typically entails designing detailed part geometry to mitigate manufacturing process constraints. However, with design for AM (DFAM), many new opportunities emerge to explore design concepts that would be difficult or impossible to achieve with conventional manufacturing processes and materials. In this talk, we present a survey of design concepts and achievements from Georgia Tech and SUTD that take advantage of the unique capabilities of TO methods and AM processes. Ideas of promising research directions will be offered as well.

Optimal Multimaterial, Multiscale Structures: The long-term objective of this first topic is the design of fiber-reinforced composites with complex shapes, where fiber loading and directions can be varied.Two broad classes of AM processes are of interest: material jetting, which can deposit multiple polymers with very different mechanical properties; and material extrusion with fiber placement. The former approach is exemplified by the Connex Polyjet technology from Stratasys, while the latter is represented by the MarkForged printers that can deposit thermoplastic as well as long fibers. Initial work utilized a homogenization approach for mechanical properties in a SIMP-based TO method where fiber orientations were design variables for short fiber-reinforced polymer composites [1]. The TO process resulted in optimal shapes and material orientations. These results were fed into a material compilation stage where geometric models of fibers of appropriate length, orientation, and volume fraction, for a given length, were generated. This multiscale, multimaterial model was then sliced into layers and voxelized to take advantage of the VoxelPrint™ technology from Stratasys. Fabricated parts consisted of the two Polyjet photopolymers, an elastomeric matrix material (TangoPlus™) and a rigid resin (Vero™) that was used for the printed fibers. The digital workflow is shown in Figure 1.

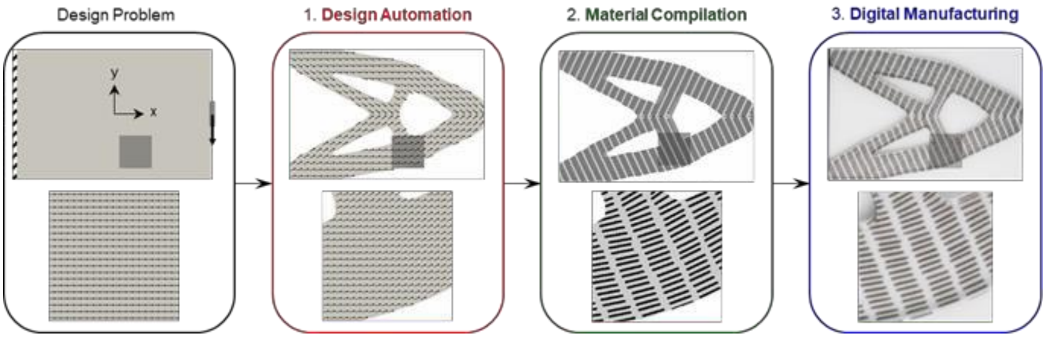

Figure 1. Workflow for simultaneous design and manufacturing of multimaterial, multiscale structures.

This design approach was extended for designing flat laminates that were intended to be printed with a MarkForged Mark 2 printer, with polyamide parts selectively reinforced with carbon fiber; laminates were the focus since the fiber reinforced layers must be planar.

Future work will extend this approach to 3D parts and structures of arbitrary shape and complexity. One needed extension is from short fibers, which can be approximated by the local fiber orientation model in our TO method, to long or continuous fibers. In principle, this can be achieved by connecting together curves of short fibers, but various constraints on fiber connectivity, loading, bending, and placement must be considered. Robotic workcells are being developed that combine material extrusion heads, 5- axis platforms, and automated fiber placement heads for the fabrication of large, complex, fiber- reinforced parts. Such workcells are the intended fabrication target for this work.

Shape-Changing Structures: The term “4D printing” is used informally to describe the 3D printing of structures that can change shape through the stimulus-response actions of shape memory polymers. We have developed a series of 4D printing technologies and demonstrated them using multimaterial rods and laminates that change from a planar, printed shape into a 3D final shape. The research to be highlighted here involves the one-way shape change of a multimaterial structure based on a consideration of Eigenstrains induced by residual stresses in one constituent material [2]. The structure design problem can be stated as: design a multimaterial structure that changes from an initial to a final shape and that can support given loads or exhibit desired stiffnesses or deformations in its final shape. Initial research has progressed in three directions. First, the material distributions in rods were designed such that rods or rod structures deformed into desired 3D shapes [3]; see Fig. 2. Second, the topology and material distribution of laminates were designed by extending the multimaterial, multiscale TO method described earlier. Lightweight, multimaterial laminates were synthesized that changed from planar to various cylindrical and saddle shapes.

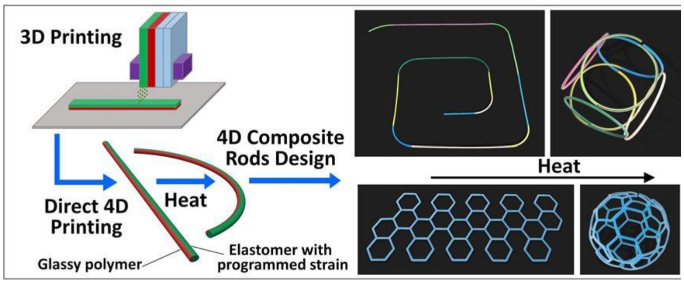

Figure 2. 4D printing examples.

The third direction has as its objective the development of TO-based design synthesis methods that can be integrated into commercial computer- aided design (CAD) systems. We are developing implicit models of part geometry, physical property distributions, and material compositions to support a wide variety of design, engineering, and manufacturing tasks [4], including all of the work described above. We hypothesize that these implicit models can be used as representations in level-set TO methods, since the level-set is a type of implicit geometric model. Initial methods and results in this direction will be presented.

AM Constraints: The last topic to be considered is constraints imposed by various AM processes. A lot of research has focused on this topic in the last several years. The state of the art will be reviewed, considerations arising from the earlier described multimaterial and shape-changing structures will be discussed, and research directions identified that will become increasingly important as the field expands and evolves. The concept of simultaneous product-material-process design can provide a framework for helping engineers to design products while considering how manufacturing processes affect properties of materials for specific part geometries, which seems necessary for effective DFAM.

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Design for Additive Manufacturing – Comprehensive Software Solutions

Ming Zhou, Fabian Fuerle, Raphael Fleury, Martin Solina
zhou@altair.com, Altair Engineering, Irvine, CA 92614, USA

In recent years additive manufacturing, known broadly as 3D-Printing, has become one of the broadest technology movements. Low cost desktop printers made the technology widely available even for elementary school kids to experience and explore. At the same time real innovative applications have emerged in many engineering fields including biomedical, aerospace and automotive industries. 3D-Printing brings almost unlimited design freedom for shape and form, hence offers unmatched symbiosis with topology optimization for creation of efficient and innovative designs. Many successful applications created with topology optimization have been showcased in real product environment by leading global companies. It is obvious that 3D-Printing is fundamentally a digital technology where real product can be printed immediately when the design is engineered on a computer. As such software solutions play a critical role for effective and efficient utilization of additive manufacturing technology. This paper focuses on creating a comprehensive and integrated software environment where: (1) Design is created via topology optimization;(2) Organic geometry is created with 3D-Printing in focus; (3) Print processing follows seamlessly from support generation to standard CLI file output. For manufacturing friendly design, overhang angle is treated either as a constraint or as a design penalty. Another strong focus is the creation of lattice structures that is unique to additive manufacturing. Lattice at mesoscale opens long thought after engineering freedom towards meta-material creation.

Topology Optimization of Structures for Additive Manufacturing with Considerations of Manufacturing Constraints and Material Properties

Weihong Zhang *, Jihong Zhu[1]

[1] *State IJR Center of Aerospace Design and Additive Manufacturing, School of Mechanical Engineering Northwestern Polytechnical University*

* Corresponding author: zhangwh@nwpu.edu.cn

Recently, the integration of topology optimization method with additive manufacturing provides a new promising approach for the achievement of lightweight and high performance structures. Topology optimization always generates structure configuration with complex and nontraditional geometries. This makes it uneconomical and even impractical for fabrication using traditional subtractive machining techniques. Comparatively, additive manufacturing (AM) is a design-oriented manufacturing technique. It forms a mechanical part layer by layer through the joining of liquid, powder or sheet materials, which allows the processing part to “grow” freely up to the optimized configuration.

The aim of this work is twofold. First, a topology optimization method is developed for the design of self-supporting structures that can directly be realized by additive manufacturing. In the proposed method, polygon-featured holes are introduced as basic design primitives whose movements, deformations and intersections allow to control the structural topology. In order to ensure the self-supporting of the optimized structure, relative vertex positions of each polygon are formulated as proportional design variables. As a result, overhang constraints are easily imposed by properly bounding selected design variables to avoid auxiliary supports. Meanwhile, unprintable V-shaped areas caused by polygon intersections are gradually eliminated through polygon modifications and re-optimization. It is shown that the elimination of artificial support materials comes at the cost of increasing structural compliance. It is also found that optimized printable configurations depend upon the imposed value of critical overhang angle (COA) and the recommended build direction. Furthermore, the realization of connectivity design is discussed for the optimized configuration to satisfy the processing condition of additive manufacturing. Numerical examples are tested to demonstrate the effectiveness of the proposed method.

Second, material properties and mechanical performances of the structure produced by additive manufacturing are investigated. To do this, standard specimens and representative structures topologically optimized and then fabricated along different building directions are studied. With the help of Digital Image Correlation (DIC) and Optical Microscope (OM), the anisotropies of stiffness and strength are experimentally explored for polymer and titanium materials processed by Stereolithography (SLA) and Selective Laser Melting (SLM), respectively. For the SLA produced structures, experimental results show that stable mechanical properties can be obtained for a batch of testing specimens. Meanwhile, the material stiffness can also be significantly enhanced with the ultraviolet post-curing. However, obvious anisotropies exist for structural performances such as stiffness, ultimate strengths and places of fractures caused by printing direction. It is confirmed that the SLA printed materials are nearly isotropic within the layer-printing plane (XOY). However, when the printing direction changes in XOZ plane from 0° to 90°, the elastic modulus is experimentally found to change in a 'V' shaped manner and the stretching capability is insufficient along the printing direction. As a result, a transversely isotropic material model is more suitable to describe the elastic behavior of SLA produced structures. In this case, the failure of tier splitting in building direction and the fourth strength theorem should be considered in the strength analysis. For this reason, it is necessary to introduce anisotropic properties instead of using 'ideal' isotropic material model for topology optimization when SLA is used for fabrication.

For the SLM produced TC4 structures, the elastic stiffness and maximum strength show a good consistency in all tests. The structural stiffness values are generally similar while the strength behaviors show a difference mainly due to the surface quality of the structure. In detail, the value of elastic modulus of unpolished specimen fluctuates between 102,863 and 106,079Mpa with a maximum variation of 3%. Meanwhile, the value of yield strength fluctuates between 926.4 and 954.2MPa with a maximum variation of 2.9%. A slight improvement in material stiffness and strength can also be noticed after the surfaces of the specimens are polished. Therefore, the SLM printed titanium material is almost isotropic in XOZ plane compared with that produced by SLA.

The above results have clearly shown that the specific behaviors and their variations affect the structural design and optimization significantly. The considerations of these properties and behaviors are therefore indispensable in improving the structural performance and strengthening practical applications of additive manufacturing.

Acknowledgments

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Multiscale Topology Optimization of Shell-infill Structures using a Distance Regularized Parametric Level-set Method

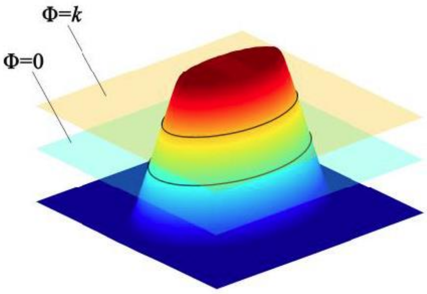
Liang Gao[1]*, Junjian Fu[1], Hao Li[1], Mi Xiao[1]
[1]*State Key Lab of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, 430074, Wuhan, China*
* Corresponding author: gaoliang@mail.hust.edu.cn

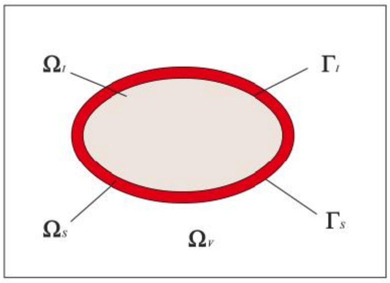
Shell-infill structures are widely used in additive manufacturing (AM) to retain the external appearance and reduce the printing costs. However, shell-infill structures are generally designed by a single-scale topology optimization method. In this case, these shell-infill structures are not optimal designs due to their incompatible shell and infill layouts. In order to obtain the optimized shell and infill simultaneously, this research presents a multiscale topology optimization method for designing shell-infill structures using a distance regularized parametric level-set method.

In macroscale optimization, as shown in Fig.1, two distinct level sets of a single level set function (LSF) are used to represent the interface of the shell and the infill, respectively. The thickness of the shell is assumed to be uniform. In order to obtain a controllable and uniform shell thickness on macroscale, a distance regularization (DR) term is introduced to formulate a weighted bi-objective function. The DR term is minimized along with the original objective, regularizing the macro parametric LSF close to a signed distance function. With the signed distance property, the area between the two level sets can be contoured as the shell with a uniform thickness.

In microscale optimization, the pattern of the microstructure is optimized to achieve the optimal macro structural performance. The numerical homogenization method is applied to evaluate the effective elasticity matrix of the microstructural infill. The shell-coated macro structure and the micro infill are optimized concurrently to achieve the optimal shell-infill design with prescribed volume fractions.

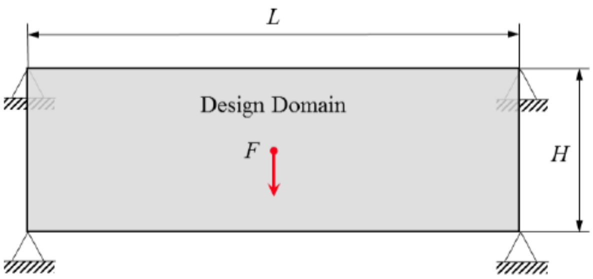
Both 2D (Fig.2) and 3D (Fig.3) examples are investigated to demonstrate the effectiveness of the proposed method. Numerical examples show that the optimal designs are different from the traditional multiscale optimization designs when a shell is considered. In the macroscopic design, the structure with a shell is thinner than the structure without a shell under the same material usage. In the microscopic design, both the topology and the effective elasticity matrix of the optimized microstructures have changed after the incorporation of a shell. The presented method is not limited to the design of shell-infill structures for AM. It can also be extended to the design of bio-inspired structures with shell and infill.



