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ABSTRACT

Recent cyclic tests on superelastic Nitinol tubing revealed that material's mechanical property quickly stabilized after several tens of cycle counts. The stabilized material's response is drastically different from the original material response. This paper presents the experimental discoveries and Finite Element Analyses (FEA) using ABAQUS to simulate the stabilized material response. The results show that the stabilized complex nonlinear mechanical response of Nitinol can be modeled very effectively and accurately using Abaqus with the new "Direct Cyclic" method.

INTRODUCTION

The successful medical applications of Nitinol implants such as filters and stents demand better understanding of Nitinol's cyclic behaviours. Strain-life approach has been adopted as the quickest phenomenological approach to predict the device safety. The key to this approach is to establish the constant life diagram using engineered fatigue samples that mimic the loading conditions an implant is subjected to in-vivo. Pelton et al [1] performed such testing on diamond-shaped specimens specific to the Nitinol implants under in-vivo pulsatile loading conditions. Their results showed, in bending, at mean strains range from 2% to 4%, Nitinol's fatigue endurance limit increases when mean strain increases (see Fig. 1).

The interpretation of these fatigue results of Nitinol in bending is based upon a finite element simulation of superelastic Nitinol; simulation is an expedite method, since the large deformations and small sample dimensions make experimental measurements very difficult. A material model that simulates the superelastic behaviour of Nitinol is necessary to accomplish this. The commercial finite element program ABAQUS/Standard contains a user defined material

subroutine that is based on the generalized plasticity theory (Auricchio and Taylor [2]). This UMAT has been shown to agree well with the mechanical responses of Nitinol devices, especially the fabrication and deployment aspects of such devices (Gong and Pelton [3]; Rebelo et al [4]; Rebelo et al, [5]).
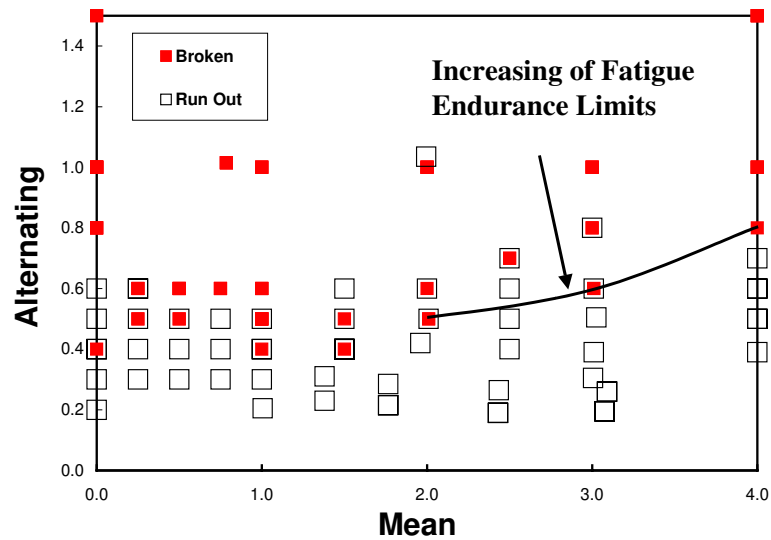

Fig. 1: Fatigue testing results on diamond shaped specimens.

However, the cyclic behaviour of Nitinol has long been known to change with the cycles and the loading conditions (Tolomeo et al. [6] and Gall and Maier [7]). Current interpretations of the fatigue results do not take into account the material response change as function of cycles and loading conditions. Rather, they are all based upon nonlinear FEA that simulates the first loading and unloading on the samples. Material input data used to generate the stress-strain response are normally based on the stress-strain response collected from a uniaxial tensile test that first pulls the sample to 6% of strain and then unloads the sample to zero stress and finally re-loads the sample until it fails. This approach is a sound engineering evaluation on the Nitinol fatigue because both the fatigue data as well as the device fatigue strains are evaluated consistently based on the same material input data. Device safety predictions on various Cordis-NDC Nitinol self-expanding stent products based on these data have been proven to be successful as the products survived 400 million cycle fatigue tests without a single strut fracture.

Yet the mystery of increasing in fatigue endurance limit when mean strain increases still has not been solved. As an attempt to better understand the fatigue behaviour of superelastic Nitinol, a systematic cyclic tensile test on Nitinol tubing has recently been performed. The purpose of this paper is to report the application of the resultant effective nonlinear FEA method on simulations of the diamond shaped fatigue samples in to produce a new look at the fatigue data.

