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A Direct Method For Predicting The High-Cycle Fatigue Regime In SMAs: Application To Nitinol Stents

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Introduction

In metal fatigue, it is common practice to distinguish between high-cycle fatigue (i.e. failure occurring after 10000-100000 cycles) and low-cycle fatigue. For elastic-plastic materials, there is an established correlation between fatigue and energy dissipation. In particular, high-cycle fatigue occurs when the energy dissipation remains bounded in time. Although the physical mechanisms in shape-memory alloys (SMAs) differ from plasticity, the hysteresis that is commonly observed in the stress-strain response shows that some energy dissipation occurs. It can be reasonably assumed that situations where the energy dissipation remains bounded are the most favorable for fatigue durability. In this communication, we present a direct method for determining if the energy dissipation in a SMA structure (submitted to a prescribed loading history) is bounded or not. That method is simple to use and could be relevant for the design of SMA systems with high durability requirements, such as stents. Some numerical results are presented for the design of Nitinol stents and compared with experimental results from the literature.

Description of the method

In most of existing material models for SMAs, the strain ε is decomposed as an elastic part $M\sigma$ proportional to the stress σ and an inelastic part $K\alpha$ related to phase transformation, i.e. $\varepsilon = M\sigma + K\alpha$. In that relation, M is the elasticity tensor, K is a matrix, and α is an internal variable that tracks the phase transformation. The above relation is complemented with an elasticity domain C and a flow rule (describing the evolution of α) akin to plasticity.

Now consider a continuum submitted to a given loading history. For determining the evolution of the continuum, the mentioned constitutive laws are to be satisfied at each point and at each time. In addition, the stress field needs to satisfy the equilibrium equations and the strain field has to derive from a displacement field that respects the boundary conditions. Together all those equations (which we do not write explicitly here) define the structural evolution problem. That last problem is nonlinear and is usually solved incrementally using space- and time-discretization techniques [1,2,3,4].

For fatigue design, we are especially interested in situations where the solutions of the structural evolution problem are such that the energy dissipation remains bounded in time (high-cycle fatigue). It can be proved mathematically that such situations occur if, up to a time-independent translation, the local elastic response remains in the elasticity domain C at each point (see [5,6] for a more detailed statement). Here the elastic response is defined as the response of the continuum if the material were purely elastic, i.e. obeying the local relation $\varepsilon = M\sigma$.

Application to biomedical stents

We now describe the application of the proposed method to biomedical stents. Such devices have a tubular geometry and are typically an assemblage of elementary 'cells'. Such a cell is represented in Fig. 1. When the stent is loaded radially (for instance a consequence of blood pressure), each cell primarily experiences some uniaxial traction (along the direction represented as arrows in Fig. 1). Extensive traction experiments on cells with a shape similar to Fig. 1 have been performed in [7]. In those experiments, each sample is submitted to a cyclic strain varying between fixed minimum value $\varepsilon^{\min}$ and maximum value $\varepsilon^{\max}$. The number of cycles to failure is recorded for each sample. The obtained experimental results showed a low- to high-cycle fatigue transition for 0.4-0.5% strain amplitude, without any clear influence of the mean strain. Here we are interesting in checking if those results are consistent with the approach described in this paper.

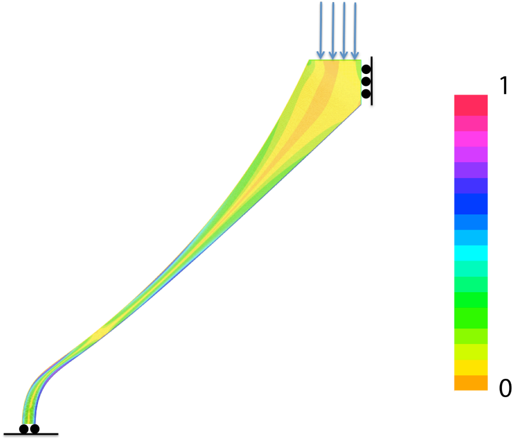

Figure 1: J_2 map on a stent cell (values are normalized with respect to the maximum value J_2^0).

For the problem at hand, applying the proposed approach merely consists in performing one single elastic calculation, namely calculating the elastic response of the structure in Fig. 1 when it is submitted to a (arbitrary fixed) reference strain ε^0. In Fig. 1 is represented the J_2-map (recall that $2J_2^2= \|\sigma^D\|^2$ when σ^D is the deviatoric stress), as obtained by a finite-element calculation in plane stress. Not surprisingly, the critical area (corresponding to maximum value of J_2) is located in the knee region of the structure. Adopting a J_2-type criterion for the phase transformation (as in [8] for instance), the general method described previously states that high-cycle fatigue occurs provided that $J_2^0.\ |\varepsilon^{max}-\varepsilon^{min}|/\ \varepsilon^0 < 2\ \sigma_y$ where J_2^0 is the maximum value reached in the map in Fig. 1 and σ_y is the yield limit for the phase transformation. Using Nitinol material parameters taken from [8], one obtains that the low- to high-fatigue transition occurs for the strain amplitude of 0.3%, which – given the uncertainties in the material parameters - is in good agreement with the experimental results. Also note that the predicted limit is independent on the mean applied strain, which again is in line with the experiments.

Conclusions

The presented method results from rigorous mathematical analysis and has the interesting feature of relying only on elastic calculations, thus bypassing the need of incremental nonlinear analysis. Moreover, only a partial knowledge of the loading (namely the knowledge of the extreme values) is needed.

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