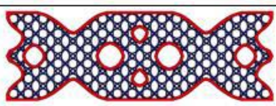
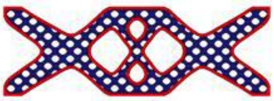
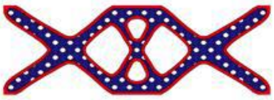


(a) The LSF intersected by Φ=0 and Φ=k   (b) The shell-infill structure with uniform thickness

Fig.1 Illustration of the shell-infill structure



(a) Design domain

V^{MA}	V^{MI}	Macro design with the shell	Micro infill design	Effective elasticity matrix
	0.4			$\begin{bmatrix} 0.1239 & 0.0964 & -0.0000 \\ 0.0964 & 0.1972 & 0.0000 \\ -0.0000 & 0.0000 & 0.0825 \end{bmatrix}$
	0.6			$\begin{bmatrix} 0.3545 & 0.1772 & -0.0000 \\ 0.1772 & 0.2778 & -0.0000 \\ -0.0000 & -0.0000 & 0.1657 \end{bmatrix}$
0.4	0.8			$\begin{bmatrix} 0.6559 & 0.2337 & -0.0000 \\ 0.2337 & 0.5413 & -0.0000 \\ -0.0000 & -0.0000 & 0.2456 \end{bmatrix}$
	1.0			$\begin{bmatrix} 1.0989 & 0.3297 & -0.0000 \\ 0.3297 & 1.0989 & -0.0000 \\ -0.0000 & -0.0000 & 0.3846 \end{bmatrix}$

(b) Design with varying micro volume fractions

Fig.2 Shell-infill design for a 2D structure

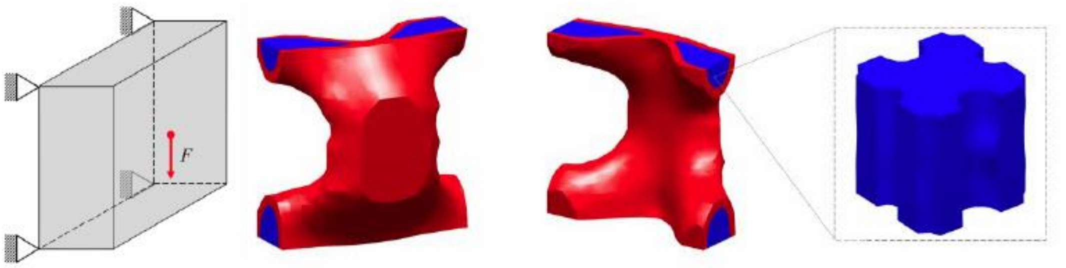


Fig.3 Shell-infill design for a 3D structure

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Design of Manufacturable Multiscale Structures using Robust Topology Optimization

Wei Chen
Northwestern University

The advances of manufacturing techniques, such as additive manufacturing, have provided unprecedented opportunities for producing multiscale structures with intricate latticed/cellular material microstructures to meet the increasing demands for parts with customized functionalities. However, there are still difficulties for the state-of-the-art topology optimization (TO) methods to successfully achieve manufacturable multiscale designs with cellular materials, partially due to the disconnectivity issue of neighboring material microstructures. In this talk, we will present two different approaches for addressing this challenge.

First, a concurrent topology optimization approach for designing multiscale structures with multiple porous materials is introduced. To determine the optimal distribution of the porous materials at the macro/structural scale, the discrete material optimization method is employed to interpolate the material properties for multiple porous materials. The material interpolation scheme integrates the SIMP (Solid Isotropic Material with Penalization) at the microscale and PAMP (Porous Anisotropic Material with Penalization) at the macroscale into a single equation.

Second, a hierarchical multiscale TO design framework based on the concept of connected morphable component (CMC) will be presented. An effective linkage scheme to guarantee smooth transitions between neighboring material microstructures (unit cells) is devised to address the disconnectivity issue. Associated with the advantages of CMC based TO, the number of design variables is greatly reduced, which makes multiscale TO design a manageable all-in-one optimization problem that can be handled using conventional mathematical programming optimization algorithms. Mathematical homogenization is employed to calculate the effective material properties of the porous materials and to correlate the macro/structural scale with the micro/material scale.

Finally, both concurrent and hierarchical multiscale TO methodologies are extended to design robust high performance multiscale structures considering random field loading uncertainties. 2D and 3D examples demonstrate the effectiveness of the proposed approach in simultaneously obtaining robust optimal macro and micro structural topologies.

Large-Scale Topology Optimization Oriented Towards Additive Manufacturing

Oded Amir, Yoram Mass and Eilam Amir
Faculty of Civil and Environmental Engineering,
Technion – Isreal Instititue of Technology, Haifa, Israel
odedamir@.technion.ac.il, http://structopt.net.technion.ac.il

Key Words: *Topology optimization, Additive manufacturing, Support structure*

Structural topology optimization procedures deal with optimizing the distribution of material within a defined volume, subjected to external loads and boundary conditions. As these methods can generate relatively complex designs, additive manufacturing (AM) technologies seem to be the perfect match for producing topologically optimized strucutres. Despite the great freedom that AM can provide to designers, the technology still suffers from various limitations. One of these is the maximum overhang angle, meaning that one cannot manufacture overhang patterns without additional supports. The most immediate idea to alleviate this limitation is to integrate the supports in the design – meaning generate topologies that include supporting structures and can thus be printed without additional scaffolding.

The topic of overhang limitations and minimization of support structure volume has attracted significant research efforts and several methods were developed recently. So far, the various research trajectories include: 1) Methods relying on filtering or projection in the density-based framework (e.g. Gaynor & Guest, 2016; Langelaar, 2016); 2) Methods relying on boundary or density gradients (e.g. Allaire et al., 2017; Qian, 2017); 3) A method using an explicit geometry representation (Guo et al., 2017); 4) A direct support volume approach (Mirzendehdel and Suresh, 2016); 5) A method relying on a pre-optimized printable virtual skeleton (Mass and Amir, 2017); and 6) A method using gravity as a surrogate load that can penalize the existence of overhanging patterns (Allaire et al., 2017; Amir and Mass, 2017). From the results in the literature and from the brief industrial experience with 3-D printing of optimized parts, it appears that fully satisfying the overhang limitation can be very challenging. Hence it is inevitable that either the structural performance, or the volume of supporting structures, will be compromised.

The talk will focus on two methods that our research group has been investigating, in the framework of an industry- academia consortium that aims to additively manufacture critical load-bearing components in Ti6Al4V for aerospace applications. In the talk, we aim to discuss not only the theoretical formulations and the implementation in academic settings, but also the applicability of the computational procedures for complex real-world design scenarios – which pose various challenges. As a consequence, the aim is to evaluate the proposed methods on industrial cases that are optimized using high-resolution voxel-based topology optimization techniques.

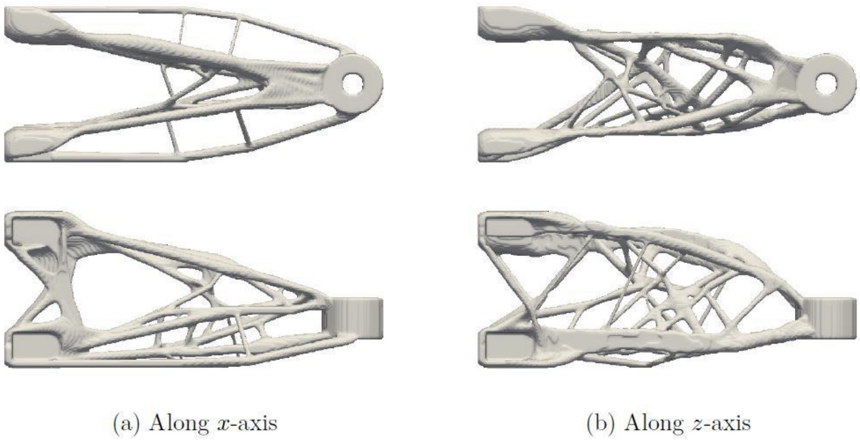

Figure 1: Topological design with the virtual skeleton approach

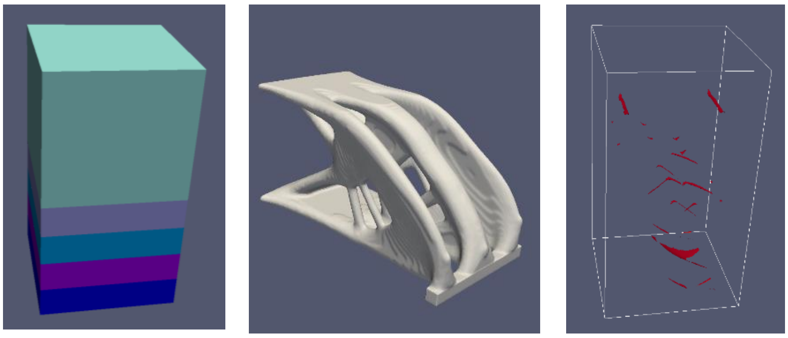

Figure 2: Topological design with a slicing approach and gravity loads

First, we will present a method that defines a “virtual skeleton” – essentially an optimal truss that is generated based on allowable directions only. The stiffness of the load-carrying continuum is subsequently linked to the existence of truss members by a geometric projection, thus giving preferred locations for material distribution in the continuum problem. Despite some encouraging results in simple 2-D and 3-D examples, the method so far did not yield good compliance-printability trade-offs in complex 3-D design scenarios. Nevertheless, it will be shown that an initial assessment of the preferable printing direction can be obtained efficiently by the truss-based optimization.

In the second part of the talk we will discuss a method that uses gravity loads as a surrogate, applied on the structure as it is built in order to prioritize self-supporting patterns. By slicing the design domain and considering several fabrication stages, optimized designs are obtained that are influenced by the building direction and by the excessive deformation of unsupported layers. Results show that the method is capable of reducing the volume of the supporting structure with relatively small compromise on the performance in terms of compliance. A promising extension of this method is formulated by allowing the existence of cellular material alongside solids and voids. It will be shown that such hybrid solutions can exhibit a superior balance between performance and printability compared to void-solid topologies.

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Optimization of Pseudo-Ductile Behavior of Hybrid Composites under Uniaxial Traction

F. Conde[*], P. Coelho[**], R.Tavares[*], J. M Guedes[*], P.Camanho[*], H. C. Rodrigues[*]
[*]*Laeta- Associated Laboratory for Energy, Transports and Aeronautics, Portugal*
[**]*FCT, UNL- Universidade Nova de Lisboa*

This study aims to realise a "pseudo-ductile" behaviour in the mechanical response of hybrid fibre reinforced composites under uniaxial traction. The composite material model is based on the combination of different types of fibres (with different failure strains or strengths) embedded in a polymer matrix. Analytical models predict the composite failure under tensile load. An optimisation problem formulation is proposed, and a genetic algorithm is used to identify "optimal designs". The design problem is formulated as a multi-objective optimisation problem balancing failure strength and ductility criteria to identify optimal mixtures of fibres. Typically, ductile failure is an inherent property of metals. Diversely, composite materials exhibit (under some loading conditions) brittle failure that may limit their widespread usage. Therefore, enhancing a "pseudo-ductile" behaviour in composites is an important design objective.

Sequential Approximate Integer Programming for Topology Optimization

Gengdong Cheng, Yuan Liang
State Key Laboratory of Structural Analysis for Industrial Equipment,
Department of Engineering Mechanics,
International Research Center for Computational Mechanics,
Dalian University of Technology, Dalian, 116023, P.R. China
E-mail address: chenggd@dlut.edu.cn

Structural topology optimization (STO) has experienced fast development during the last three decades. Various methods and related mechanical and mathematical theories were proposed. Recent years also witnessed many successful applications in the field of aerospace, aeronautic, automobile and mechanical engineering, where many innovative designs were produced with the help of STO. Dedicated commercial software also played an important role at this splendid stage. The recent integration of additive manufacturing and topology optimization (TO) further adds new impetus to the field of STO.

The Solid Isotropic Material with Penalty (SIMP) approach, the most popular approach for TO, is actually a pixel-based approach and describes structural topology by a 0-1valued density function characterizing the material distribution at each material point of the design domain. Under this circumstance, the corresponding problem is essentially a NP-hard 0-1 discrete optimization problem. To overcome the huge computational burden for solving the aforementioned large-scale integer programming problem, the popular way is to relax the 0-1 constraints imposed on the design variables, and transform the original 0-1 integer programming problem to a relaxed one with continuous design variables that can be solved with use of gradient-based optimization algorithms. While great success has been achieved, a number of unwanted features of the SIMP method remains to be further addressed.

Firstly, the pixel-based design description in SIMP and Evolutionary Structural Optimization (ESO) methods is not consistent with the geometry representation schemes adopted in current computer aided design (CAD) systems. Secondly, optimization results obtained by the pixel-based method often exhibit grey regions where the corresponding element densities are not pure 0/1, blurred structural boundary and uncontrolled structural features. These problems become even more severe in three- dimensional cases. Moreover, additive manufacturing also introduces some special constraints (e.g., overhang angle constraints, structural connectivity constraint and thermally-induced distortion constraint) to ensure the manufacturability of an optimized design. Solving these problems calls for the development of new numerical algorithm for topology optimization.

In this presentation, authors follow the classic idea of sequential approximation programming (SAP) in structural optimization and utilize the sensitivity information to construct the approximated Sequential Quadratic/Linear Integer Programming (SQIP/SLIP) sub-problems explicitly. These SQIP/SLIP sub-problems can then be solved with the so-called canonical relaxation algorithm constructed from the canonical dual theory. The new method supplemented with two different move limit strategies successfully solves a set of different topology optimization problems. Numerical examples demonstrate that compared to the classical branch and bound approach, large-scale discrete TO problems with a large number of 0-1 design variables can be solved with the proposed approach in a computationally very efficient way, and pure black-and-white design can be generated when combined with the move limit strategy of controlling the volume fraction parameter. The new method can also efficiently solve the discrete variable topology optimization problems with multiple nonlinear constraints or lots of local linear constraints such as the infill design problem in a unified and systematic way. It is very interesting that the optimum solution of maximum heat conduction efficiency problem obtained by the new algorithm has the appearance of grass instead of tree, which resembles the recent results by Sigmund' group.

Topology Optimization of Non-linear Structures

Mathias Wallin[1], Niklas Ivarsson[1], Anna Dalklint[1] and Daniel Tortorelli[2]

[1]*Division of Solid Mechanics, Lund University, Box 118, SE-22100 Lund, Sweden.*
E-mail: mathias.wallin@solid.lth.se
[2]*Center for Design and Optimization, Lawrence Livermore National Laboratory, Livermore, CA, USA*

For structures operating in the linear regime, numerical design optimization schemes has successfully been applied to generate optimal designs. Simple objectives such as stiffness and eigenfrequency for linear elasticity can be found in commercial softwares packages and they are today used on daily basis in industry. For non-linear systems, design performance is predicted by complex simulations which exhibit, multiple length scales, nonlinearities and transients. Numerical models that can predict the non-linear and irreversible response of structures are well established, thus needed is the link that connects the simulation schemes to computational optimization schemes. In this talk, recent steps towards closing the gap between non-linear analysis and topology optimization will be discussed. For all applications we use density based topology optimization and gradient based optimization. To regularize the problem formulation we use a PDE based filter technique. All problems are solved using the MMA scheme.

Stiffness optimization of non-linear structures

A common objective of small strain topology optimization is stiffness maximization. This objective has for instance the advantage of being self-adjoint, which leads to that the sensitivities are trivially obtained. The generalization of the small strain stiffness optimization to large strains is not unique and in this talk we show that the choice if objective plays an important role for the optimized design. In the area of finite strain topology optimization the vast majority of the contributions are based on Saint-Venant's elasticity where the Green-Lagrange strain is linearly connected to the second Piola stress. This model is known to perform poorly and therefore we use a neo-Hookean strain energy. From the implementation point of view this choice of material model adds complexity, but we show that it can be handled efficiently within the standard finite element framework. In the numerical examples we compare the secant stiffness, minimum potential and the tangent stiffness for some well-known structures and we show that the optimized designs are higly influenced by the choice of definition of the stiffness.

Energy absorbing structures of visco-plastic structures

Path-dependent material response has previously been used in the context of topology optimization but the amount of research is limited. The research that address irreversible response has so far been limited to small strains and are it is therefore of lesser relevance for design of energy mitigating structures since the strains and deformations in general are large during such processes. In the present talk, we extend the topology optimization framework to take large plastic strains into account. Since energy absorption frequently takes place at elevated strain rates, visco- plasticity is utilized and, moreover, since inertial effects might be of importance we solve the transient response using the Newmark time stepping procedure. The sensitivities required to update the design is obtained by the adjoint approach which for the transient visco-plastic problem becomes a terminal value problem, i.e. we first solve the primal visco-plastic problem and then based on this solution we calculate the sensitivity with respect to the element densities. We apply the theory to design structures that are optimized for energy absorption. The results show that the rate of impact plays an important role when designing energy absorbing structures.

