Design of spatially-varying orthotropic infill structures using multiscale topology optimization and explicit de-homogenization

Authors: Jaewook Lee\textsuperscript{a,*}, Chiyoung Kwon\textsuperscript{a}, Jeonghoon Yoo\textsuperscript{b}, Seungjae Min\textsuperscript{c}, Tsuyoshi Nomura\textsuperscript{d}, and Ercan M. Dede\textsuperscript{e}

\textsuperscript{a} Gwangju Institute of Science and Technology (GIST), Gwangju, South Korea
\textsuperscript{b} Yonsei University, Seoul, South Korea
\textsuperscript{c} Hanyang University, Seoul, South Korea
\textsuperscript{d} Toyota Central R & D Labs, Aichi, Japan
\textsuperscript{e} Toyota Research Institute of North American, Ann Arbor, MI, USA
\textsuperscript{*} Presenting author
Part I
Introduction
Background

Coated orthotropic infill (shell porous-infill) structures

✓ Biomimetic structure - Exists in nature such as animal bones, and plant stems

✓ Advantages of shell porous-infill structure: Superior energy absorption, high strength-weight ratio, Robustness to load variation and material deficiency

✓ Uninform infill versus Graded (spatially-varying thickness and orientation) infill

Human femur bone*

Y. Luo, Q. Li, and S. Liu, Topology optimization of shell-infill structures using an erosion-based interface identification method, CMAME, 2019


V. Hoang, P. Tran, N. Nguyenb, K. Hackl, H. Nguyen-Xuan, Adaptive concurrent topology optimization of coated structures..., CAD, 2020

S. Chu, L. Gao, M. Xiao, Y. Zhang, Multiscale topology optimization for coated structures with multifarious-microstructural infill, SMO, 2020

J.P. Groen, J. Wu, O. Sigmund, Homogenization-based stiffness optimization and projection of 2D coated structures with orthotropic infill, CMAME, 2019
Background

Topography Optimization for Shell-infill Structures

- Requires two design schemes for (1) Coated macrostructure, (2) Graded porous Infill

(1) Coated macrostructure design

- Various approaches have been proposed based on smoothed (filtered) density field.
- Coating region is identified as material interface between void and solid region.

Single smoothing and projection approach

Double smoothing and projection approach

Erosion-based approach

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* A. Clausen, N. Aage, O. Sigmund, Topology optimization of coated structures and material interface problems, CMAME, 2015
** J.P. Groen, J. Wu, O. Sigmund, Homogenization-based stiffness optimization and projection of 2D coated structures with orthotropic infill, CMAME, 2019
*** Y. Luo, Q. Li, and S. Liu, Topology optimization of shell-infill structures using an erosion-based interface identification method, CMAME, 2019
Background

Topology Optimization for Shell-infill Structures

(2) Graded porous infill design: Three approaches

A. Local volume constraint in single macroscale

- Straightforward single-scale approach
- High computational cost for large-sized macrostructure with small-sized infill

B. Concurrent topology optimization

- Abundant flexibility in infill design
- High computational cost
- Require to work on connecting infill microstructures

C. Homogenization-based multiscale approach

- Computationally efficient
- Post-processing is required to restore infill microstructures

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* J. Wu, N. Aage, R. Westermann, O. Sigmund, Infill optimization for additive manufacturing, IEEE VCG, 2018
** M. Schmidt, C.B.W. Pedersen, C. Gout, On structural optimization using graded porosity control, SMO, 2019
*** S. Chu, L. Gao, M. Xiao, Y. Zhang, Multiscale topology optimization for coated structures with multifarious-microstructural infill, SMO, 2020
**** V. Hoang, P. Tran, N. Nguyen, K. Hackl, H. Nguyen-Xuan, Adaptive concurrent topology optimization of coated structures..., CAD, 2020
***** P. Geoffroy-Donders, G. Allaire, G. Michailidis, O. Pantz, Coupled optimization of macroscopic structures and lattice infill, IJNME, 2020
****** J.P. Groen, J. Wu, O. Sigmund, Homogenization-based stiffness optimization and projection of 2D coated structures with orthotropic infill, CMAME, 2019
Research Objective

Proposed topology optimization of shell-infill structure for additive manufacturing

- Five sequential design procedures based on homogenization-based multiscale approach
- Design of coated structure with spatially-varying (functionally graded) infill microstructures
- Limited in two-dimensional single-load problem

additive manufactured design result
Key Ideas

A. Design of coated macrostructure

✓ Straightforward sequential post-processing approach based on filtered density
✓ Suitable for graded infill structure
✓ Not suitable if coating structure is critical

B. Design of infill microstructures

✓ Orthotropic infill microstructure is restored as explicit geometry using rotated rectangular
✓ Easy to generate mesh of design result for re-analysis
✓ Suitable for additive manufacturing
Part 2

