THE ROLE OF INELASTIC DEFORMATIONS IN THE MECHANICAL RESPONSE OF ENDOVASCULAR NICKEL-TITANIUM DEVICES

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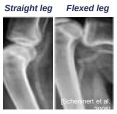
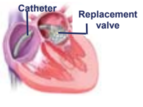
INTRODUCTION

Cardiovascular & peripheral diseases

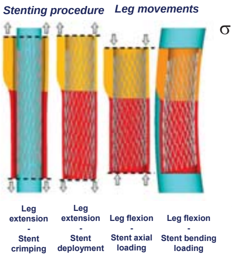
Clinical treatment with Nitinol stent and percoutaneous valves[1]

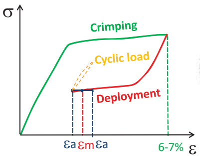


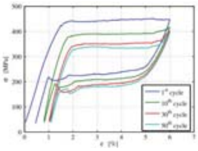


Biomedical devices working conditions

The loading cycles are responsible of functional fatigue







Cyclic loads are responsible for the **progressive weakening** of the material and its subsequent failure

Open issue

Pre-operative crimping: to fit the dimension of the deployment cather[2]

Excessive deformations during crimping may lead to **yielding**

⇩

Altered mechanical response due to **inelastic strains**

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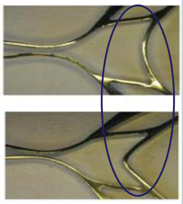
A **proper constitutive model** is needed for a **reliable estimation** of the device fatigue performance



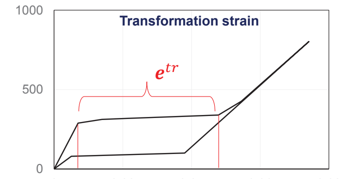
MATERIALS AND METHODS

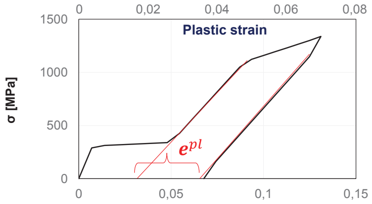
Material model formulation

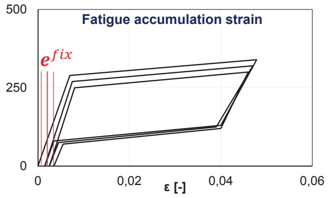
External variables: T, ε

Internal variables:

$$\xi = e^{tr} - e^{fix} - b e^{pl}$$







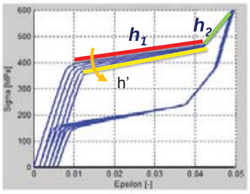
The thermodynamic potential

$$\Psi = \frac{1}{2}K\theta^2 + \underbrace{G\|\boldsymbol{e} - \boldsymbol{e}^{tr} - \boldsymbol{e}^{pl}\|^2}_{\text{Elastic energy}} \underbrace{-3\alpha K\theta(T - T_0)}_{\text{Thermal energy}} + \underbrace{\Psi_{tr}}_{\text{Transformation strain energy}} + \underbrace{\tau'_M\|\boldsymbol{\xi}\|}_{\text{Chemical energy}}$$

$$\Psi_{tr} = \begin{cases} \frac{1}{2}\{h_1 + [h'(\omega(t) + \eta(t))]\}\|\boldsymbol{\xi}\|^2, & \|\boldsymbol{\xi}\| \le \varepsilon_L(t) \\ \frac{1}{2}h_2\big(\|\boldsymbol{\xi}\| - \varepsilon_L(t)\big)^2 + \{h_1 + [h'(\omega(t) + \eta(t))]\}\varepsilon_L(t)\|\boldsymbol{\xi}\|, & \|\boldsymbol{\xi}\| > \varepsilon_L(t) \end{cases}$$

$$\tau'_M = \left\{\tau_M - \frac{A(1+\phi)}{2}[\omega(t) + \eta(t)] - \frac{B}{2}\eta(t)\right\}$$

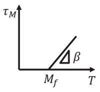
h1 and h2 control the slopes during transformation phase



h' controls the slope modification of the transformation plateau due to evolution of fatigue and plastic effects through ω and η

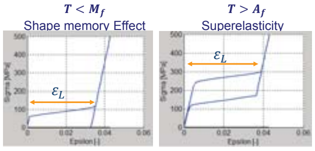
$$\omega(t) = \int_0^t \|\dot{\boldsymbol{e}}^{fix}\| dt$$

$$\eta(t) = \int_0^t \|\dot{\boldsymbol{e}}^{pl}\| dt$$

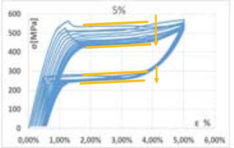


$$\boldsymbol{\tau_M} = \beta\langle T - M_f\rangle$$

controls the material response at different temperatures



A, Φ and B control the lowering of the loading – unloading transformation plateaus due to fatigue accumulation