Buckling and eigenvalue optimization of hyper-elastic structures

Topology optimization often renders structures where the load is transferred in pure tension and compression. Since the load carrying members that are subject to compression are at the risk of buckling, this must be taken into account in the design process. A simple route to address this problem is to make use of a linearized buckling which leads to an eigenvalue problem. This approach may be used for small strains, however, for situations where buckling is preceded by large deformations it can not be used. In the present talk, we show possible routes to include buckling constraints into topology optimization. The buckling modes that the algorithm detect may occur in void regions, i.e. artificial buckling modes may be present. In the talk we will illustrate possible routes to eliminate these artificial modes. A companion problem to the buckling problem is that of eigenvalue optimization. Also for this problem, we will show that the deformation level will significantly influence the eigen frequency; a matter that is often ignored.

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Parallel Multi-scale Topology Optimization of Lattice Materials in Point View of Additive Manufacture

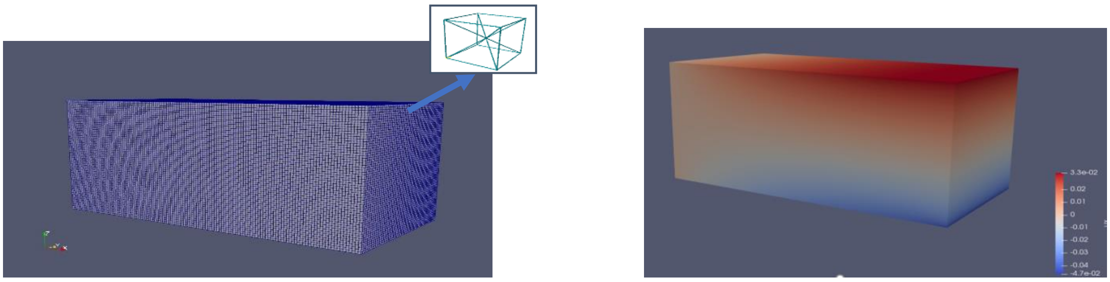
Jun Yan[1]*, Tao Yu[1], Chenguang Zhang[1], Junhui Guo[2], Qiang Zhou[2]
[1]*State Key Laboratory of Structural Analysis for Industrial Equipment, International Research Center for Computational Mechanics, Dalian University of Technology, 116023, Dalian, China*
* Corresponding author: yanjun@dlut.edu.cn
[2]*Institute of Manned Spacecraft System Engineering, China Academy of Space Technology,100094, Beijing, China*

With the rapid development in additive manufacturing technologies, lightweight porous materials have been increasingly utilized in many application areas as load-bearing members, heat exchangers, energy absorbers, and key components of aircraft engines, etc. An important kind of such materials is the so-called “structured porous materials” which feature porous constructions with periodical microstructures (e.g., metallic honeycomb, truss-like lattice materials and some cellular alloys). Besides their multifunctionality, structured porous materials also show unique designability across both the microscale (i.e. design of microstructural patterns) and the macroscale (i.e. design of structural configurations). As such, there is an utmost need for multiscale optimization methodologies to achieve optimal structures with optimal microstructures given any specific design objectives and constraints.

A successful design approach has to address three critical challenges that are unique to the multiscale nature of the posed optimization problems. First, the number of dimensions of the structural design space multiplied by that of the microstructural design space leads to a huge amount of dimensions for the concurrent design, making it almost unsolvable by conventional single-scale design approaches. Second, even with advanced manufacturing technologies such as the 3D printing, manufacturability is still a topic of concern, making it necessary to have some control over the microstructural optimization in the multiscale design. Third, due to the multifunctional utilization of lightweight porous materials, it is essential to consider mechanical, dynamical and thermal objectives and constraints, and their combined effects in the multiscale design.

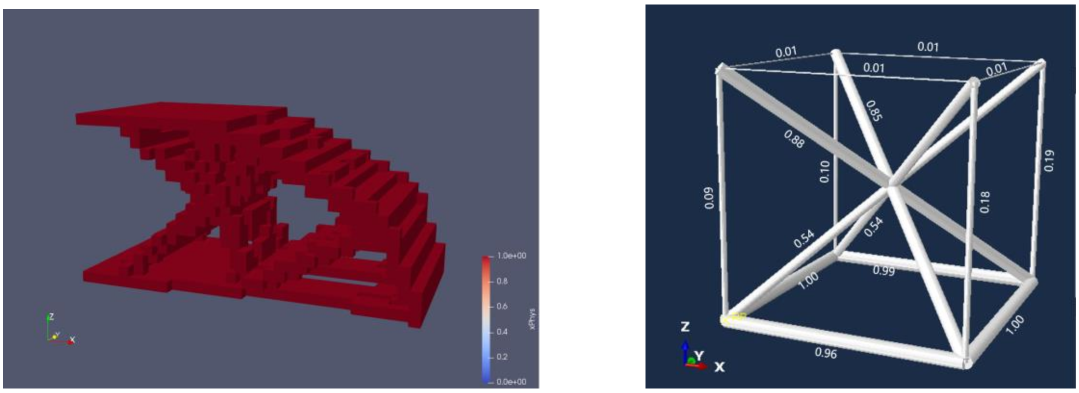
A computationally effective solution framework for multi-scale structural topology optimization had been established in this research. A so-called Porous Anisotropic

Material with Penalty (PAMP) material-based method (PAMP method) had been developed to resolve the challenging issues arising from the ultra-large dimension of design space.The asymptotic homogenization theory and the Extended Multi-scale Finite Element Method (EMsFEM) were utilized to realize the coupling of the materials and structures.



(a) Structural macroscopic configuration (b) X direction displacement cloud map

Fig.1 Numerical example:8,388,608 micro element



(a) Optimal structural macroscopic configuration (b) Optimal material microscopic configuration

Fig.2 Numerical example of multiscale design of lattice materials based on parallel optimization

The multi-scale topology optimization base on a fully parallel and easy-to-implement topology optimization framework is established for minimum structural compliance problems. The presented framework makes it possible to solve large scale concurrent optimization problems and makes optimization procedure more efficient. The capabilities of this parallel concurrent optimization framework are exemplified by some numerical examples of three-dimensional lattice structures with large scale finite elements. And the multiscale concurrent optimization model is extended to thermo-elastic, and coupled thermal-elastic lattice structures. The effects of optimization of size of unit cells, the size of thermal load and the amount of base material are considered.By using such fine discretization, the optimization result reveals new design features and becomes more conducive to manufacturing through 3D printing technique.

This presentation mainly reports on the progress of multi-scale analysis and optimization design of the ultra-light porous structure and material, thermo-elastic ultra-light porous materials and structures, zero-expansion material optimization, bionic optimization design of thermal structure, and engineering application of the multi-scale topology optimization methods.

Key words: Parallel computing, Multi-scale concurrent topology optimization, Lattice structure, Extended multi-scale finite element method, Additive Manufacturing

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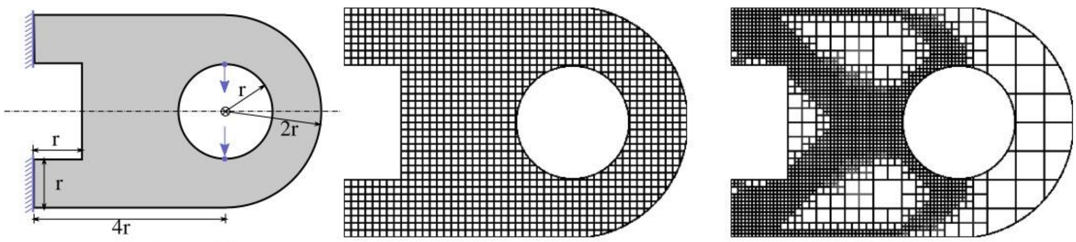
Topology Optimization of Adaptively Refined Infill Structures for Additive Manufacturing

Jun Wu
Dept. of Design Engineering Mechanics, Delft University of Technology,
Landbergstraat 15, 2628 CE Delft, The Netherlands
j.wu-1@tudelft.nl

Rather than fabricating fully solid models, engineering practices in additive manufacturing seem to favour porous structures. For instance, in fused deposition modelling (FDM), the interior of 3D models is often filled with repetitive triangular or rectangular grids known as infill. See Figure 1 (b) for an illustration of uniform, rectangular infill pattern within a 2D bracket-shaped domain. The concept of porous infill is initially introduced to roughly balance cost and mechanical properties: A larger infill volume percentage leads to a stronger print at the cost of more material and longer printing time. Recent research found out that infill structures can obtain significantly increased stability with respect to buckling [1] and unpredicted loading conditions [2] at the expense of a minor decrease in stiffness. These works have assumed a constant infill volume percentage across the design domain: In [1] the base material is interpreted as uniform, isotropic infill, and in [2,3] anisotropic infill is generated yet the effective local volume percentage is constant.



(a) Boundary condition (b) Uniform pattern (c = 566.2) (c) Balanced quadtree (c = 143.4)

Figure 1. (a) Illustration of the design domain and boundary conditions. (b) The 2D design domain is filled with uniform infill structures. (3) Adaptive quadtree infill by the proposed continuous topology optimization approach. The adaptive infill is four times stiffer than the uniform infill.

In this work we break the assumption of uniform infill volume percentage as in [1,2,3] and propose a topology optimization method to generate adaptively refined infill structures. An optimized quadtree for the bracket shape is shown in Figure 1 (c). Adaptively refined structures are a good option for 3D printed infill. On the one hand, the adaptivity can be exploited to enhance regions where denser structures are beneficial to support the mechanical loads. For instance, in the bracket example the optimized quadtree infill performs four times stiffer than the uniform infill. On the other hand, the structures on a uniform coarse grid filling the part's interior make the printed part robust for uncertain and smaller loads, such as forces during transportation and manipulation that possibly happen to any surface region of the printed model. Furthermore, doing topology optimization by adaptive structure refinement allows for an intuitive control over some structural features. For instance, the coarsest and finest grids effectively determine the maximum and minimum void sizes, respectively. The interior structures have a uniform thickness, which simplifies tool-path generation in 3D printing. The uniform thickness and the minimum void size have positive implications on thermal effects in the additive manufacturing process.

The problem under consideration is the finding of a quadtree structure that maximizes the stiffness regarding prescribed mechanical loads, under the constraint of a given material budget. This is a discrete optimization problem: for each cell, to refine or not to refine it. Accurately solving discrete optimization problems is challenging, especially when the number of design variables is large. Moreover, in (discrete) quadtree optimization the number of design variables is not constant: new cells (and thus design variables) are created as the refinement progresses. A greedy approach to the discrete quadtree optimization problem is suggested in [4] where (rhombic) cells are selectively refined based on a heuristic criterion. While it has been demonstrated that the greedy approach can find a quadtree structure that is stiffer than a uniform pattern with the same amount of material, it is known that heuristic refinements result in a local optimal solution, and it might be away from the global optimum [4].

In this work we present a novel continuous optimization method to the discrete problem of quadtree optimization. The optimization aims at achieving a quadtree structure with the highest mechanical stiffness, where the edges in the quadtree are interpreted as structural elements carrying mechanical loads. We formulate quadtree optimization as a continuous material distribution problem. The discrete design variables (i.e., to refine or not to refine) are replaced by continuous variables on multiple levels in the quadtree hierarchy. In discrete quadtree optimization, a cell is only eligible for refinement if its parent cell has been refined. We propose a continuous analogue to this dependency for continuous multi-level design variables, and integrate it in the iterative optimization process. A sequence of the quadtree infill demonstrating the convergence of the continuous optimization approach is shown in Figure 2. Our results show that the continuously optimized quadtree structures perform much stiffer than uniform patterns and the heuristically optimized counterparts [5]. We demonstrate the use of adaptive structures as lightweight infill for 3D printed parts, where uniform geometric patterns have been typically used in practice.

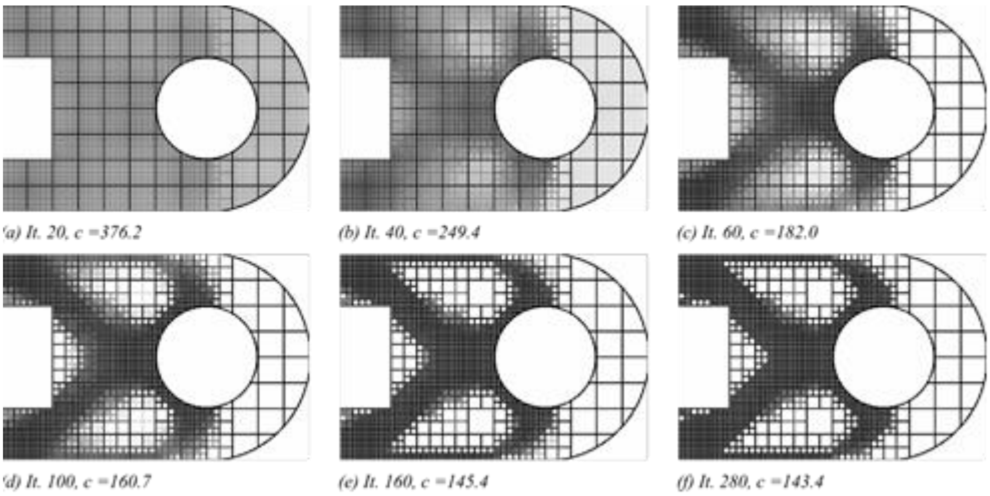


Figure 2. A sequence of the quadtree infill during the optimization process. The number of iterations (It.) and the compliance value (c) are reported.

It shall be noted that obtaining spatially adaptive structures clearly distinguishes from previous use of adaptive mesh refinement in topology optimization, where the motivation is to reduce the intensive finite element analysis by reducing the number of elements. Spatial adaptive meshes (i.e., quadtree in 2D and octree in 3D) are often employed in numerical analysis to attain a required accuracy for a minimum amount of computation. In the context of topology optimization, adaptive techniques for reducing the number of design variables date back to [6]. The adaptive mesh used in the literature represents the finite elements for elasticity analysis, and its refinement criterion is based on estimated errors. The obtained structures are similar, if not identical, to the structures optimized with uniform fine meshes. In contrast, here the adaptive mesh, its edges in particular, represents the physical structures to be obtained from optimization. The structural refinement respects global measures on the structural stiffness and the material volume. The structures our method is aiming at cover the entire closed-walled design domain (see Figure 1 (c)).

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The Opportunities and Challenges Brought by Additive Manufacturing to Topology Optimization

Haihui Liu[1*], Lyu Zhang[1], Jiyuan Ye[1]

[1]*EOS Electro Optimal Systems (Shanghai) Co., Ltd., 200233, Shanghai, China*

* Corresponding author: alex.liu@eos.info

Abstract Topology optimization (TO) is a design approach which aims to find the optimal distribution of material in a given design space under certain loading and boundary conditions. Because of the design complexity from TO, however, the optimized parts are sometimes difficult to be manufactured. With Additive manufacturing (AM), also known as 3D printing, it is possible to handle such complexity, which in turn to shorten the distance between design and manufacturing. Meanwhile, there are some factors, such as material properties, design restrictions, cost and efficiency, need to be take into account when using AM technology, especially on the Direct Metal Laser Sintering process (DMLS). This paper will discuss the impact of those factors to TO design.

Keywords: Topology Optimization, Additive Manufacturing, Design Guidelines, Structural Optimization, DMLS

Scratch Analysis and Optimization Design for Fan Blade and Case of Aero Engine

Chai Xianghai[1,2], Shi Tongcheng[1,2]
[1]*Department of Discipline Engineering, AVIC Commercial Aircraft Engine Co., LTD, Shanghai 200241, China;*
[2]*Shanghai Engineering Research Center of Civil Aero Engine, Shanghai 200241, China*

Abstract: The application of wide-chord swept fan blades in advanced high bypass ratio turbofan engines makes the influencing factors of rubbing between fan blade and case become more and more complex. However, the traditional design method for the tip clearance considers only radial elongation of the fan blade, which leads to rubbing risk between fan blade and case. Based on the rubbing test results of an aero engine, the simulation model is built to analyze blade transformation and case failure. The rubbing problem is optimized by the optimization design of the blade, the abradable coating, and the case. The analysis method for rubbing between fan blade and case can improve the control precision of tip clearance, which can reduce the rubbing risk and decrease the rubbing damage of fan blade and case.

