Identification of NiTi Stent Material Parameters Through Surrogate-assisted Optimisation

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Abstract—NiTiNol peripheral stents fatigue behaviour is widely investigated in literature by numerical analyses. Simulations provide a valuable support for design with several advantages, but the NiTi material characteristics, often limited or unavailable, have to be specifically reproduced in order to obtain reliable results. The present work proposes a methodology based on surrogate-assisted optimization methods, to obtain the material properties from experiments directly on the stent. The application of the method gives robust results in the identification of the correct material properties in improving the reliability of numerical study on NiTi stents.

Keywords—Cardiovascular, NiTiNol, Stent, Optimisation.

I. INTRODUCTION

NiTiNol (NiTi) peripheral stents are widely used for endovascular treatment of peripheral artery disease. However, the peripheral vascular district is characterized by complex movements which impose cyclic multi-axial loadings to the implanted device that may result in stent failure due to fatigue [1]. Finite Element (FE) analysis can be a powerful method to assess the state of stress of the device in a specific loading condition and is widely employed in academia and industry [2, 3]. To obtain reliable predictions, both the in-vivo loading conditions and specific device characteristics (in terms of geometry and material properties) must be modelled accurately [4, 5]. Whereas the geometry of the device can be obtained by optical measurements, the information about material properties is often limited and difficult to estimate. Indeed, NiTi material behaviour is strictly dependent on the alloy composition and the manufacturing treatments. In literature, a range of parameters for the material model are reported and these characteristics deeply affect the stent’s global and local behaviour. The present work proposes a methodology, based on surrogate-assisted optimization methods [6, 7], to obtain the parameters for the Shape Memory Alloy (SMA) model, available in ANSYS [8], from experimental tests on the stent. The methodology has been developed for a virtual case study on a reference geometry with NiTi material made in-house and then validated on experimental tests conducted on real stents of the same geometries and material, where variability and experimental noise could be present.

II. MATERIALS AND METHODS

A. Numerical analysis: Stent FE Model, Boundary conditions & NiTiNol material

The geometrical design chosen for the reference virtual case study is a peak-to-peak design. The reference stent geometry, as the most of the peripheral stent geometries, is made by a functional unit that is repeated circumferentially and axially to obtain the whole stent. To simplify the model and to reduce the computational cost, the analyses have been made on this functional unit (Figure 1a). A comparison between the whole stent and the unit has been made to establish the accuracy of the model results. A cycle of axial tensile loading and releasing has been chosen as numerical simulation on the stent functional unit. A NiTi biomedical material made by our LaBS group, studied experimentally and implemented in the ANSYS constitutive material (9 parameters: \(E_A\), \(v\) (constant=0.3), \(\sigma_{SAS}\), \(\sigma\_{FAS}\), \(\sigma\_{SSA}\), \(\sigma\_{FSA}\), \(\varepsilon\), \(a\), \(E_M\)) [8] has been chosen for the virtual reference case study.

B. Physical behaviour: Analysis of the mechanical stent axial behaviour

The mechanical behaviour of the stent unit when subjected to an axial loading and releasing has been analysed and three different phases, describing the nonlinear NiTi characteristic, have been highlighted (Figure 1b).

In the first phase the stent behaviour is linear elastic, involving \(E_A\). In the second phase the stent stiffness decreases, the material starts the transformation on the upper plateau involving \(\sigma\_{SAS}\), \(\sigma\_{FAS}\), \(\varepsilon\), \(a\). In the third phase the behaviour is firstly linear and then it starts the transformation on the lower plateau, involving \(E_M\), \(\sigma\_{SSA}\), \(\sigma\_{FSA}\). Each of these three phases, in term of force in time, will be the input (measurement) for the identification method.

C. Parameters identification through optimization process

The surrogate-assisted optimization process is decomposed in to the aforementioned three phases to separately estimate the parameters affecting each phase. The process starts by defining the lower and upper bounds for all the parameters based on literature (Table I). Then, for each phase, the parametric space is sampled through the quasi-random space-filling SOBOL sequence. Each sample point is numerically analysed in an FE simulation and a loss function (L2 error) between the reference behaviour and the behaviour of the stent with material properties corresponding to the sample is calculated. The loss function is then used to construct a

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Gaussian Process (GP) surrogate model (often referred to as a Kriging model in literature) [7]. The GP model is then searched (minimised) using a genetic algorithm (GA) followed by an L-BFGS descent from the best point predicted by the GA. The final solution, with the lowest loss function, is taken as an estimate of the parameters.

III. RESULTS

The method predictions, about the development of the method on the virtual case study, have been evaluated by comparison between the parameters identified and the reference values through several measures: the error between values in a normalized space (Table I); the material behaviours in terms of stress-strain curve (Figure 2); the stent global static behaviour in terms of force over displacement (Figure 3); the stent fatigue local behaviour in terms of first principal mean strain and equivalent alternate strain for an example loading conditions (Figure 4). The results highlight a high predictivity of the methodology with low errors (< 10% in the parameters values) in all the evaluations.

### Table I

<table>
<thead>
<tr>
<th>Type</th>
<th>E_s</th>
<th>σ_s</th>
<th>σ_m</th>
<th>σ_M</th>
<th>E_F</th>
<th>α</th>
<th>E_M</th>
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<tbody>
<tr>
<td>Reference</td>
<td>0.36</td>
<td>0.1</td>
<td>0.414</td>
<td>0.5</td>
<td>0.091</td>
<td>0.32</td>
<td>1</td>
</tr>
<tr>
<td>Identified</td>
<td>0.3541</td>
<td>0.0856</td>
<td>0.4097</td>
<td>0.5591</td>
<td>0.1729</td>
<td>0.3475</td>
<td>1</td>
</tr>
<tr>
<td>Error</td>
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<td>0.0144</td>
<td>0.0043</td>
<td>0.0592</td>
<td>0.0819</td>
<td>0.0275</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2 – The mechanical Stress-Strain static behavior of the material for the reference and the identified values.

Figure 3 – The static behavior of the stent functional unit has been analyzed with the reference and the identified material. A good agreement is showed.

Figure 4 – The fatigue behavior for an example loading case has been analyzed for the reference and the identified material. The comparison shows a good match between fatigue predictions.

IV. EXTENSIONS

The method described has been applied to an experimental case study to validate its effectiveness. Stent specimens in-house-made by our group at LaBS with the same material and same peak-to-peak geometry considered for the virtual case have been tested under axial tension in a temperature controlled chamber (Figure 5a). The experimental outcomes have been used as input for the identification method performed as explained above. Unlike the virtual case the experimental data (Figure 5b) are affected by experimental variability induced by possible slight differences in the stent structures and experimental noises.

Figure 5 – Experimental axial test on the stent sample(a); Experimental mechanical behaviour of 2 stent samples axially loaded and realessed(b).

V. CONCLUSION

The work proposes a new and robust methodology able to identify the NiTi material parameters directly from the stent using optimization algorithm. The use of this method gives an improvement on the reliability of the numerical study on NiTi peripheral stent when a stent sample is available for experimental tests. At the moment the experimental validation analyses are promising and still ongoing.

VI. ACKNOWLEDGEMENT

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REFERENCES

[8] ANSYS mechanical APDL material reference, Shape Memory alloy (SMA) material models (3.19)