FEA of a Trancatheter Aortic Valve Implantation (TAVI)

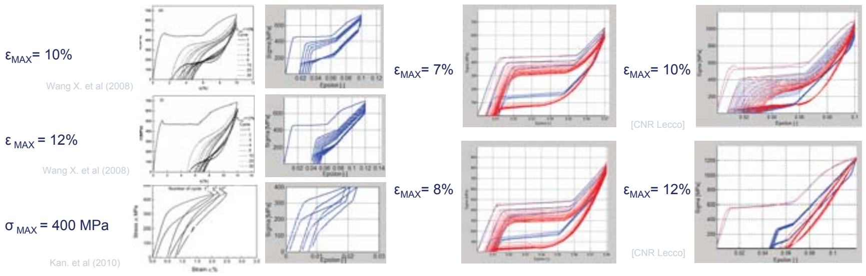
- The new constitutive model was implemented as an **UMAT** for User Defined Materials in Abaqus
- The stent frame of a TAVI device was modelled in **ABAQUS 6.14-5**
- The simulation of a **durability test** was reproduced twice to account for plasticity and fatigue or not [3]:

- Step 1: **pressurization** of the silicone compartment at 100 mmHg
- Step 2: **crimping** and **deployment** of the valve
- Step 3: **cyclic pressure loads** to mimick the in-vivo boundary conditions

RESULTS

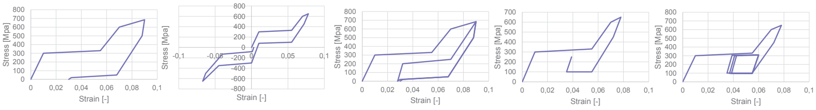
Material model

Comparison with experimental data

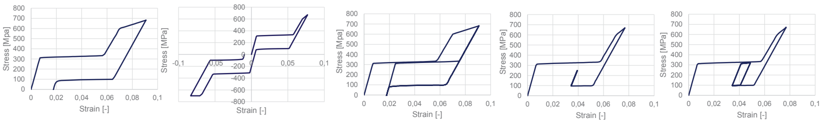


Comparison with the existing model implemented in Abaqus

UMAT

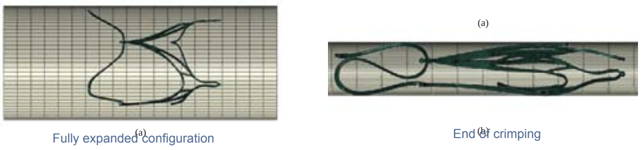


ABQ_SUPER_ELASTIC

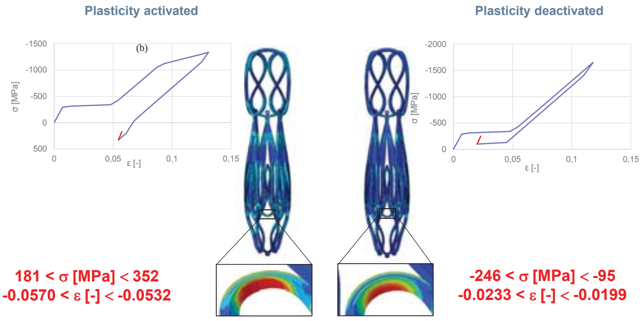


Finite Element

TAVI simulation



Most stressed element



181 < σ [MPa] < 352
-0.0570 < ε [-] < -0.0532

-246 < σ [MPa] < -95
-0.0233 < ε [-] < -0.0199

✓ Compressive vs tensile stress
✓ Doubled strain in the plasticity activated model

CONCLUSIONS

Devices are in-vivo subjected to a complex state of stress and in particular to cyclic loadings and post-yielding stress and strain

✓ A new constitutive model for shape memory alloys with plasticity, structural fatigue and their interaction was implemented and validated: it could be a useful tool for studying the device response under in-vivo BCs

➢ Next step: Validation of device behavior prediction

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References:

[1] Duerig T. et al. An overview of nitinol medical applications. Materials Science and Eng. A273-275 (1999) 149-160
[2] Petrini L. et al. Simplified multi-stage computational approach to assess the fatigue behaviour of NiTi transcatheter aortic valve during in vitro tests: a proof-of-concept study. Journal of Medical Devices (2017)
[3] Wu W. et al. Fluid structure interaction model of a percoutaneous aortic valve: comparison with an in vitro test and feasibility study in a patient-specific case. Ann Biomed Eng (2016) 44(2): 590-603