Material behavior and manufacturing solutions for biomedical applications: from computational optimization to 3D printing

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Outline

Medical devices
- Impact of TEVAR on longitudinal strain
- Multi-objective optimization of Nitinol stent design

Non-Fourierian Heat Conduction
- Anomalous heat conduction
- Thermo-mechanical coupling

3D Printing
- Influence of meso-structure and chemical composition on FDM 3D-printed parts
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Objectives and methods

Goals

- Investigate impact of TEVAR on aorta longitudinal strain
- Assess aortic tensile properties

Methods

- Hydraulic circuit, strain measurement
- Tensile tests
Results

![Graph showing longitudinal strain (%) vs. pressure (mmHg) for Total aorta and Stented segment.](image)

**Total aorta**
- Pre: Blue line, Post: Red line
- Significant difference at p<0.001 for pressures 140, 160, and 180 mmHg

**Stented segment**
- Pre: Blue line, Post: Red line
- Significant difference at p<0.001 for pressures 120 and 140 mmHg
Mean longitudinal strain at 180 mmHg
Results

### Figure A

<table>
<thead>
<tr>
<th>Zone</th>
<th>CIRC</th>
<th>LONG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distal Zone</td>
<td></td>
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</tr>
</tbody>
</table>

### Figure C

<table>
<thead>
<tr>
<th>Zone</th>
<th>Circ</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal</td>
<td>2.33</td>
<td>1.17</td>
</tr>
<tr>
<td>Central</td>
<td>2.20</td>
<td>1.34</td>
</tr>
<tr>
<td>Distal</td>
<td>2.35</td>
<td>1.80</td>
</tr>
</tbody>
</table>

Significant differences are indicated by *P* values:
- *P* < 0.001
- *P* = 0.01

### Figure D

Bar graphs with error bars showing the true stress (MPa) for different zones.
Conclusions

• TEVAR induced a longitudinal strain decrease from 11.9% to 5.6% in the stented segments

• TEVAR induced a longitudinal strain mismatch between stented (5.6%) and non-stented segments (9.1%)

• Tensile testing showed that peak stress was lower for longitudinal (1.4MPa) than for circumferential fragments (2.3MPa)

• Longitudinal fragments were more prone to rupture proximally than distally
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Stent failures with a rate of 37% after 9 months

Restenosis and reduction of vessel diameter

Fatigue failure

[Scheninert et al. 2005]

[Petrini et al. 2013]
Objectives and methods

Goals
- Maximize stent fatigue life
- Maximize stent radial stiffness

Methods
- FEM
- Multiobjective optimization

Conflicting objectives
Methods

Optimization is performed on the stent cell

\[ L = Ml_z \]

\[ N l_c = \pi D \]
Optimization workflow

\[ \mathbf{x} \rightarrow \text{CAD} \rightarrow \text{FEA} \rightarrow \text{B.C.} \rightarrow f(\mathbf{x}) \]
Optimization workflow

\[ \mathbf{x} \rightarrow \text{CAD} \rightarrow \text{FEA} + \text{B.C.} \rightarrow f(\mathbf{x}) \]

- Crimping
- Stent release
- Diastolic pressure
- Systolic pressure

Fatigue Million Cycles

- Cycle 1
- Cycle 2
- Cycle N
Optimization workflow

1. **X**
2. **CAD**
3. **FEA**
4. **B.C.**
5. **f(x)**

A: Static Structural
Expression: EPT01 (Elemental Mean)
Unit: micro
Time: 235
Custom
13/11/2013 18:34

0.015794 Max
0.014039
0.012284
0.010529
0.0087746
0.0070196
0.0052647
0.0035098
0.0017649
4.7703e-12 Min

ANSYS

Gianluca Alaimo
Optimization workflow

- **x** → **CAD** → **FEA** → **f(x)**

**DOE** → **Response Surfaces** → **54 FE analyses** → **Optimization**
Optimization workflow

\[ x \rightarrow \text{CAD} \rightarrow \text{FEA} \rightarrow \text{f(x)} \]

- **DOE**
- **Response Surfaces**
- **Kriging RS: 44 FE analyses**
- **Optimization**
Optimization workflow

\[ x \rightarrow \text{CAD} \rightarrow \text{FEA} + \text{B.C.} \rightarrow f(x) \]

- **DOE**
- **Response Surfaces**
- **MOGA Genetic Algorithm**
- **Optimization**
\[ S_R = \frac{0.4}{0.19} = 2.1 \]

\[ S_o = \frac{0.4}{0.08} = 5 \]
Results

Reference design - $S=2.1$

Optimized design - $S=5$

Shape optimization
Results

Reference design

Optimized design

[Petrini et al. 2013]
The obtained Pareto set allows the designer to select the optimal solutions, according to the specific design requirements.