EXPERIMENTAL METHODS

Uniaxial cyclic tensile tests were performed under strain-controlled condition using MTS system with customized grips and an extensometer. The test datum points were selected based on the possible fatigue boundaries observed by Pelton et al. [1]. For simplicity and demonstration purposes, this paper focuses on four datum points on the mean and alternating fatigue strain plane. Fig. 2 superimposes these datum points on the 10-million cycle constant fatigue-life diagram. The datum points are selected on the possible failure-survival boundary from 2% to 4%. An additional datum point of 0.8% alternating strain magnitude at 2% mean strain was also included to check the FEA prediction abilities. Notice that each mean and alternating strain magnitude datum point contains two tests, one starts the fatigue test directly, the other starts the fatigue tests after a pre-load up to 6% strain and a partial unloading.
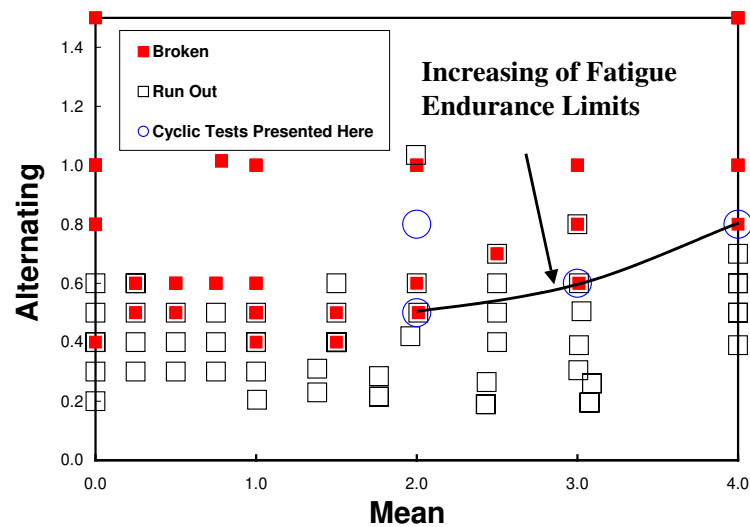

Fig. 2: Test datum points are shown in cycles on the constant life diagram.

Fig. 3 to Fig. 6 shows the experimental data for the mean strains from 2% to 4% and alternating strain magnitudes of 0.5 to 0.8% at the first and the 100th cycle counts. The first cycle results are plotted as dashed lines and the 100th cycle results are plotted in solid lines. Notice that each plot contains two testing conditions, one directly cycling (in blue and finer lines) and another one load up to 6% and then cycling (in black and wider lines). These test results reveal that Nitinol's stiffness and stress changes as function of the cycles and magnitude of the mean strain and alternating strains. Measurable elongations of all samples after tests are observed. They indicate the existence of permanent deformation due to cycling. Material responses are stabilized quickly in less than 100-cycle count. The stabilized direct cycling material responses tend to merge with the loading to 6% and then cycling material response. This indicated that the stabilized material response of superelastic Nitinol is history independent. Therefore, the high cycle fatigue of superelastic Nitinol can be concluded to be path independent.

It is also interesting to notice that at lower mean strains, the stabilized material responses is inside the loading to 6% and then unloading hysteresis loop as shown in Fig. 3 and Fig. 4. However, the stabilized lower stress moved down below the unloading plateau when the mean strains are higher than 3% as shown in Fig. 5 and Fig. 6.
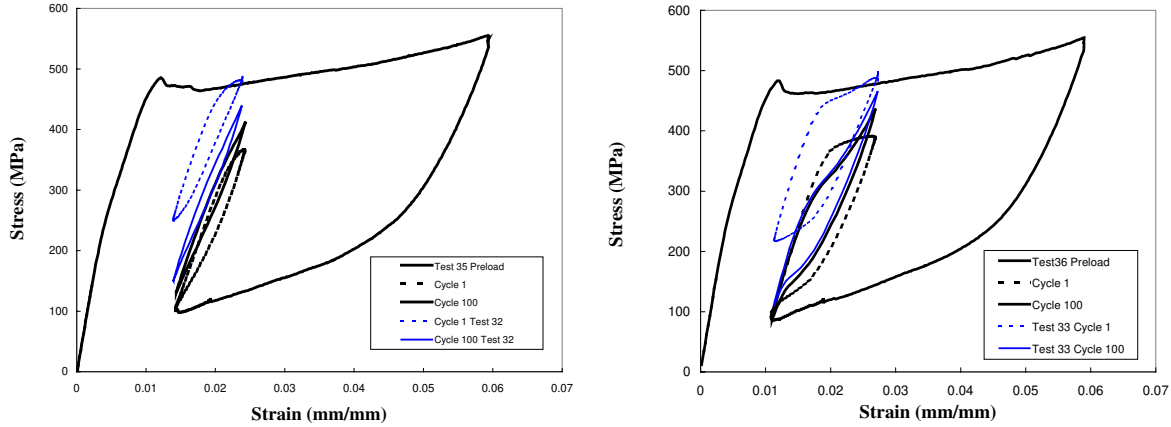