Key words: aero engine; wide-chord fan blade; fan case; crash; numerical simulation; optimization design

The wide-chord swept fan blade (WCSFB) has been extensively used in the advanced high bypass ratio turbofan engines. The application makes the influencing factors of rubbing between fan blade and case become more complex. And the transformation and failure characteristics of a fan blade and case are vastly different from those of a narrow-chord blade under the crash loads. So the crash design method for fan blade and case of aero engine is needed.

1. Influence Factor Analysis of Crash between Fan Blade and Case

The scratch between the blade and the case is usually simplified as a rotating cantilever beam with periodic variable load, which is solved by a nonlinear dynamic response method.

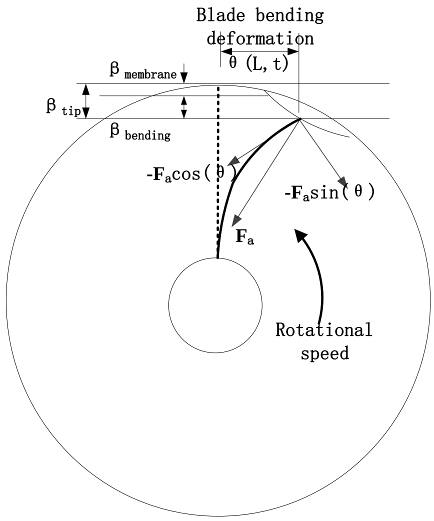
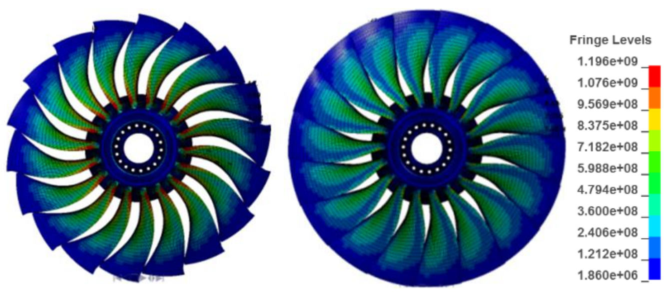


Fig.1 Dynamic characteristics for scratching between the blade and the case

When the fan blade scratches with the case, as shown in Fig. 1, the bending deformation of the blade tip can be decomposed into the bending deformation of the blade and the blade shortening caused by the spreading effect. The scratch force F_a is composed of radial load and circumferential shear force which is the value changing with time.

Based on the fan blade and case structure of an aero engine, the heavy rub reason is analyzed by the dynamic analysis method. The result shows that the crash between fan blade and case will occur at some special condition, such as the big accelerate load due to abnormality of control system or vibration.



25ms 500ms

Fig.2. Blade stress under different acceleration load

2. Analysis Method of Crash between Fan Blade and Case

The numerical simulation need conform to the dynamic characteristics of the scratch between the blade and the case, and are validated by physical test. For example, based on the rubbing test results showing in figure 3, the simulation model is built to analyze the crash and failure of blade and case as shown in figure 4, which can ensure the simulation model has enough accuracy to use the crash optimization design between fan blade and case.

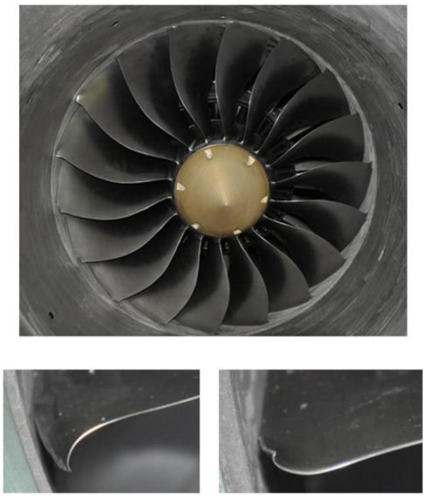


Fig.3 Rubbing between fan blade and case in fan rig test

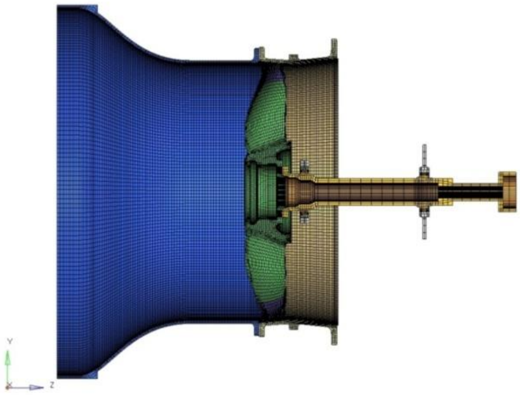


Fig.4 Dynamic analysis model for rubbing between fan blade and case

3. Crash Optimization Design between Fan Blade and Case

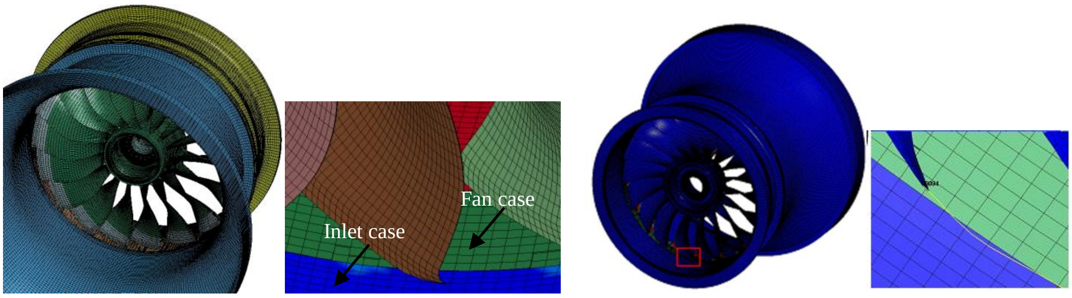
The rubbing problem can be controlled by the control design of blade, abradable coating, and case. First, before conducting physical tests， the tip clearance is designed by numeral simulation method. For example, as shown in table 1, the blade radial elongation of leading edge and trailing edge under inertia force is analyzed. As shown in table 2, the blade radial elongation under different acceleration load is analyzed. As shown in figure 5, the fan case axis size is designed by the axis displacement analysis of the blade tip under crash loads. As shown in figure 6, the thickness and strength of abradable is designed by the sensitiveness analysis of abradable parameters. Based those analysis result, the blade torsion angle need optimal design to control the tip elongation of the blade; and the axial length of the case need optimal design to control the scratch occurring within the range of the fan case, and the thickness of abradable coating need optimal design to reduce the risk of the scratch between the blade and the case. The above design variables can be obtained by numerical simulation.

Table 1 Analysis results for blade elongation under inertia force

Running Speed (rpm)	Radial elongation of leading edge (mm)	Radial elongation of trailing edge (mm)
4000	0.0327	0. 288
6000	0.193	0.647
8000	0.472	1.14

Table 2 Blade elongation under different acceleration load

Accelerating time(ms)	12.5	25	50	125	250	500
Blade elongation (mm)	3.67	3.51	3.36	2.50	1.52	0.84



(a) Axis displacement of leading edge (b) Axis displacement of trailing edge

Fig.5 Variation of the blade tip with crash loads and case design

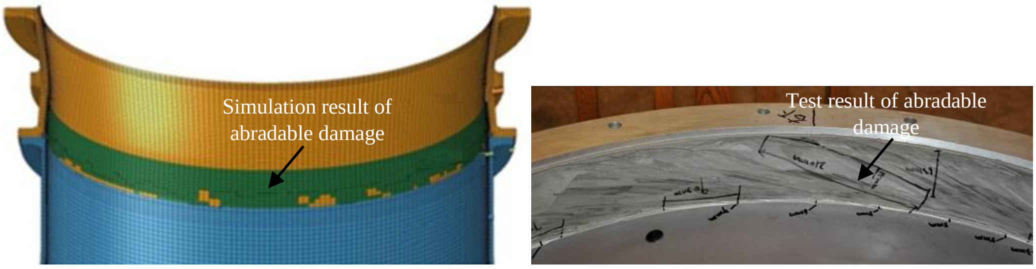


Fig.6 Comparison of the abradable coating failure

4. Conclusion

The influence factor analysis results of crash between fan blade and case show that the design of fan blade and case should consider not only traditional static analysis. The dynamic analysis should be done also. The paper provides suggestion for crash optimization design between fan blade and case based on the rubbing test results.

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A Numerical Efficient Approach of Aggregation Process for Additive Manufacturing Constraints in Topology Optimization

P. Duysinx[1]*, E. Fernandez-Sanchez [1]
[1]*Dept. of Aerospace and Mechanical Engineering, University of Liege, 4000, Liege, Belgium*
* Corresponding author: P.Duysinx@uliege.be

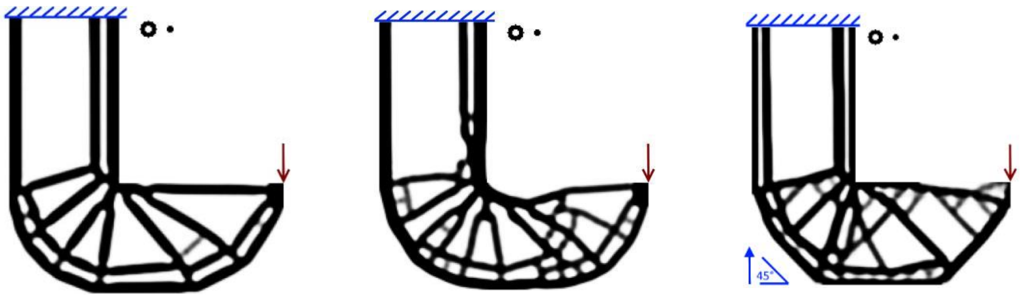
Abstract The combination of topology optimization and additive manufacturing has brought a recent break-through in engineering. Topology optimization aims at generating innovative concepts with high performance to weight ratio, but the optimized designs are often difficult to fabricate as-it-is using classical fabrication processes. On another hand, additive manufacturing technologies experience a rapid developing process and, within a decade, they have moved from simple rapid prototyping tools to industrial fabrication processes that are now able to fabricate components with high mechanical properties. In addition additive processes are able to manufacture parts with complex shapes. Thus topology optimization is a well indicated companion of additive manufacturing technologies: Topology optimization can handle the redesign process of parts that can take the best of the great capabilities of additive manufacturing (AM) techniques. Despite the enormous freedom offered by the AM approach, there are still technological limitations. In the European Project FRED[1], it has been pointed out that there is great interest in being able to consider the AM manufacturing constraints as soon as the preliminary design step handled by topology optimization. Thus the generated optimized designs require only a limited post processing operation before 3D printing so that there is nearly no degrading of the high performance of the optimized design. This work is devoted to enhance topology optimization in order to account for the characteristics of additive manufacturing constraints and to propose designs which are fitted to AM processes.

In the AERO+ research project[2], we focus on metal additive manufacturing processes, and particularly on Electron Beam Melting (EBM) and Selective Layer Manufacturing (SLM) processes. Among others, several manufacturing limitations have been reported for these processes: minimum and maximum width of structural walls, minimum size of channels for powder evacuation, no-closed cavities, overhanging angles of surfaces, presence of residual stresses and cracks, thermal deformation during the layer deposition process, geometrical precision of the final shape, surface quality and roughness, etc. In the present work, we consider some manufacturing constraints, which can be classical considered via projection filters and geometrical restrictions over the material distribution. Minimum size filters and Heaviside thresholding projections[3] are recommended to eliminate chattering designs and small size members. Maximum size filters[4] are indicated to control the bulky structural members and to reduce the hot spots during layer deposition. Recently it has also been showed that a combination of two complementary maximum size constraints[5] can control the minimum gap between members so to guarantee a good power evacuation. Finally there is a growing amount of research studies devoted to limit overhanging angles. Among others, one can cite approaches based on filtering techniques[6, 7] or on the solution of adjoin physical problems like wave propagation[8].

A vast amount of methods addressing the hereunder manufacturing limitations are based on local formulations, thus introducing a huge set of local constraints within the optimization problem. Local approaches naturally call for the use of aggregation functions in order to cut the computational burden on the optimizer. Collecting the local constraints within a few representative ones may usually seem as a simple implementation detail coming at the final stage of the formulation. Therefore it is often neglected in the discussion. However if this aggregation step is not well carefully treated the success of the whole method may be compromised and, in many cases, the simplest part of the constraint becomes time-consuming or even, the hardest point of the formulation. This work aims at treating in detail this aggregation step and tailoring a numerically efficient aggregation approach to account for the additive manufacturing constraints.

Aggregation functions are built to be smooth and differentiable approximations of the max (or min) function. In addition their sensitivity information should be smooth and easy to calculate in order to be used in efficient continuous optimization algorithms like MMA. They have also to catch accurately the most critical constraints to mimic the locally constrained problem. In the classical application in the field of stress constraints, a large number of contributions have been made on the subject (see for instance[9]), but in this case, emphasize has been put into catching efficiently the maximum value of the aggregated local constraints at the lowest possible cost while keeping a smooth convergence. Conversely, to tailor high quality global manufacturing constraints, we need to make further progress in the understanding of the aggregation functions when used in the topology optimization. To this end, we perform a deep theoretical investigation and a quantitative numerical assessment of the behavior of these functions when being used in different formulations of AM-constraints. Our work begins with a theoretical and statistical analysis of the K-S, p-mean and p-norm aggregation functions. To exhibit the performance and properties of the different aggregation functions, we use random sets of data and we show how the distribution of the data influences the aggregated value. An interesting finding here is that p-norm exhibit the stronger dependence on the amount of data that is being aggregated, which would make it more unstable under mesh refinement compared to p-mean. In any case the K-S function exhibit the worst performance. We also carefully look at efficient implementation of the sensitivity analysis, which bring a further CPU reduction.

In the last part of the work, we illustrate the behavior of the p-norm and p-mean functions in the framework of 2-D density-based topology optimization. The selected test cases cover various design problems including minimum compliance and stress constrained problems (MBB beam), heat conduction problems or compliant mechanisms design. The test cases are used to yield the real statistical analysis data, which are used to further illustrate the various properties of p-norm and p-mean aggregation functions. As depicted in Fig.1 with the L-shape problem, we also address design problems involving multiple manufacturing and mechanical constraints (like stress constraints). This enables to investigate the interaction of AM manufacturing constraints with other complex design constraints. Finally 3D implementation is described.



(a) (b) (c)

Figure 1: L-shape design domain for compliance minimization. In (1.a) minimum size and aggregated maximum size constraints using p-mean. In (1.b) same problem as 1.a with stress constraints using aggregated using p-mean. In (1.c) overhanging constraints are aggregated using p-norm and added to min and max size constraints.

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Thermal Constraints in Topology Optimization of Structures Built by Additive Manufacturing

Grégoire Allaire and Lukas Jakabcin
CMAP, Ecole Polytechnique, F-91128 Palaiseau, France
{gregoire.allaire, lukas.jakabcin}@polytechnique.edu, http://www.cmap.polytechnique.fr/

Key Words: *Topology optimization, thermal constraints, level set method*

Our goal is to take into account the additive manufacturing process (selective laser melting) in shape and topology optimization of structures. We discuss models and results from [2] (and more general ones) which can be used to minimize the thermal deformation or the thermal residual stresses induced by additive manufacturing. If we denote by Ω the final structure which is subject to optimization, the main idea (already discussed in [1]) is to introduce a sequence of intermediate shapes $\Omega_i = \{(x, y, z) \in \Omega \text{ s.t. } z \leq h_i\}, 1 \leq i \leq n$, obtained from the previous one by adding a layer, at each stage of the fabrication process, and to formulate a constraint on this collection of intermediate shapes. This constraint is evaluated thanks to a new time-dependent state equation which is composed of the heat equation and the quasi-static thermo-elastic system. We follow the lead of [3] for modelling thermal residual stresses.