Enhancement of stent fatigue life can be obtained combining tapered strut profile with the following changes in the cell design:
- an increase of 25% of the strut length
- an increase of 40% of the strut width at its extremities.

Under such indications, it is possible to achieve a marked improvement of the fatigue safety factor, i.e., about 2.4 times, compared to the typical design (strut with constant section), without any loss of scaffolding capabilities.
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Anomalous heat transfer

Unpredicted (non-Fourierian) effects in heat transport

- Nano-tubes
- Resins
- Biological tissues
- Fiber composites
- Inert non homogeneous solids
- Combustion in solid reagents
References

Transport equation/heat conduction equation

\[ \mathbf{q} = -\lambda \frac{\partial^0}{\partial t^0} \nabla T \]

\[ \mathbf{q} = -\lambda_\beta \left( cD_0^\beta \right) (t) \quad 0 \leq \beta < 1 \]

where \( \left( cD_0^\beta f \right) (t) = \frac{1}{\Gamma(1 - \beta)} \int_0^t \frac{f'(\tau)}{(t - \tau)^\beta} d\tau \) is the Caputo fractional derivative.

\( \Gamma(z) = \int_0^\infty e^{-x} x^{z-1} dx \) is the Euler Gamma function and \( \lambda \) is the thermal conductivity.

Energy balance

\[ \nabla^2 T (\mathbf{x}, t) = \frac{1}{\gamma_\beta} \left( cD_0^{1-\beta} T \right) (\mathbf{x}, t) \]
Example of 1D problem

Transient heat 1D problem in cartesian coordinates

\[
\frac{\partial^2 T}{\partial x^2} = \frac{1}{\gamma_\beta} \left( c D_0^{1-\beta} T \right)(t) \quad \text{with} \quad 0 \leq x < L, \ t > 0, \ 0 \leq \beta < 1
\]

\[|T|_{x=0} = T_0, \quad \forall t > 0\]

\[|T|_{x=L} = T_0, \quad \forall t > 0\]

\[|T|_{t=0} = F(x) = T_0 + 4(T_0 - T_M) \left[ \left( \frac{x}{L} \right)^2 - \frac{x}{L} \right], \quad 0 < x < L\]

Solution

\[
T(x,t) = T_0 + \sum_{n=1}^{\infty} D_n \sin(\lambda_n x) E_{1-\beta,1} \left[ -\lambda_n^2 \gamma_\beta t^{1-\beta} \right]
\]

\[
E_{\xi,\eta}(z) = \sum_{n=0}^{\infty} \frac{(z)^n}{\Gamma(\xi n + \eta)}
\]
Example of 1D problem
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Thermo-mechanical coupling

\[
\begin{align*}
K_\beta \left( c D_{0+}^\beta \right) T_{xx} - \rho c_v T_t - \alpha E A T_0 u_{xx} + Q &= 0 \\
E A (u_{xx} - \alpha T_x) + \rho p &= 0 \\
N &= E A (\varepsilon - \alpha (T - T_0)) \\
\varepsilon &= u_{,x}
\end{align*}
\]

Solution

\[
\begin{align*}
T(x,t) &= T_0 + 4(T_0 - T_M) \sum_{m=2}^{\infty} \frac{1}{\pi^2 (m-1)^2} \left( \cos \left( \frac{2(m-1)\pi x}{L} \right) - 1 \right) E_{1-\beta,1} \left( -\frac{4(m-1)^2\pi^2}{L^2 \delta} t^{1-\beta} \right) \\
u(x,t) &= \alpha (T_0 - T_m) L \sum_{m=2}^{\infty} \frac{1}{\pi^3 (m-1)^3} \sin \left( \frac{2(m-1)\pi x}{L} \right) E_{1-\beta,1} \left( -\frac{4(m-1)^2\pi^2}{L^2 \delta} t^{1-\beta} \right) \\
N(t) &= 2 \alpha E A (T_0 - T_M) \sum_{m=2}^{\infty} \frac{1}{\pi^2 (m-1)^2} E_{1-\beta,1} \left( -\frac{4\pi^2 (m-1)^2}{\delta} t^{1-\beta} \right)
\end{align*}
\]
Results/temperature field