Fig. 3 and 4: Test results of 2% mean strain, 0.5% half alternating strains (test 32 and 35). Test results of 2% mean strain, 0.8% half alternating strains (test 33 and 36).
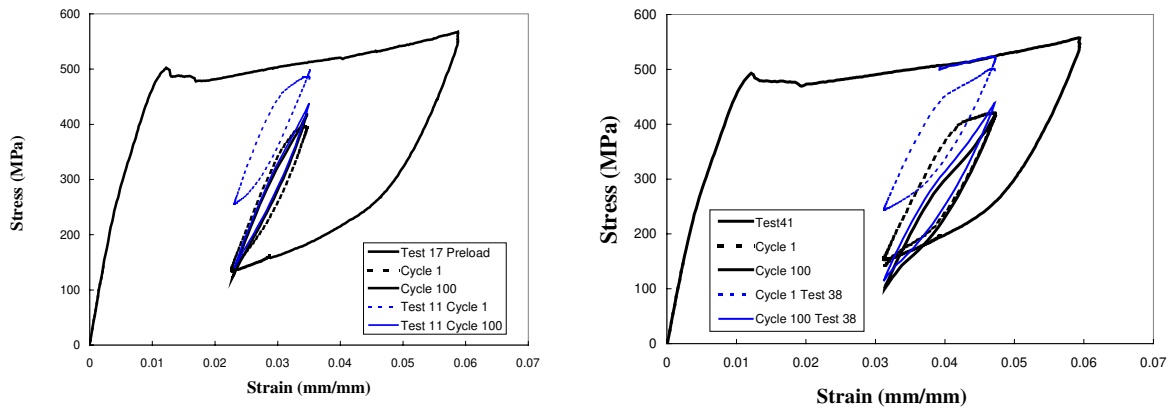

Fig. 5 and 6: Test results of 3% mean strain, 0.6% half alternating strains (test 11 and 17), test results of 4% mean strain, 0.8% half alternating strains (test 38 and 41).

FINITE ELEMENT ANALYSIS

In a previous publication [8], the authors reported simulations of the uniaxial tubing experiments. First they were conducted based on the currently available Nitinol UMAT. Material properties were entered based on a single loading and unloading experimental stress strain curve of the material tested at room temperature.

The four test datum points referred above were simulated both cycling from the forward transformation curve, and from the backward transformation curve. The model settles on

stabilized cycles after a few cycles only; typically the stabilized cycles are the same whether the cycling originates from the forward or from the backward transformation curves. Although the model captures some of the observations previously made, the experiments show that stabilized cycles are much narrower than these computations, and tend to settle at lower stresses.

ABAQUS introduced recently a new analysis procedure named Direct Cyclic procedure. For cases in which it is known that the response to cyclic loading is a stabilized cyclic response, this procedure computes directly a stabilized cycle, without having to compute a number of sequential cycles that would lead to such stabilized cycle.

Taking advantage of the direct cycling procedure just described, the authors computed direct stabilized cycles for the same tests. However, we assumed that cycling modifies the material behaviour, and therefore modified material constants were used. The direct cyclic procedure always starts from an equilibrium state with the original properties corresponding to the preloading, and iterates with the modified properties to obtain the stabilized cycle. The modified properties were estimated (but not optimized) from observation of the multiple uniaxial cyclic tests. Moreover, post-test elongations were observed on all test samples that indicate cyclic loading produces a permanent set possibly resulting in residual of Martensite phase or accumulations of microplasticity. We assumed that half of the fractions of Martensite at the beginning of the cycling become permanent, and compensated the transformation range accordingly.

The stabilized cycles for forward and backward transformations are close, and substantially below the original cycles. A substantial decrease in the dissipated energy per cycle (size of the cycle) is also noted. Both of these features have been observed in the physical tests described above.

In this paper we have extended cyclic computations to the diamond shaped fatigue specimen, therefore addressing the issue of cyclic behavior in bending. A quarter model of the specimen was used, and a series of simulations performed. First, from a single load/unload cycle, it was determined the imposed displacements which cause a maximum principal strain in the model to match the bounds of the four uniaxial experiments. Then cyclic analyses were made by pulling the specimen to cause the highest maximum principal strain, unload to the bottom of a cycle, and apply a direct cyclic procedure. In Fig. 7 the load displacement curves of the four tests are shown. The jumps from before cycling to after cycling are quite large. For comparison purposes, we also show in Fig. 8 the solution for the 4% mean, 0.8% half alternate strain cycling test with and without the direct cyclic procedure. It is observed that the modification of material properties has a substantial impact on the load curves.