We consider a thermo-elastic evolution with unknowns: the temperature T and the displacement vector field u. The i-th layer, which is added to the intermediate shape Ω_{i-1} to obtain the new shape Ω_i, is built between times ti−1 and ti, where t0 is the initial time and tn the final time. The equations are

- heat equation:

$$\rho \frac{\partial T}{\partial t} - \operatorname{div}(\lambda \nabla T) = Q \quad \text{in } (t_{i-1}, t_i) \times \Omega_i \tag{1}$$

- thermoelastic equilibrium equation:

$$\begin{cases} -\operatorname{div}(\sigma) = f & \text{in } (t_{i-1}, t_i) \times \Omega_i, \\ \sigma = \sigma^{el} + \sigma^{th} & \text{in } (t_{i-1}, t_i) \times \Omega_i, \\ \sigma^{el} = Ae(u) & \sigma^{th} = K(T - T_{init})\mathbb{I}_n, \end{cases} \tag{2}$$

where the Cauchy stress tensor σ is the sum of the elastic stress σ^{el} and the thermal stress σ^{th}.

From this we build an objective function which is

$$J(\Omega) = \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} \int_{\Omega_i} j(u, T)\, dx\, dt$$

where (u, T) is the solution of (1), (2). Typical example of objective functions are given by

$$j(u,T) = |\sigma_D|^2 \quad \text{or} \quad j(u,T) = |\max(0, u \cdot e_d - u^{max})|^2$$

where σ_D is the deviatoric part of the stress, e_d is the building direction and u^{max} is a maximal allowed vertical displacement. The objective function J (Ω) is minimized with a constraint on another objective function (typically compliance) for the final use of the shape

$$C(\Omega) = \int_{\Omega} j_{final}(u_{final})\, dx\,,$$

where u_{final} is the elastic displacement for the final shape submitted to its own loads. We compute the shape derivative of J (Ω) by an adjoint method and optimal designs are obtained numerically by the level set method [2] (see Figure 1).

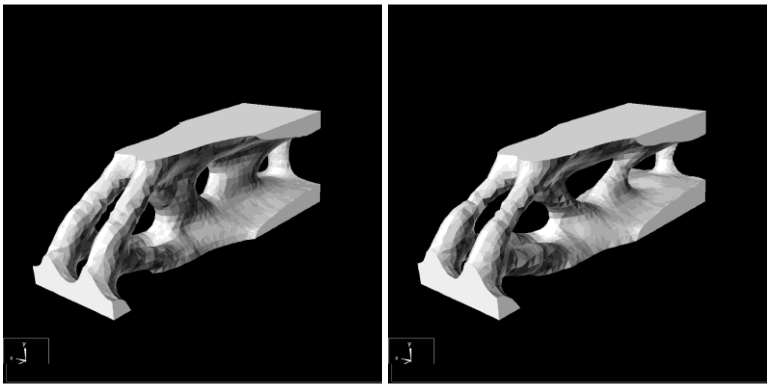

Figure 1: Half MBB beam: optimal shape for compliance minimization (left) and optimal shape for minimal vertical displacement during the additive manufacturing (right).

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Improvements to Projection-based Topology Optimization for Overhang Constraints

Reza Behrou[1], **Mikhail Osanov**[1], **James K. Guest**[1*]

[1]*Dept. of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA*
[*] Corresponding author: jkguest@jhu.edu

Additively manufactured components often require temporary support structures to prevent the component from collapsing or warping during fabrication. Whether these support materials are removed chemically as in the case of many polymer additive manufacturing processes, or mechanically as in the case of (for example) Direct Metal Laser Sintering (DMLS), the use of sacrificial material increases total material usage, build time, and time required in post-fabrication treatments. One of the strategies for minimizing support material is to minimize the appearance of overhang features within the component design. Overhang features refer to regions of material that rise from the build plate at a shallow angle, below what is termed the critical angle. The critical angle, above which features become self-supporting and do not require support structures, is process-dependent. Although often overhang features are removed manually in a post-processing / clean-up design stage, such post-optimization manipulations may erode part performance and negate potential gains that can be achieved given the design freedom provided by additive manufacturing. Ideally, support structures and overhang constraints would be considered in the topology optimization design formulation and thus formally accounted for in the design process.

This talk will discuss approaches for embedding an overhang constraint within the topology optimization framework such that designed components and structures may be manufactured without the use of support material. Specifically, we build on the idea of [1,2] which utilized a series of operations that combine a local projection to enforce minimum material deposition length scale requirements [3] and a support region detection operation to ensure a feature is adequately supported from below. Although the approach results in a strict implementation of both constraints, the primary disadvantage of the existing approach is that sensitivity calculations become cumbersome and computationally expensive due to the embedded nature of the projection operations, particularly for 3-D design problems. This essentially results in sensitivity calculations whose operations are on the order of n^2, where n is the number of independent design variables. Various strategies are discussed for dramatically reducing this cost while maintaining accuracy of the sensitivity estimations. Of particular note is the idea proposed in [4,5], which provides a computationally efficient adjoint scheme for computing the sensitivities associated with the embedded overhang operations. This approach is extended to the projection-based overhang approach of [1,2] to achieve strict implementation of local length scale and overhang angle, as well as computational efficiency. Although projection operations (and sensitivity calculations) still must progress layer-by-layer, computational expense is dramatically reduced.

The resulting projection-based approach to overhang constraints is applied to 3-D design domains, including both structural and fluidic design problems. The approach is shown to produce solutions that satisfy user-defined requirements concerning minimum material deposition length scale, minimum self-supporting angle, and maximum and/or minimum material volume requirements, considering a variety of process-dependent critical angles. Examples of designs that were successfully fabricated using metal and polymer additive manufacturing processes without the use of internal support structures will also be presented.

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A Reduced-Order Model Approach for Topology Optimization of Natural Convection Problems with Additive Manufacturing Constraints

Nicolo Pollini[1]*, Joe Alexandersen[1], Casper Schousboe Andreasen[1], Ole Sigmund[1]

[1]*Dept. of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark*
* Corresponding author: nipol@mek.dtu.dk

We discuss recent developments in topology optimization of heat sinks passively cooled by natural convection. Heat sinks are often used to enhance the rate of dissipation of heat generated by different power sources within computers, other electronic enclosures and heat producing machinery. Both forced and natural convection have received much attention in recent years, motivated by the increase of package density, and power dissipation rate demands. In the design of heat sinks many dimensions may be constrained by product size requirements and the fin array geometry is in many cases one of the few parameters left to the engineer's discretion.

Topology optimization has proved to be an effective tool for the identification of unintuitive and unexpected designs of heat sinks. For example, in Alexandersen et al. (2014) a density-based topology optimization approach was first presented for the design of heat sinks and micro pumps based on natural convection. The problem was formulated under the assumptions of steady-state laminar flow, using the incompressible Navier-Sokes equations coupled to the convection-diffusion equation through the Boussinesq approximation. The formulation was then extended to large scale 3-D topology optimization of passive heat sinks in Alexandersen et al. (2016). The developed framework was then applied to topology optimization of light-emitting diode lamps in Alexandersen et al. (2018). Through numerical verification, it was shown that topology optimization can identify unintuitive designs that outperform more simple designs obtained by intuition or parameter optimization. The numerical results presented in Alexandersen et al. (2018) were completed with experimental validation in Lazarov et al. (2018) using additive manufacturing in aluminium, closing for the first time the design-validation-manufacturing cycle for topology optimization of passive heat sinks. The superior performance of topology optimized heat sinks compared to lattice designs was also confirmed. Further experimental validation has been discussed recently in Lei et al. (2018). In this case, stereolithography-assisted investment casting (SLA-assisted IC) was used to fabricate heat sink devices designed through topology optimization. It was shown that SLA-assisted IC is a valuable alternative to more traditional metal additive manufacturing, and that it requires lower costs and is more flexible with regards to part size and metals that can be used.

One of the main limitations of topology optimization of natural convection problems is the high computational effort and time that it requires. To overcome this limitation, Asmussen et al. (2018) proposed a simplified methodology for topology optimization of 2-D heat sinks cooled by natural convection. A reduced-order model based on a potential flow model was considered for the fluid flow, leading to optimized designs that were in good agreement with those achieved considering a fluid flow modeled with the full set of Navier-Stokes equations. Recently, a similar approach has been considered in Zhao et al. (2018) for 2-D topology optimization of cooling channels based on forced convection.

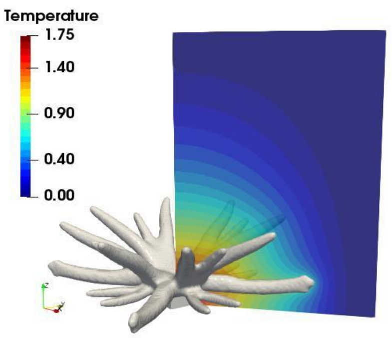

Figure 1. Optimized heat sink for Gr=10^3 considering a mesh resolution of 160x160x320 elements and a fictitious fluid permeability k_f=0.00513. Final value of thermal compliance f=8.53

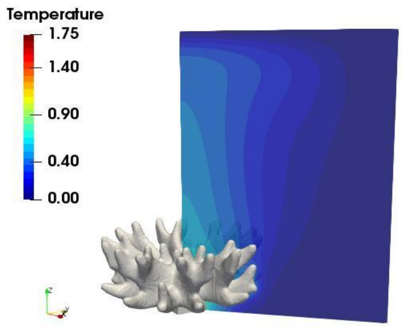

Figure 2. Optimized heat sink for Gr=10^6 considering a mesh resolution of 160x160x320 elements and a fictitious fluid permeability kf=0.00036. Final value of thermal compliance f=4.81

Herein, we extend the reduced-order model approach presented in Asmussen et al. (2018) to high-resolution topology optimization of 3-D passive heat sinks (e.g. Fig. 1 and Fig. 2). Moreover, the optimization problem formulation is extended to include additional requirements related to the fabrication of the designs through additive manufacturing. In particular, we introduce a constraint on the overhang angle. In this way, we reduce the amount of support structures needed for additive manufacturing, facilitating the production of the optimized designs. In the problem formulation, the Darcy flow model is coupled to the thermal convection-diffusion equation, and the resulting nonlinear system of equations is solved using stabilized finite elements in a parallel framework that allows for optimizing high-resolution problems. The simplified problem formulation allows for a significant reduction of the computational effort and time required in the optimization, and at the same time is significantly more accurate than simpler models that rely on convection boundary conditions based on Newton's law of cooling.

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Design for Discovery: Generative Design of Conformal Structures Using Level-Set-Based Topology Optimization and Conformal Geometry Theory

Shikui Chen[1] and Xianfeng David Gu[2,3]
Department of Mechanical Engineering
[1]*Department of Computer Science*
[2]*Department of Applied Mathematics and Statistics*
[3]*State University of New York at Stony Brook*

Topology optimization is an optimization-driven methodology capable of generating an optimal design without depending on the designers' intuition, experience, and inspiration. Topology optimization is playing a crucial and rapidly expanding role in design innovation in the 3D printing age. In this talk, the speaker will make a brief review of state of the art and introduce a level-set based topology optimization framework. After that, the speaker will report some of our recent efforts to advance the topology optimization methodology by combining the level set approach with the Conformal Geometry Theory. Level set approach has been considered as a powerful topology optimization (TO) tool for generating innovative designs, but the conventional level set framework is built in the Euclidean space ($\mathbf{R}^2$ and $\mathbf{R}^3$), which cannot satisfy the increasing demands of topology optimization on free-form surfaces. We propose a new method to address the problem of topology optimization for conformal structures on freeform surfaces which are mathematically termed as 'manifolds.' By using conformal parameterization, we extend the conventional level-set-based topology optimization framework from Euclidean space ($\mathbf{R}^2$ and $\mathbf{R}^3$) to surface with arbitrary topologies.

In this method, a manifold (or free-form surface) is conformally mapped onto a 2D rectangular domain, where the level set functions are defined. With conformal mapping, the corresponding covariant derivatives on a manifold can be represented by the Euclidean differential operators multiplied by a scalar. Therefore, the TO problem on a free-form surface can be formulated as a 2D problem in the Euclidean space. To evolve the boundaries on a free-form surface, we propose a modified Hamilton- Jacobi Equation and solve it on a 2D plane following the Conformal Geometry Theory. In this way, we can fully utilize the conventional level-set-based computational framework.

Compared with other established approaches which need to project the Euclidean differential operators to the manifold, the computational difficulty of our method is highly reduced while all the advantages of conventional level set methods are well preserved. The proposed computational framework provides a solution to increasing applications involving innovative structural designs on free-form surfaces for different fields of interests.

Interactive Conceptual Design of AM Components using Layout & Geometry Optimization

Linwei He[1], Matthew Gilbert[1*], Hongjia Lu[1], Thomas Johnson[2], Tom Pritchard[3]
[1]*Faculty of Engineering, University of Sheffield, S1 3JD, Sheffield, UK*
* Corresponding author: m.gilbert@sheffield.ac.uk
[2]*SMT, Nottingham, UK*
[3]*LimitState Ltd, The Innovation Centre 217 Portobello, Sheffield, UK*

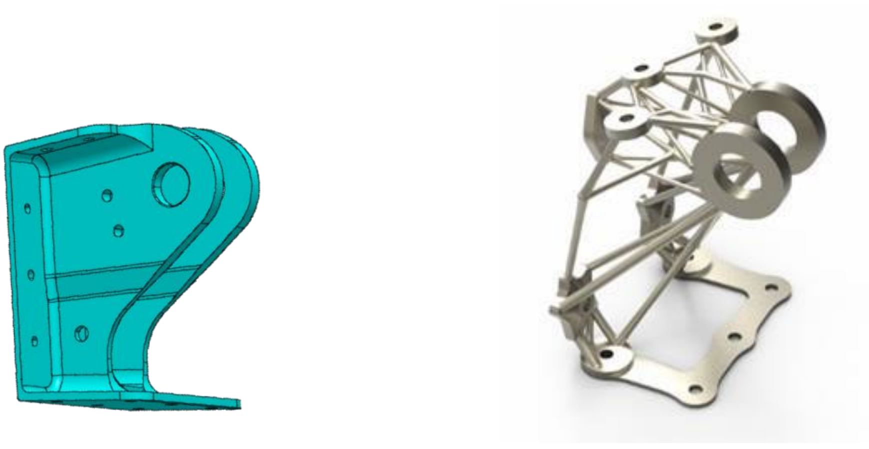
Additive manufacturing (AM, or '3D printing') techniques have developed rapidly in recent years, allowing highly complex geometrical forms to be manufactured for the first time. However, to benefit from the unprecedented design freedoms offered, effective design optimization techniques are required. Although traditional continuum topology optimization techniques have proved popular for this purpose, they are not especially well suited to problems involving low volume fractions (i.e. when the component occupies only a small proportion of the available design space). Also, topology optimization approaches can be computationally expensive and normally require labour intensive post-processing in order to realize a practical component. This means that they are not ideally suited for use at the conceptual design stage, where frequent design iterations are usually required.

As an alternative to traditional continuum topology optimization techniques, so-called 'layout optimization' can be employed. This technique is particularly useful when the degree of design freedom is high, where truss-like forms are found to be extremely structurally efficient. With truss layout optimization the design domain is discretized using a grid of nodes which are interconnected with discrete line elements to form a 'ground structure'. Linear programming can be used to identify the subset of elements forming the minimum volume structure required to carry the applied loading [1]; the use of an adaptive solution scheme enables solution of very large-scale problems [2]. As well as providing a means of generating very accurate (near-)optimum benchmark solutions, layout optimization provides a means of rapidly generating strong and light design concepts for AM component designers, with line-element solutions readily converted to solid models. The current study describes a systematic means by which layout optimization can be employed for this purpose.