$\beta = 0$ (Fourier)

$\beta = 0.2$

$\beta = 0.4$

$T$ at $x = 0.5$
Results/displacement and axial force

\[ N \]

\[ \beta = 0 \]
\[ \beta = 0.2 \]
\[ \beta = 0.4 \]

\[ t \]

\[ U \]

\[ \beta = 0 \]
\[ \beta = 0.2 \]
\[ \beta = 0.4 \]

\[ x \]

\[ t \]

\[ U \text{ at } x = 0.25 \]

\[ \beta = 0.2 \]

\[ \beta = 0.4 \]
• The solution of the fractional heat equation \((0 < \beta < 1)\), governed by Mittag-Leffler functions, exhibits:
  - a much faster rising for small times
  - a much slower decay for large times
  compared with the solution of classical heat equation

• Thermal steadiness is achieved, by anomalous conductors, employing longer times than Fourier ones

• All the resulting fields, namely the axial stress, the displacement, and the temperature, are influenced by the thermal and elastic deformability of the bar. The higher is the deviation from the Fourier-like behavior, the more rapid becomes the rise in time
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Advantages of 3D-printing:

- Complex geometry
- Accurate printing
- Less waste material
- Short time-to-market
- Many available materials, included biocompatible ones

Fused Deposition Modeling (FDM)

- Thermoplastic filament
- Heated extruder
- Deposition of semi-molten material on the build surface
- Movement in X and Y directions
- Build surface lowered in Z direction

Resulting 3d-printed FDM object
Goal: Investigate how filament dimensions, orientation and chemical composition affect the FDM 3D-printed part mechanical properties.

Inner structure at a sub-millimeter scale resulting from FDM extrusion process.
ABS properties investigated:

Mechanical behaviour evaluation

Classical Lamination Theory (CLT)

Four elastic constants required:

- $E_1$: longitudinal Young’s modulus
- $E_2$: transverse Young’s modulus
- $\nu_{12}$: major Poisson’s ratio
- $G_{12}$: shear modulus

Material strength evaluation

Tsai-Hill failure criterion

Three admissible stresses required:

- $S_1$: strength in the fiber direction ($\theta=0^\circ$)
- $S_2$: strength in the transverse direction ($\theta=90^\circ$)
- $S_{12}$: in-plane shear strength ($\theta=45^\circ$)
Specimen **features**:  
- **Unidirectional fibers**  
- **Fibers aligned** in the plane  
- **10% overlap** between fibers  
- **No perimeters**  

Five different **fiber orientations** \((\theta)\) have been considered:

- 0°  
- 45°  
- 90°  
- 20°  
- 70°  

**Methods**
Two different types of ABS have been tested, in **different configurations**:

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Type</th>
<th>Layer Height (mm)</th>
<th>Extrusion Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 B432</td>
<td>0,2</td>
<td>0,4</td>
<td></td>
</tr>
<tr>
<td>A2 B432</td>
<td>0,25</td>
<td>0,5</td>
<td></td>
</tr>
<tr>
<td>A3 B432</td>
<td>0,3</td>
<td>0,6</td>
<td></td>
</tr>
<tr>
<td>B1 B322</td>
<td>0,2</td>
<td>0,4</td>
<td></td>
</tr>
</tbody>
</table>

**Tensile test features:**

- Displacement control
- Test running time: 1-10 min
- Displacement rate: 2 mm/min
- Gage length: 30-50 mm
Results – Elastic modulus

A1 – B432 – 0.2 x 0.4 mm
A2 – B432 – 0.25 x 0.5 mm
A3 – B432 – 0.3 x 0.6 mm
B1 – B322 – 0.2 x 0.4 mm
Results – Yield stress

\[ \sigma [\text{MPa}] \]

A1 – B432 – 0.2 x 0.4 mm

A2 – B432 – 0.25 x 0.5 mm

A3 – B432 – 0.2 x 0.4 mm

B1 – B322 – 0.2 x 0.4 mm
Conclusions

• We investigated how fiber orientation, filament dimensions and chemical composition affect the mechanical properties of ABS 3D-printed components

• We verified that a 3D-printed FDM material shows anisotropic mechanical properties

• CLT and Tsai-Hill yielding theory were found to be well capable of predicting in-plane stiffness and strength at the macro-scale
Thanks for your attention
Results – Yield stress

\[ \sigma \text{ [MPa]} \]

\[ \theta \text{ [°]} \]