Cycling redistributes stresses through a double effect: the non-linear and hysteretic behaviour of Nitinol, and the modification of material properties during cycling. As a result, cycling based on predetermined displacements imposed on the specimen has the consequence of an evolution of the cycling parameters at the point with maximum principal strain. The values obtained for the four test parameters are summarized in Tab. 1 and indicate a considerable reduction of alternate values as compared to nominal values.
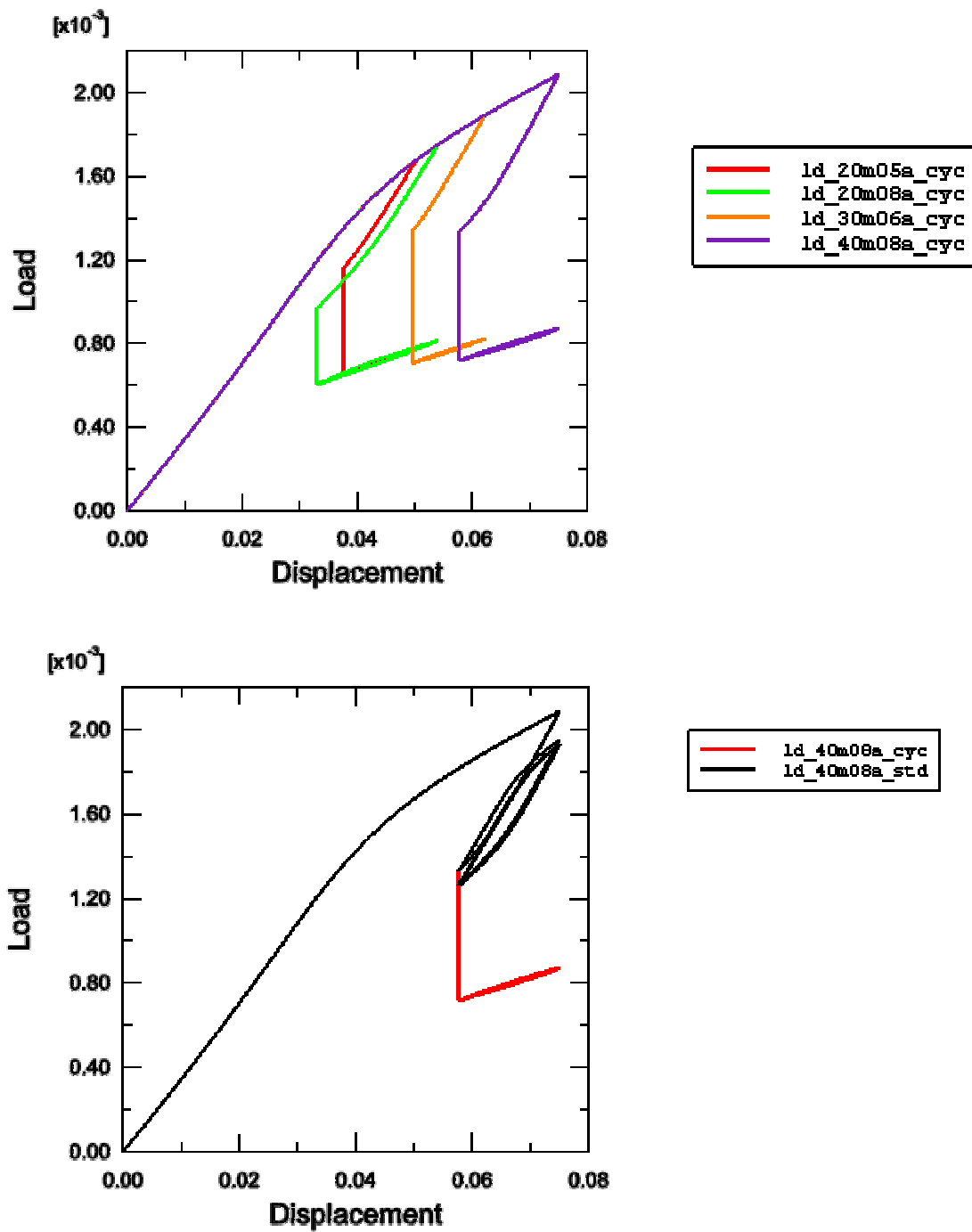
Fig. 7 and 8: Direct cyclic load displacement curves of the diamond shaped test specimen. Direct cyclic and regular cycling load-displacement curves.

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