Firstly, currently AM processes have certain limitations. For example, with many AM processes elements inclined at shallow angles to the build direction cannot be fabricated without supports. This requirement is addressed here by using either a hard constraint approach, in which members inclined below a given threshold angle are eliminated, or a soft constraint approach, in which the manufacturing costs associated with shallow inclined members are included in the formulation. In addition, the physical sizes of members and joints are represented in the layout optimization problem formulation to ensure that the final expanded solid structure lies entirely within the prescribed design domain.

Secondly, developments which allow designers to step into the design loop to intervene in the optimization process if desired are described. This functionality is important as it is difficult to foresee all design requirements in advance. To achieve this, a layout optimization is initially performed, which takes into account practical issues such as build direction constraints, followed by automatic refinement via a geometry optimization step [3] and an optional simplification step. Then line-elements and nodes are expanded to corresponding solid models [4], allowing designers to inspect and modify the structural layout and/or to apply additional design constraints. Since changes made by the designer at this point may adversely affect the structural integrity of the component, measures are taken to restore this, whilst still taking account of the requested changes. The modified design can then be optimized further, if necessary using geometry optimization. Finally, the preferred design can then be refined prior to final validation and manufacture via AM.

The approach described seeks to strike a balance between theoretical rigour and practical design needs, between automatic and interactive processes, and between computational optimization and human intelligence. Several practical design problems are presented to demonstrate the efficacy of the proposed optimization framework, including the redesign of an aircraft elevator hinge, which led to a 60% weight saving (Figure 1).



(a) (b)

Fig. 1. Comparison of (a) original aircraft elevator hinge design, and (b) new design obtained in a few minutes on a desktop PC using the described interactive layout and geometry optimization design approach (solution 60% lighter than original and satisfies all force, displacement and stress requirements)

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Eigenfrequency Optimization of Non-linear Hyperelastic Structures

Anna Dalklint[1], Mathias Wallin*, Daniel Tortorellib[2,*]
[1]*Division of Solid Mechanics, Lund University, Box 118, SE-22100 Lund, Sweden*
E-mail: math- ias.wallin@solid.lth.se
[2]*Center for Design and Optimization, Lawrence Livermore National Laboratory, Livermore, CA, USA*

Topology optimization of nonlinear elastic structures has previously been studied in detail by e.g Buhl et al. [1], Wallin et al. [2] and Daeyoon et al. [3] to mention a few. However, most of the work on this subject has been restricted to compliance minimization, or rather displacement minimization since the load vector is constant. On the other hand, for linear elastic structures, many types of objectives are available in the literature. Topology optimization with respect to eigenfrequencies is one example of an objective that has been studied extensively for small deformations in e.g Pedersen [4] and Jianbin et al. [5], however few have investigated this type of optimization for structures undergoing finite deformations. In this work, we hence expand topology optimization formulations to a nonlinear hyperelastic material model.

One issue with performing topology optimization with respect to the eigenfrequencies for a nonlinear material model is that the stiffness depends on the displacements. This entails a different definition of the usual equations of motion for free vibrations, presented as

$$\mathbf{M}(\mathbf{z})\ddot{\mathbf{a}}+\mathbf{r}(\mathbf{a},\mathbf{z})=\mathbf{0} \tag{1}$$

Where **M(z)** denotes the mass matrix, **z** the design variables, **a** the nodal displacements and **r(a, z)** the residual of the internal and external forces. However, by performing an Taylor series expansion around a deformed equilibrium state and identifying the stiffness matrix as the linearization of the internal force internal force vector with respect to the nodal displacements one will end up with an eigenvalue problem similar to the one in the linear case, i.e.

$$(\mathbf{K}(\mathbf{a},\mathbf{z})-\omega^2\mathbf{M}(\mathbf{z}))\boldsymbol{\varphi}=\mathbf{0} \tag{2}$$

Where **K(a, z)** denotes the stiffness matrix (We assume dead loading), ω the eigenfrequencies and φ the corresponding eigenvectors. Hence, the main difference between the linear and the nonlinear material model from an topology optimization perspective lies in the sensitivity analysis, since the eigenvalue problem now depends on the displacements. To find the sensitivities, we employ the adjoint approach where the implicit derivatives with respect to the displacements are eliminated by introducing adjoint vectors.

In this work we implement constraints for the eigenfrequencies such that a number of the smallest eigenfrequencies must be larger than a prescribed value while minimizing the displacement of the structure at the operating load under a volume constraint. Several similar eigenvalue formulations exist, e.g maximization of a specified structural eigenfrequency or maximization of the distances between two adjacent frequencies. However, motivated by the work of Jianbin et al. [5] we choose to look at only one possibility.

The method of moving asymptotes is used to solve the topology optimization problem. Moreover, the Helmholtz PDE-filter is utilized to introduce a minimum feature size in the design and hence generate a well-posed topology optimization problem. From the numerical examples we conclude that the magnitude of the load will influence the eigenvalues. Hence, it should be taken into account when analyzing nonlinear structures.

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Graded Cellular Hip Implant Design through Topology Optimization and Additive Manufacturing

Yingjun Wang[1*]

[1] *School of Mechanical and Automotive Engineering, South China University of Technology, 510641, Guangzhou, China*

* Corresponding author: wangyj84@scut.edu.cn

Even in a well-functioning total hip replacement, significant peri-implant bone resorption can occur secondary to stress shielding. Stress shielding is caused by an undesired mismatch of elastic modulus between the stiffer implant and the adjacent bone tissue. To address this problem, we present here a cellular hip implant that consists of a three-dimensional graded cellular material with properties that are mechanically biocompatible with those of the femoral bone. A gradient-free scheme of topology optimization (TO) is used to find the optimized relative density distribution of the cellular implant under multiple constraints, and the implant model is additively built through a selective laser melting (SLM) 3D printer. The result shows that bone loss for the optimized cellular implant is only 42% of that of a fully solid implant, here taken as benchmark, and 79% of that of a cellular implant with uniform density.

Total hip arthroplasty (THA) is an effective treatment for osteoarthritis and has been successfully performed on over 1 million patients every year worldwide [1]. The cause for bone resorption secondary to stress shielding is that current orthopedic prostheses are made of solid metals, e.g. titanium-based alloys, cobalt chromium alloys, 316L stainless steel, and tantalum, that are much stiffer than the bone surrounding them [2]. When the hip is loaded during gait or other physical activities, the stiffer prosthesis is prompt to absorb a substantial percentage of stress, thereby leaving only a smaller portion of load transfer to the adjacent bone. To solve this problem, we extend a recently introduced proportional topology optimization (PTO) [3] to design a graded cellular hip implant subjected to multiple constraints with the purpose of greatly reducing the bone resorption, and use a SLM 3D printer to build the implant with complex geometry to demonstrate our design concept.

Figure 1 shows the scheme proposed in this paper to design a graded cellular implant with minimal bone resorption.The main steps are briefly described below.

(1) A CAD model is created by processing CT-scan data from the femur of a 38-year-old patient. Two numeric models are then generated, one for the intact femur and the other for the implanted femur, the difference in strain energy between them is used as proxy to quantify bone resorption [4]. The distal end and condyle are fixed and the loads, written in the (X, Y, Z) coordinate system, are F1 (-486, -295.2, 2062.8), F2 (64.8, 104.4, -118.8), F3 (522, 38.7, -778.5), F4 (-4.5, -6.3, 171) and F5 (-8.1, 166.5, 836.1).

(2) The implant macrogeometry has a minimally invasive shape that is clinically relevant to current THA, whereas a tetrahedron-based topology defines the unit cell, which is used to tessellate the implant domain. This unit cell is selected for its smooth mapping relationship to the tetrahedral solid element.

(3) The homogenized properties are assigned to the numerical model to build the global stiffness matrix, which in turn is used to solve the boundary value problem. As a result, the strains and stresses of both bone and implant are retrieved to calculate the difference in strain energy density between intact and implanted femur, a figure of merit that indicates bone resorption.

(4) A multi-constraint TO scheme that extends the previously introduced PTO [3] is used to optimize the relative density distribution of the elements that are associated to the 3D domain of the implanted femur. In particular, minimum bone resorption is converted into maximum compliance, and the problem is solved to yield a density-continuous distribution. To prevent bone-implant micromotion, an additional constraint is applied to the interface failure. At each iteration failure and fatigue analyses are performed, and the design variables are updated to guarantee the necessary level of strength for the implant under service physiological conditions. In addition, the constraints of average porosity, pore size and minimum cell wall thickness that can be manufactured with current additive technology are converted into lower and upper bounds of relative density.

Figure 2 (a) shows the optimal relative density distribution, and Figure 2 (b) the graded cellular implant obtained with an in-house code that can create the geometric model which is additively built out of Ti6Al4V by a SLM 3D printer Laseradd DiMetal (Laseradd, Guangzhou, China) and the printed model is shown in Figure 2 (c). The performance of the optimized cellular implant is compared with a fully solid implant and a uniform density implant in Figure 2 (d). Bone resorption of the optimized implant is 41.9% of that of the fully solid implant and 78.8% of that of the uniform cellular implant, which demonstrates the proposed method can reduce stress shielding. Furthermore, the graded cellular implant satisfies implant micromotion, failure and fatigue requirements, besides being able to meet bone ingrowth and manufacturing requirements.

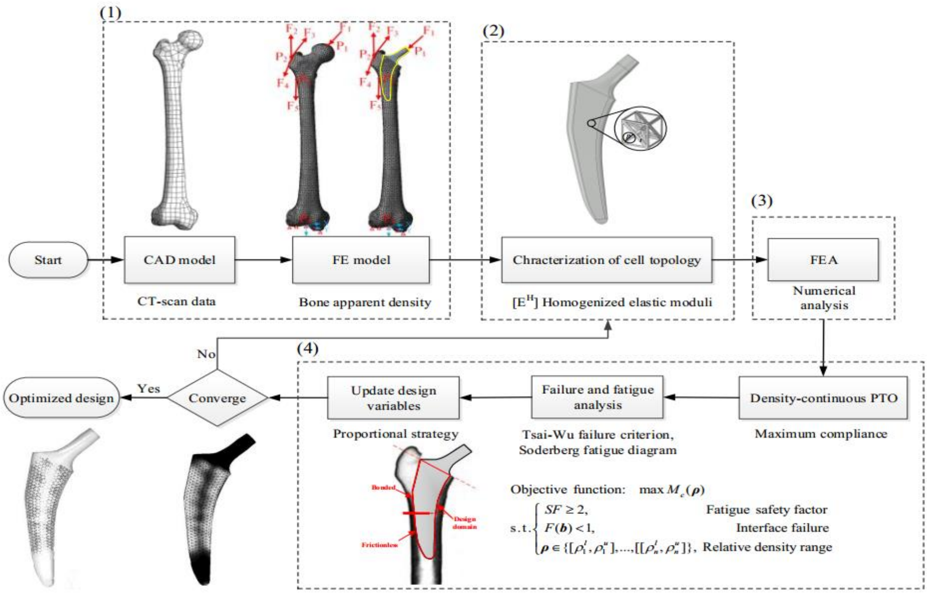

Figure 1. Design flow chart of the PTO followed in this work for the 3D design of the hip implant

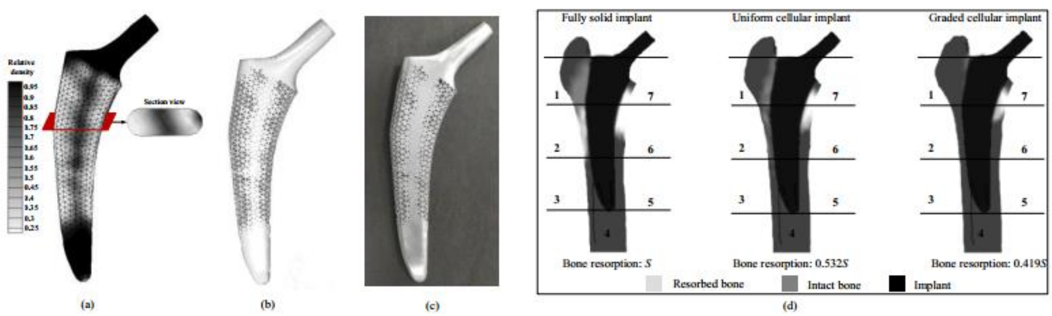

Figure 2. Results of optimized cellular implant: (a) relative density distribution, (b) CAD model of the implant, (c) 3D printed implant, and (d) bone resorption comparison with a fully solid implant and a uniform density cellular implant.

In this work, a multi-constraint PTO is proposed to optimize the relative density distribution of a 3D hip implant made of graded cellular material, and additively built the implant by a SLM 3D printer. Compared to a fully solid implant and a uniform cellular implant, the optimized implant here presented can reduce bone resorption 58.1% and 21.2% respectively.

Integrated Modelling of Process-property-structure in Friction Stir Additive Manufacturing and the Data-driven Design

Z. Zhang[*], Z.J. Tan, J.Y. Li, X.X. Bai

State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

Corresponding author. Email: zhangz@dlut.edu.cn

Abstract: Friction Stir Additive Manufacturing (FSAM) is a new AM technology in solid state developed based on Friction Stir Welding (FSW). Metal powder, plate and rod can be Available to be AM materials. To study the mechanism for controlling of product quality, numerical method becomes an efficient tool. Precipitate evolution model is developed to investigate the volume fraction and sizes of precipitates. Monte Carlo method is then used to simulate the recrystallization and grain growth with consideration of the precipitate effects. Mechanical property can be then predicted based on the precipitate calculations. Experiments are performed to show the grain differences between different AM layers. The re-stirring and re-heating effects in FSAM are then studied experimentally and numerically. Artificial neural network is applied to this new AM technology for data driven design and optimization of FSAM.

Key words: Friction stir additive manufacturing, data driven design, optimization, Monte Carlo method, precipitate evolution model

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A Poor Man's Topological Derivative based on BESO for Stable Hole Nucleation in Level Set Optimization

Qi Xia, Tielin Shi, Liang Xia
The State Key Laboratory of Digital Manufacturing Equipment and Technology,
Huazhong University of Science and Technology, Wuhan, China
qxia@mail.hust.edu.cn

A method is proposed to nucleate holes during the level based topology optimization by using the material removal scheme of the bi-directional evolutionary optimization (BESO). Because the BESO takes discrete design parameterization (0 representing void and 1 representing solid material), when a small amount of inefficient material is removed from the interior of a structure, the effect is essentially the same as that of using the topological derivative to nucleate a hole. As compared with the topological derivative, the BESO is more accessible to engineers because of its conceptual simplicity and easiness of numerical implementation. In other words, the material removal scheme of the BESO is used as a poor man’s topological derivative. Such a poor man's topological derivative may not be as theoretically strict as the true topological derivative. Nevertheless, we do not need it to be theoretically strict. All we need is that it can give us a hole. It doesn't matter if the position or size of hole is not so accurate, because the level set will take over and correct it. For removing material, a threshold of sensitivity number is determined. It is the minimum of two tentative thresholds. The first is determined according to the percentage of material to be removed in each iteration of optimization. The second is determined according to the average sensitivity number along the boundary to be optimized, and it is helpful to stabilize hole nucleation. The results of several numerical examples prove that the proposed hole nucleation method is effective and efficient.

Keywords: hole nucleation; level set method; BESO; topology optimization

Structural Topology Optimization for Thermal Stress Control in Laser Additive Manufacturing

Mingdong Zhou, Yichang Liu
State Key Laboratory of Mechanical System and Vibration,
Shanghai Key Laboratory of Digital Manufacture for Thin-walled Structures,
Shanghai Jiao Tong University, No. 800 Dong Chuan Rd. Shanghai 200240, P.R. China.
Corresponding author: mdzhou@sjtu.edu.cn

Abstract

The laser heat induced residual stress in Additive Manufactured (AM) parts can result in undesirable structural deformation and degradation of mechanical properties. This work introduces a topology optimization approach to design the supporting structures in AM that lead to well-forming parts of minimized structural deformation and reduced residual stress. By explicitly considering the AM-process simulation model in the optimization process, the layout of supporting structure is designed such that the laser heat can be efficiently transferred from the part to the heat-sink plate during the fabrication process. As a result, the overall deformation and stress level in the final manufactured part can be properly controlled. Gradient based topology optimization is performed to design the supporting structure for a given prototype shape. Test examples and verifications are given to demonstrate its applicability. Some numerical issues and possible extensions are also discussed.