- **A1 – B432 – 0.2 x 0.4 mm**
- **A2 – B432 – 0.25 x 0.5 mm**
- **A3 – B432 – 0.2 x 0.4 mm**
- **B1 – B322 – 0.2 x 0.4 mm**

Experimental data:
- Solid circles

Validation data:
- Open circles
Enhanced Design
Examples of «anomalous» heat transfer

The temperature evolution for an unit step LPR power source follows a power law of time different than expected by the Fourier law that is exponential. Therefore, the temperature evolution due to a generic LPR power history is a convolution integral with power law kernel. FRACTIONAL DERIVATIVE?

\[ T - T_0 = c_1 t^{0.33} \]
\[ T - T_0 = c_2 t^{0.37} \]

[Banerjee et al., 2008]
Constitutive law for FDM parts

We use CLT and Tsai-Hill yielding criterion in finite element analysis to predict FDM parts mechanical behavior. Both models are calibrated using experimental data.

**Linear elastic mechanical behaviour**

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**Classical Lamination Theory (CLT)**

Four elastic constants required:
- $E_1 =$ elastic tensile modulus in material direction 1
- $E_2 =$ elastic tensile modulus in material direction 2
- $\nu_{12} =$ ratio between strain in direction 2 and strain in direction 1
- $G_{12} =$ shear modulus in plane 12

---

**Plastic mechanical behaviour**

**Tsai-Hill yielding surface**

Three admissible stresses required:
- $\sigma_1 =$ maximum tensile stress in material direction 1
- $\sigma_2 =$ maximum tensile stress in material direction 2
- $\tau_{12} =$ maximum shear stress value in plane 12

---
Classical Lamination Theory (CLT)

- $\theta=0^\circ$: $E_1, \nu_{12}$
- $\theta=90^\circ$: $E_2$
- $\theta=45^\circ$: $G_{12}$

Orthotropic fiber (layer) under plane stress

$$
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\tau_{12}
\end{bmatrix} = \frac{1}{1 - \nu_{12}\nu_{21}} \begin{bmatrix}
E_1 & \nu_{12}E_2 & 0 \\
\nu_{12}E_2 & E_2 & 0 \\
0 & 0 & G_{12}(1 - \nu_{12}\nu_{21})
\end{bmatrix} \begin{bmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\gamma_{12}
\end{bmatrix}
$$

Elastic moduli for ABS 3D-printed specimen through Classical Lamination Theory

Elastic modulus [MPa]

Shear modulus [MPa]
Yielding criterion for FDM parts

Formulation of suitable yielding criteria, using Tsai-Hill approach

- $\theta=0^\circ \rightarrow S_{Lt}$
- $\theta=90^\circ \rightarrow S_{Tt}$
- $\theta=45^\circ \rightarrow S_{LTs}$

Tsai-Hill criterion: failure occurs in an orthotropic lamina when

$$\frac{\sigma_1^2}{S_{Lt}^2} - \frac{\sigma_1 \sigma_2}{S_{Lt}^2} + \frac{\sigma_2^2}{S_{Tt}^2} + \frac{\tau_{12}^2}{S_{LTs}^2} = 1$$

Uniaxial tensile strength according to Tsai – Hill Theory
Validation: experimental data vs FEA

Plate with hole - two cases considered:

- Circular hole
- Elliptic hole

Layer sequence through the thickness:

<table>
<thead>
<tr>
<th>s₁, θ₁</th>
<th>s₂, θ₂</th>
<th>s₂, -θ₂</th>
<th>s₁, -θ₁</th>
</tr>
</thead>
</table>

Experimental data vs Finite element analysis

<table>
<thead>
<tr>
<th>Force [N]</th>
<th>Δl [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0,5</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>300</td>
<td>1,5</td>
</tr>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
</tbody>
</table>
Solid 186: 3D 20-node layered element that exhibits quadratic displacement behavior.

Shell 181: 4-node layered element with six DOF at each node.

- Large displacements
- Plasticity with isotropic hardening rule
Validation - Plate with elliptical hole

Load [N] – displacement [mm] curve
Validation - Plate with elliptical hole

Using 8 elements through the thickness (1 element for each layer) the response curve is almost the same.
Conclusions:

• CLT has seems to be accurate enough in predicting mechanical response in *elastic domain* using both shell and solid elements.

• In plastic region the simulated response curve does not accurately match experimental data. Solid elements are more precise.

• More accurate or different constitutive models are needed to capture mechanical response in plastic region.