Topology Optimization Formulation
A. Design of coated macrostructure

Sequential post-processing step after designing macrostructure and infill

- Simultaneous design of coated macrostructure and infill densities may cause 0-1 convergence problem
- Ambiguity between macrostructure density $\rho$, and microstructure hole size fields $l_{y1}$ and $l_{y2}$
- Coating region may cause sudden change in material property

$$-R^2 \nabla^2 d_\phi (x) + d_\phi (x) = d_\phi (x)$$

$$\rho (x) = H_r (d_\phi (x))$$

$$l_{y1}(x) = \frac{l_{\text{upper}} - l_{\text{lower}}}{2} (d_{y1}(x) + 1) + l_{\text{lower}}.$$  

$$l_{y2}(x) = \frac{l_{\text{upper}} - l_{\text{lower}}}{2} (d_{y2}(x) + 1) + l_{\text{lower}}.$$  

$$C^p_{ij} (x) = C^{\text{void}} + \rho (d_\phi)^p (\tilde{C}^{H}_{ij} (d_{y1}, d_{y2}, d_{\zeta}, d_{\eta}) - C^{\text{void}})$$

Problem in 0-1 convergence of macrostructure density
A. Design of coated macrostructure

Post-processing step after designing macrostructure and infill

- To avoid this convergence problem, sequential approach is proposed for coated structure design.

- After designing macrostructure without coating and infill density, infill density is set to 1 (i.e. hole sizes $l_{y1}$ and $l_{y2}$ is forced to be 0) at the interface of macrostructure density.

Macrostructure density $\rho$

Macrostructure boundary density $\rho_{bnd}$

Infill density $(1-l_{y1})(1-l_{y2})$ before and after proposed post-processing

\[
\begin{align*}
-P_{\rho}^2 \nabla^2 \tilde{\rho}(x) + \tilde{\rho}(x) &= \begin{cases} 
\rho(x) & \text{in } D \\
0 & \text{in } D_{\text{ext}} 
\end{cases} \\
\rho_{bnd}(x) &= \begin{cases} 
1 & \text{if } 0.1 < \tilde{\rho}(x) < 0.9 \\
0 & \text{otherwise} 
\end{cases} \\
\end{align*}
\]
De-homogenization using explicit geometry (rotated rectangular)

- Explicit geometry representation imitating microstructure base cell
- Easy to handle small-sized microstructure unit cell
- Easy to generate mesh for re-analysis

Infill structure with very small-sized microstructure unit cell

Microstructure with rectangular hole

Finite element mesh for re-analysis of design result
From microstructure orientation fields $\zeta, \eta$, the density field $\rho_{\text{void}}$ representing square void region is obtained. Then, its centroid location is determined using image processing.

Rectangular voids are then removed from the macrostructure.
Part 3
Numerical Examples
MBB Beam Design

Shell-infill design for compliance minimization problem

Design problem

Microstructure density field $\rho_m$

Microstructure orientation

Coated structure after post-processing

Restored infill structure

<table>
<thead>
<tr>
<th>Compliance value ($\Phi$)</th>
<th>Volume fraction ($V/V_{tot}$)</th>
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<tbody>
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<td>233.90</td>
<td>0.3988</td>
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<tr>
<th>Compliance value ($\Phi$)</th>
<th>Volume fraction ($V/V_{tot}$)</th>
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<tbody>
<tr>
<td>232.64</td>
<td>0.4004</td>
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CAD model for additive manufacturing
Shell-infill design for compliance minimization problem

Number of cell per unit length $P = 15$

- Compliance value ($\Phi$): 244.64

$l_{\text{lower}} = 0$, $l_{\text{upper}} = 0.9$

- Compliance value ($\Phi$): 194.73

Number of cell per unit length $P = 25$

- Compliance value ($\Phi$): 238.81

$l_{\text{lower}} = 0.2$, $l_{\text{upper}} = 0.8$

- Compliance value ($\Phi$): 224.60

Number of cell per unit length $P = 45$

- Compliance value ($\Phi$): 231.87

$l_{\text{lower}} = 0.5$, $l_{\text{upper}} = 0.8$

- Compliance value ($\Phi$): 263.91
Bell Crank Design

Shell-infill design for compliance minimization problem

Design problem
Microstructure density field $\rho_m$
Microstructure orientation
Design result with restored infill structure
CAD model for additive manufacturing
Bell Crank Design

Shell-infill design for compliance minimization problem

CAD model and its reanalysis result

Additive manufactured design result

Size: 240 X 150 X 30 mm
Model: A multi-jet printing machine (Projet 3510 SD)
Resolution: 0.0250-0.05 mm per 25.4mm
Printing material: Ultraviolet curing plastic (Visijet M3 Crystal)
Bell CrankDesign

Shell-infill design for compliance minimization problem

Design result with various loading conditions

loading conditions

<table>
<thead>
<tr>
<th></th>
<th>$t_{d1}$ (traction at $\Gamma_{d1}$)</th>
<th>$t_{d1}$ (traction at $\Gamma_{d2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(1, 0) $N/m^2$</td>
<td>(0, 1) $N/m^2$</td>
</tr>
<tr>
<td>B</td>
<td>$(-\frac{3}{3}, 0)$ $N/m^2$</td>
<td>$(0, \frac{4}{3})$ $N/m^2$</td>
</tr>
<tr>
<td>C</td>
<td>$(-\frac{4}{3}, 0)$ $N/m^2$</td>
<td>$(0, \frac{5}{3})$ $N/m^2$</td>
</tr>
<tr>
<td>D</td>
<td>$(-\frac{5}{3}, 0)$ $N/m^2$</td>
<td>$(0, \frac{6}{3})$ $N/m^2$</td>
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Any Questions?