Keywords: Laser additive manufacturing; Topology optimization; Structural deformation; Thermal stress

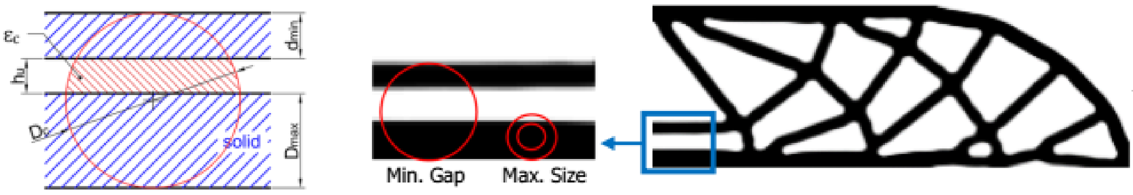
Imposing the Distance between Solid Members Generated by Maximum Size Constraints in Topology Optimization

E. Fernandez-Sanchez [1*], P. Duysinx [1]

[1] *Dept. of Aerospace and Mechanical Engineering, University of Liege, 4000, Liege, Belgium*
[*] Corresponding author: efsanchez@uliege.be

The combination of topology optimization and additive manufacturing has brought a recent break-through in engineering. Topology optimization aims at generating innovative concepts with high performance to weight ratio, but the optimized designs are often difficult to fabricate as-it-is using classical fabrication processes. In the AERO+ research project [1], we focus on metal additive manufacturing processes, and particularly on Electron Beam Melting (EBM) and Selective Layer Manufacturing (SLM) processes. Among others, the maximum size of structural elements has been reported as a manufacturing limitation for these processes mainly due to overheating problems. The maximum size constraint in topology optimization is based on restricting the amount of material within the neighborhood of each point in the design domain [2]. Its role is to split the bulky material during the topology optimization process. The constraint introduces extra structural members in the design, such as bars or sheets, which tend to remain very close to each other. This greatly increases the complexity of the design and therefore of the manufacturing process, as pointed in [3]. This work aims to improve the manufacturability of such designs. To this end, a new constraint is proposed capable of separating the structural members according to the user's needs.

The proposed constraint, as well as the maximum size, restricts the quantity of material within the neighborhood of each point in the design domain. This is achieved by asking for a specific amount of voids within the test region. However, there is a small difference in the involved parameters which allows to separate the structural members instead of constraining their size. For this purpose, the amount of voids to be included within the test region is a function of the distance between bars, as shown in Figure 1. The local constraints are aggregated using the p-mean function in order to avoid the computational overburden on the optimizer. The method is validated for compliance minimization on 2D and 3D design domains (Figure 2 and 3), showing that the proposed constraint is capable of reducing the geometric complexity of designs with maximum size constraints.

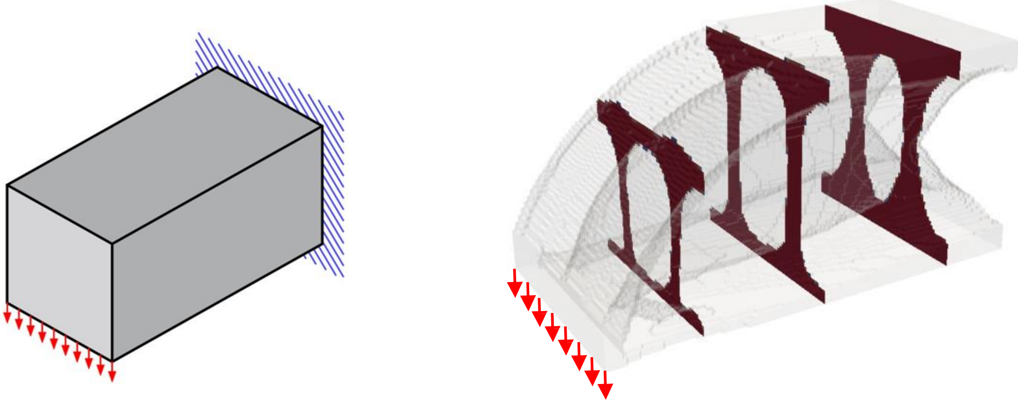


(a) (b) (c)

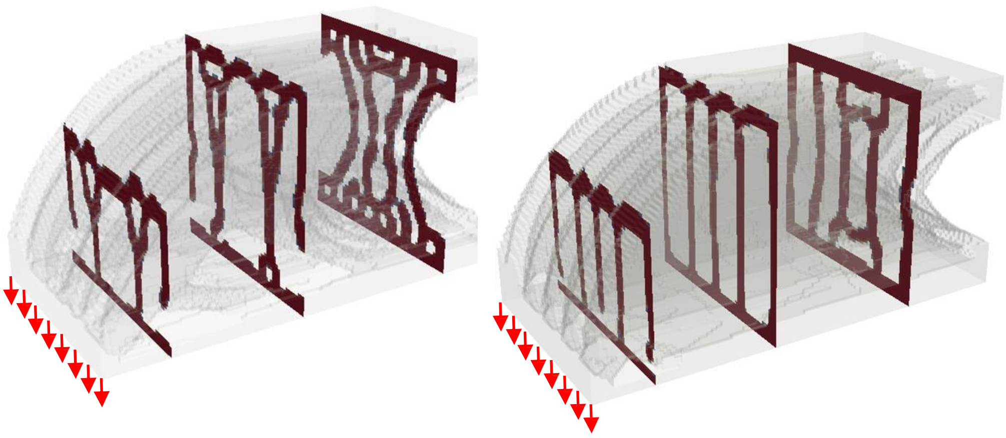
Figure 1: In (a) the minimum gap constraint introduces amount of voids inside the test region. is a function of the desired distance between solid members. In (b) the interpretation of the minimum gap constraint from the solution shown in (c) which includes minimum size[5], maximum size[4] and minimum gap constraints.

(a) (b)

Figure 2: Solutions of the MBB beam for compliance minimization with minimum size constraints [5]. In (b) the optimization problem includes maximum size[4] and the proposed minimum gap constraints.



(a) (b)



(c) (d)

Figure 3: Sectioned solutions of the 3D cantilever beam for compliance minimization. In (a) the design domain. In (b) the solution with minimum size imposed through Heaviside projection. In (c) the maximum size constraint is included [4]. In (d) the proposed minimum

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Topology Optimization for Designing Periodic Microstructures based on Finite Strain Visco-plasticity

Niklas Ivarsson[1],*, Mathias Wallin[1], Daniel Tortorelli[2]

[1]*Division of Solid Mechanics, Lund University, Box 118, SE-22100 Lund, Sweden*
[2]*Center for Design and Optimization, Lawrence Livermore National Laboratory, Livermore, CA, USA*
E-mail: niklas.ivarsson@solid.lth.se

In the current work, we present a topology optimization framework for designing periodic microstructures with viscoplastic constitutive behavior under finite deformation. Materials with tailored macroscopic mechanical properties, i.e. maximum viscoplastic energy absorp- tion and prescribed Poisson's ratio, are designed by performing numerical tests of a single unit cell subjected to periodic boundary conditions. The kinematic and constitutive models are based on finite strain isotropic hardening viscoplasticity, and the mechanical balance laws are formulated in a total Lagrangian finite element setting. To solve the coupled momentum balance equation and constitutive equations, a nested Newton method is used together with an adaptive time-stepping scheme. The optimization problem is iteratively solved using the method of moving asymptotes (MMA), where path-dependent sensitivities are derived using the adjoint method. The applicability of the framework is demonstrated by numerical examples of optimized continuum structures exposed to multiple load cases over a wide macroscopic strain range.

Keywords: Topology optimization, Material design, Finite strains, Rate-dependent plasticity, Discrete adjoint sensitivity analysis

Optimization problem

In this density based topology optimization we formulate a well-posed problem by introducing a periodic version of the Helmholtz partial differential equation filter. Near black and white solutions are obtained through penalization of intermediate densities and a Heaviside thresholding technique. The optimization problem is to maximize the dissipated energy, subject to constraints on the maximum mass and a prescribed

Poisson’s ratio. Residual equations for the global equilibrium and the local constitutive response are treated as implicit constraints in the optimization problem.

Results

To show the applicability of the presented framework, we will solve several different topology optimization design problems. The unit cell whose homogenized properties are used in the macroscopic simulation is discretized using 8-node linear brick elements, thus the framework is applicable to the general three dimensional case. For simplicity, we restrict ourselves to the two-dimensional case. Multiple load cases are considered by prescribing displacement differences between opposite boundaries. Both longitudinal and transverse tensile tests are simulated, and symmetry within the design is enforced. Fig. 1 shows a material tailored for maximum viscoplastic energy absorption and a nearly constant Poisson’s ratio in the macroscopic engineering strain interval $\varepsilon \in$ [0 0.05].

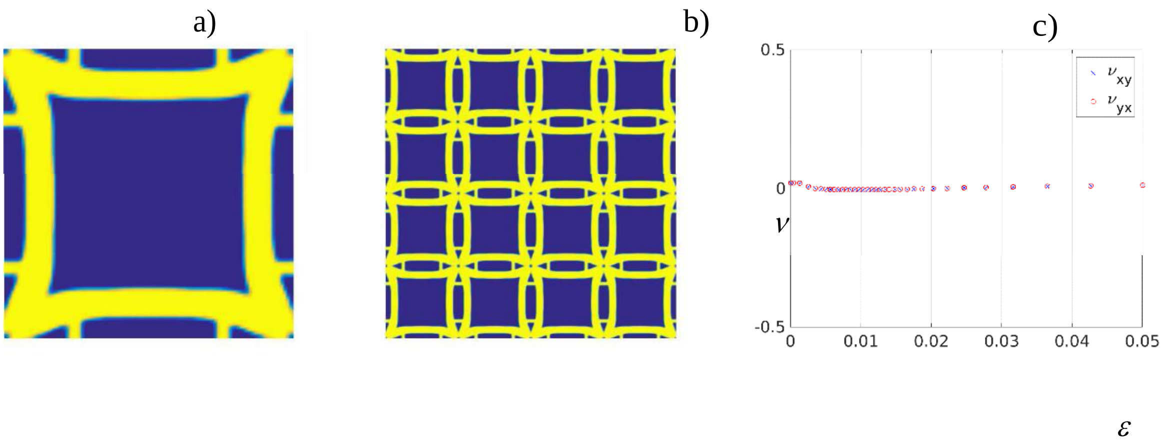

Figure 1: Optimized undeformed design for the prescribed engineering macroscopic strain ε = 0.05 and target Poisson’s ratio ν^* = 0. a) Topology of the unit cell, b) 4×4 array of unit cells and c) Poisson’s ratios ν_{xy} and ν_{yx} under axial and transverse tensile tests, respectively, versus engineering strain.

Conclusions

We have established a topology optimization framework for designing periodic microstructural materials with maximum viscoplastic energy absorption. Materials that posses near strain-independent Poisson's ratio have been designed. The optimization prob- lem is solved using the MMA scheme. Sensitivities required to form the MMA approxi- mation are obtained using the adjoint method. The finite strain viscoplastic effects on the designs are shown by simulation of several macroscopic load cases.

Acknowledgements

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Mechanical Performance of Additively-Manufactured Three-dimensional Lattice Meta-Materials Designed via Topological Optimization

Sheng-Yu Duan[1], Wei-Bin Wen[2*], Dai-Ning Fang[1,3]**

[1]*Institute of Advanced Structure Technology, Beijing Institute of Technology, 100081, Beijing, China*
[2]*School of Civil Engineering, Central South University, 410083, Changsha, China*
[3]*College of Engineering, Peking University, 100081, Beijing, China*
* Corresponding author: wenwbin@126.com
** Corresponding author: fangdn@pku.edu.cn

Abstract Topological optimization have been wildly used for designing mechanical meta-materials. This study focusses on the investigation of the mechanical properties of three-dimensional (3D) lattice meta-materials designed by topological optimization and manufactured by selective laser sintering. The adopted topological optimization method is based on the bidirectional evolutionary structural optimization (BESO) technique. Maximizing bulk modulus or shear modulus was selected as the object of the material design subject to a volume constraint. The effective properties of the lattice material were obtained by an energy-based homogenization method. The optimized 3D lattice meta-materials of volume fraction 10%, 20% and 30% are selected to investigate the mechanical properties (e.g., elastic modulus, compressive strength and energy absorption) of the 3D lattice meta-materials. The mechanical properties obtained from the compression test are compared to the mechanical performance of conventional body centred cubic (BCC) and octet-truss lattice meta-materials. Experimental results show that the optimized 3D lattice meta-material can achieve more desirable mechanical performance than the conventional lattice meta-materials.

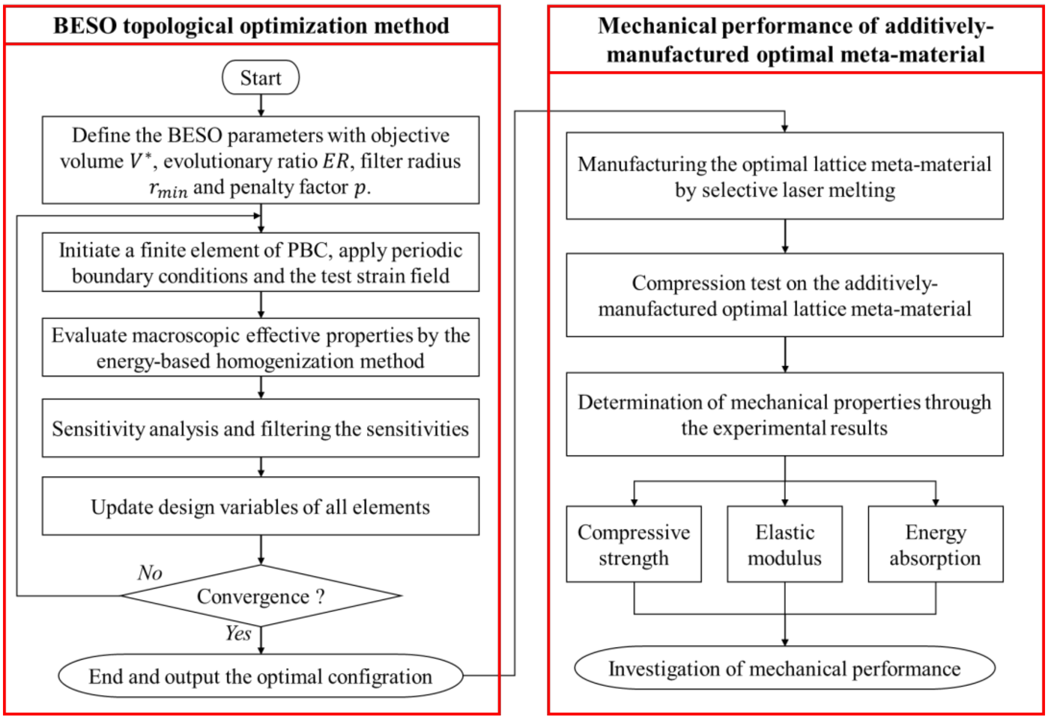

Fig. 1. The flowchart of this study.

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Evaluation of Topology-Optimized Metallic Pentamode Material Manufactured by Selective Laser Melting

Lei Zhang, Bo Song*, Yusheng Shi

State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, China

Corresponding authors: bosong@hust.edu.cn

Abstract:

With the increasing demands for functional product development, metamaterials have been shifted their focus onto producing, characterized by periodic microstructure and possessing special properties that natural materials do not have, such as negative moduli, negative Poisson's ratio and negative refractive index which can present extraordinary functions and potential applications. Pentamode material (PM) is of interest for its acoustic stealth and special mechanical properties in biomedicine and acoustic equipment. The metallic PM exhibits a complicated periodic structure, and conventional manufacturing methods, such as casting, machining and forming, are required a long time period and specific tooling for the fabrication of these complex structure, will not be suitable. In this study, two-dimensional water-like pentamode structure of Ti-6Al-4V, showing a honeycomb structure with different node, have been topology-optimized by FEM package of ANSYS and fabricated by using a selective laser melting (SLM) 3D-printing technology. Selective laser melting (SLM) is considered to be one of the most promising additive manufacturing (AM) technologies that can directly manufacture near-net shape components with a complex structure by layer-by-layer building process. This work is first time to study the coupling of acoustic and mechanical properties of metallic PM manufactured by SLM process. Ti-6Al-4V was presented good processability and high strength for the SLM fabricated the water- like PM structure. We designed water-like PM structures with different node shape utilizing homogenization theory. By tuning the node structure, mechanical response and acoustic properties of the PM structures was modulated to obtain suitable pentamodal properties with water-like stealth cloak. The different node of PM structure was designed as circle, star and triangle shape, respectively, to explore the effect of nodal shape. The variation in the compressive response with different node structure is incongruous, which the circle and triangle node PM structure exhibited the elastic- brittle characteristic, while the star node PM structure shows the elastic-plastic characteristic. The acoustic field results of simulation and experiment was researched with the different PM node shape.

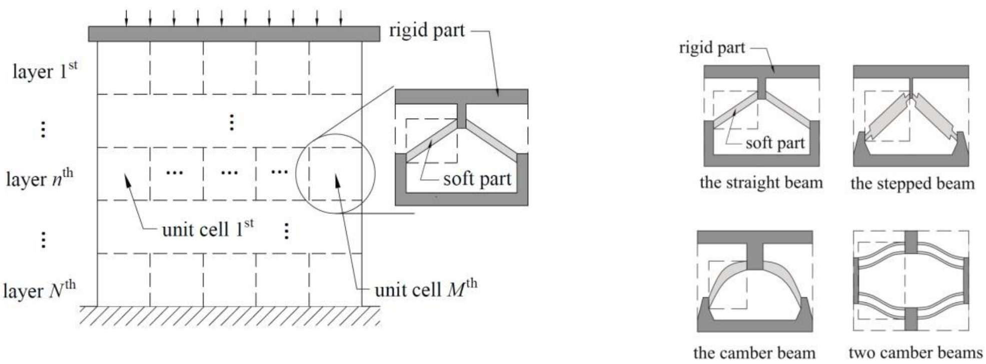
Keywords: Pentamode material; Selective laser melting; Mechanical response; Acoustic properties

Topology Optimization and Experimental Study on Buckling-induced Mechanical Metamaterials

Qi Chen, Xianmin Zhang, Benliang Zhu
Guangdong Key Laboratory of Precision Equipment and Manufacturing Technology, South China University of Technology, Guangzhou, China

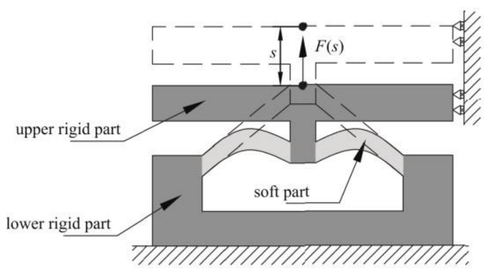
Buckling-induced mechanical metamaterials for energy absorption are different from traditional crashworthy structures, although both types are designed for impact energy absorption. Traditional crashworthy structures convert impact energy into two components elastic strain energy stored in the structure and plastic work which is partly converted into heat. Studies on buckling-induced mechanical metamaterials propose that part of the input energy can be converted into vibrations of the whole structure by snap-through instability. Then, the vibration is converted into heat by the viscoelasticity of the materials.

Generally, buckling-induced mechanical metamaterials consist of N layers. One layer consists of M unit cells, and one unit cell consists of two parts, a rigid part for support and a soft part for snap-through instability and energy absorption, as shown in Fig. 1. The dark parts are rigid parts and the light parts are soft parts.

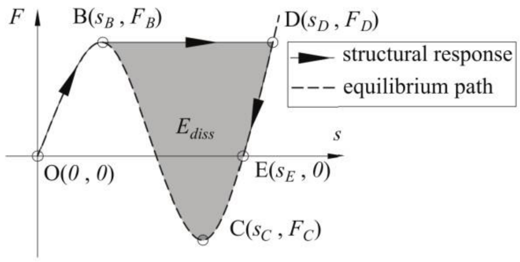


(a)Composition (b) Structural prototypes of the unit cells

Fig.1 Buckling-induced mechanical metamaterials.



(a)The boundary condition of a unit cell.



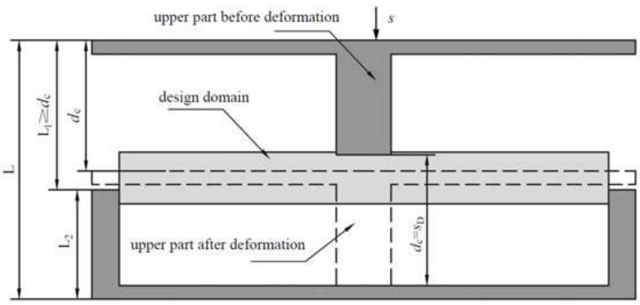
(b) The curve of a unit cell.

Fig.2 A unit cell of the mechanical metamaterials

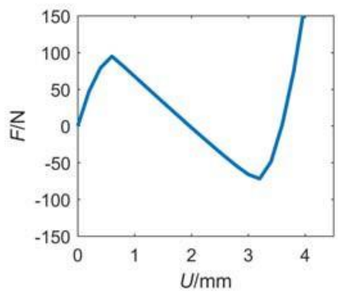
curve of a bi-stable unit cell is shown in Fig. 2b. If the unit cell is loaded under load control, the unit cell will snap from point B to point D in Fig. 2b. During the snap-through behavior, the load is greater than the reaction force in the equilibrium path, which leads to transient oscillation of the unit cell. This elastic vibration is damped by the viscoelasticity of the constituent material; thus, the vibration energy is eventually dissipated to heat. The buckling induced dissipated energy is maximized with a mass constrain in our optimization model.

$$\begin{aligned} &\max_{\mathbf{x}} E_{diss} \\ &s.t. \quad m_a(\mathbf{x}) < M^* \end{aligned} \tag{1}$$

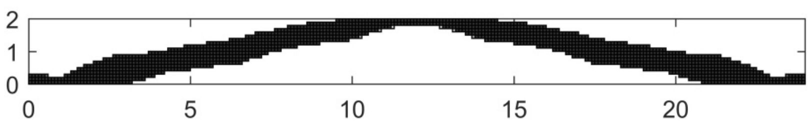
The design domain of a unit cell is given in Fig. 3a. The optimized results of Eq. (1) are given in Fig. 3b.



(a) The design domain and the boundary condition of a unit cell



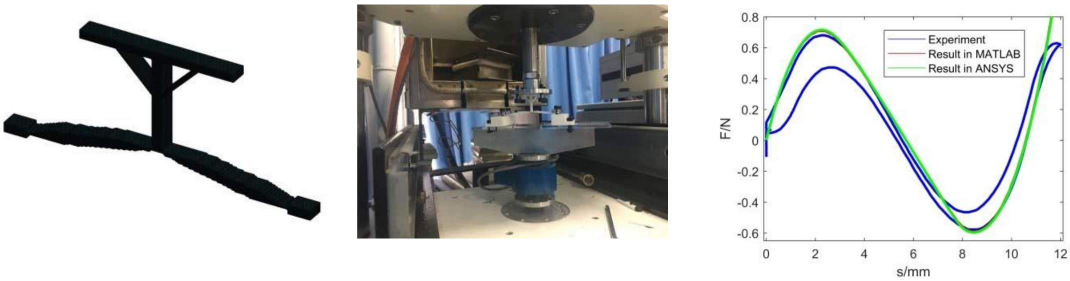
(b) Force-displacement curve



(c)The optimized result

Fig. 3 The optimized result

The optimized result is fabricated. The width of the unit cell is 3 times that in the optimization problem. The STL file for 3D printing is given in Fig. 8a. The force displacement curves are tested on bose electroforce 3330.The result is given in Fig.4.



(a) STL file for 3D printing (b) Installation (c)The force-displacement curve

Fig.4 The experiment study

We have proposed a method to design buckling-induced mechanical metamaterials for energy absorption using topology optimization. The vibration energy has been maximized in the topology optimization. Buckling-induced mechanical metamaterials with high energy absorption have been successfully designed. Experimental studies on the mechanical metamaterials developed using the proposed method is performed. For a rubber-like material, the distance between the pick value point and the valley value point coincides with that in the finite element analysis.

Bracket Design by Topology Optimization and Manufactured by Additive Manufacturing

Dongliang Quan*, Guanghui Shi, Chengqi Guan
Beijing Aerospace Technology Institute
* Corresponding author: quandl@163.com

Abstract

Topology optimization, which is a technique to seek the best structural configuration, has been widely accepted and adopted as an innovative design method in both academic research and applications in aircraft, aerospace and mechanical engineering. Additive manufacturing, which is a technique of layer-by-layer build-up of a product from a computer aided design model, has seen unprecedented growth as a manufacturing tool in some corporations for reducing mass and shortening reaction cycle.

Combination of optimization and additive manufacture could make structure optimization, especially for topology optimization, more effectively in improving structure performance and mass reduction. A large load bearing aerospace mount structure had been design under the guidance of topology optimization theory and manufactured with additive manufacture method. And on the basic of topology optimization, taking the lightweight structure and optimal performance as ultimate target, taking the necessary installation space requirement into account, the parameterized mount model had been reconstructed for size optimization. Further, the optimized mount lightweight structure design had finished. Then, the formability improvement had been done, additional test bars are added in the manufacturing process for performance testing, and process support is added inside the specimen to meet the requirements of the hanging angle process. Finally the mount was printed with the selective laser melting (SLM) equipment. The mechanical properties test of the test rod shows that the mechanical properties of the specimen meet the requirements. The main contributions are focused on the following points. In order to meet the requirement of thermal load optimization for the aerospace mount, special topology optimization and sensitive analysis formulation had been adopted. The additive manufacture method had been considered in the same processing with topology initial structure reconstruct after topology optimization, which

could improve the lightweight level of optimized structure, without the constrain of traditional manufacture requirement, such as openness requirement. In order to cooperate with the SLM equipment, elaborately designed structure rotation and process support had been done, which guaranteed the final structural quality by additive manufacture.

This work indicates that the combination of topology optimization and additive manufacturing technology provides a powerful tool kit to the engineering designers and they are an amazingly good fit.

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Additive Manufacturing Spacecraft Structure: Design and Evaluation

Xiaoyu Zhang, Hao Zhou, Huizhong Zeng
Beijing Institute of Spacecraft System Engineering, China Academy of Space Technology, Beijing, 100094

Abstract: Lattice structures have great advantage in lightweight, multi-function and high stiffness properties, which provide wide application potential in spacecraft engineering. However, the report of applications of lattice structures in spacecraft structure is rare due to the difficulties in cross-scale topology optimization method, the manufacturing dimensional precision and the complex connection between parts. In recent years, the development of topology optimization method and additive manufacturing techniques, such as selective laser melting, make the heteromorphic structure with internal high-precision lattice structures become reality. In this work, the topology optimizations of the several satellite structures, such as bracket structure, thermal control device structure and mini-satellite structure based on lattice cells are achieved using multi-scale design method. The satellite structure is manufactured with AlSi10Mg by direct metal laser melting. The dimensions of the satellite structure are $400\times400\times400$ mm^3. The main structure plays the role of mechanical support of various equipments. The weight of structures made of lattice cells is much lighter than traditional structures made of solid materials or honey comb plates. The mass of the structure and its carrying capacity are 8 kg and 104 kg, respectively. The structure mass-to-satellite mass ratio is 7.7%, which is lighter than most traditional satellite made of honeycomb sandwich panels, about 15~25%. The weight reduction is extremely important for the achievement of the spacecraft system engineering. The vibration test verified that the satellite structure could endure the vibration loads resulted from the rocket launching.

Keywords: Spacecraft Structure; Lattice Structure; Topological Optimization; Selective Laser Melting

Finite-Element-Mesh Based Method for Modeling and Optimization of Lattice Structures for Additive Manufacturing

Wenjiong Chen, Xiaonan Zheng and Shutian Liu
State key laboratory of structural analysis for Industrial Equipment, Dalian University of Technolgy, Dalian 116024, China

Abstract: Lattice structures play a vital role in design of lightweight structures for modern industry. Due to traditional manufacturing methods, most available designs are uniform lattice structures composed of periodic unit cells. The advances in additive manufacturing (AM) technology make non-uniform lattice structure with variable unit cells (conforming to the structural shape) and complex microstructures possible. Thus, it is very important to develop parameterization method for modeling the non-uniform lattice structures with variable unit cells and optimized bar sizes and/or orientations to achieve better performance than the uniform one. In this paper, a parametrization modeling method based upon finite element mesh to create complex large-scale lattice structures for AM is presented, and a corresponding approach for size optimization of lattice structures is also developed. In the modeling method, meshing technique is employed to obtain the meshes and nodes of lattice structures for a given geometry. Then, a parametric description of lattice unit cells based on the element type, element nodes and their connecting relationships is developed. Once the unit cell design is selected, the initial lattice structure can be assembled by the unit cells in each finite element. Furthermore, modification of lattice structures can be operated by moving mesh nodes and changing cross-sectional areas of bars. The graded and non-uniform lattice structures can be constructed easily based on the proposed modeling method. Moreover, a size optimization algorithm based on moving iso-surface threshold (MIST) method is proposed to optimize lattice structures for enhancing the mechanical performance. The strain energy expression of the bar element is chose as physical response function in the MIST, and cross-sectional areas of bars are considered as design variables. To demonstrate the effectiveness of the proposed method, 2-dimensional and 3-dimensional numerical examples are presented and several new and interesting lattice structures with optimized properties are found and presented.

Key words: Lattice structures; Additive manufacturing; Parametric description of lattice Structure, Finite-element-mesh based method; Moving iso-surface threshold method

A Novel Asymptotic-Analysis-Based Homgenisation Approach towards Fast Design of In-Fill Graded Microstructures

Yichao Zhu[a,b], Shaoshuai Li[a,b], Zongliang Du[c], Chang Liu[a,b], Xu Guo[a,b,*], Weisheng Zhang[a,b,*]

[a]*State Key Laboratory of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian, 116023, P. R. China*

[b]*International Research Center for Computational Mechanics, Dalian University of Technology*

[c]*Structural Engineering Department, University of California, San Diego, CA 92093, U.S.A.*

Abstract

Graded microstructures have demonstrated their values in various engineering fields, and their production becomes increasingly feasible with the development of modern fabrication techniques, such as additive manufacturing. With the use of asymptotic analysis, we propose in this article a homogenisation framework to underpin the fast design of devices filled with quasi-periodic microstructures. With the introduction of a mapping function which transforms an in-fill graded microstructure to a spatially-periodic configuration, the originally complicated cross-scale problem can be asymptotically decoupled into a macroscale problem within a homogenised media and a microscale problem within a representative unit cell. The stress field and overall compliance computed by the proposed method are shown, both theoretically and numerically, to be consistent with the underlying fine-scale results, while the computational cost associated with the corresponding linearised formulation is found to be as low as that in existing asymptotic-analysisbased homogenisation approaches, where only spatially periodic microstructures are considered. The present framework also exhibits outstanding features in several other aspects. Firstly, smooth connectivity within graded microstructures is automatically achieved. Secondly, the configuration obtained here is naturally characterised by a finite length scale associated with the resolution of fabrication. The proposed approach demonstrates its effectiveness by reproducing optimal microstructures where explicit solutions are available.