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Analysis of Thermal Mechanical Fatigue in Titanium Matrix Composites

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INTRODUCTION

Titanium metal matrix composites are being evaluated for structural applications on advanced hypersonic vehicles. These composites are reinforced with ceramic fibers such as silicon carbide, SCS-6. This combination of matrix and fiber results in a high stiffness, high strength composite that has good retention of properties even at elevated temperatures. However, significant thermal stresses are developed within the composite between the fiber and the matrix due to the difference in their respective coefficients of thermal expansion. In addition to the internal stresses that are generated due to thermal cycling, the overall laminate will be subjected to considerable mechanical loads during the thermal cycling. In order to develop life prediction methodology, one must be able to predict the stresses and strains that occur in the composite's constituents during the complex loading. Thus the purpose of this presentation is to describe such an analytical tool, VISCOPLY.

COMPOSITE CONSTITUENT PROPERTIES

The mechanical properties of the fibers and the matrix materials at room temperature are shown in Table I.

Table I. Mechanical Properties

FIBERS	MATRIX
Silicon-carbide (SCS-6)	Ti-15V-3Cr-3Al-3Sn (Ti-15-3)
E = 400 GPa	E = 93 GPa
$\nu = 0.25$	$\nu = 0.36$
$\sigma = 3.6 \times 10^{-6}$ mm/mm/°C	$\sigma = 8.2 \times 10^{-6}$ mm/mm/°C
Diameter = 0.14 mm	$\sigma_{ys} = 690$ MPa

THERMOMECHANICAL FATIGUE TEST SETUP

The schematic diagram of the thermomechanical fatigue test setup is shown in Fig. 1. Liquid nitrogen is used in conjunction with induction heating to allow for precise specimen cooling rates.

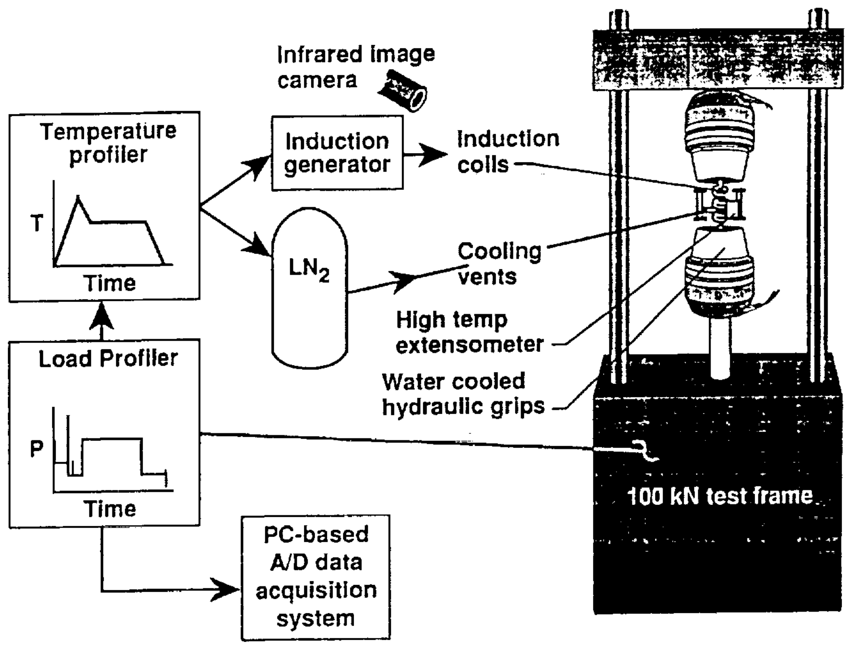

Figure 1. Thermomechanical fatigue test setup.

VISCOPLY PROGRAM DESCRIPTION

The VISCOPLY program is a two-dimensional symmetric laminate analysis code that can account for thermoviscoplastic response of both the fiber and/or the matrix material. The program combines the vanishing fiber diameter (VFD) model, a thermoviscoplasticity theory, and laminated plate theory. The program is based on the constituent properties of the fiber and the matrix. The fiber and matrix properties can both be nonlinear with time and temperature. VISCOPLY accepts any combination of in-plane normal and shear loading, out-of-plane normal loading and temperature change and can load in stress or strain control. Sequential jobs which allow any order and rate of load and temperature can be performed. The VISCOPLY program predicts the average stresses and strains in the fiber and matrix, and determines the overall laminate response.

THERMOVISCOPLASTICITY THEORY

The VISCOPLY program is based on the viscoplasticity theory of Eisenberg and Yen (1981), which was modified by Bahei-El-Din (1990). The theory assumes an existence of a rate-independent equilibrium stress-strain response. Inelastic deformation takes place if the current stress state is greater than the equilibrium stress state. The uniaxial constitutive equation, ε_{in}=k R^p, is a power law relationship requiring only two experimentally determined parameters, k and p. These parameters are determined from two monotonic, uniaxial tests performed at each temperature of interest. A strain-controlled test is conducted to determine the equilibrium curve and a load-controlled test is conducted to determine the overstress, R, and the inelastic strain rate, ε_{in}. The equilibrium curve and the load-controlled test results are then used to determine k and p as described in the following sections.

EQUILIBRIUM CURVE

The equilibrium curve is established by conducting a strain-controlled relaxation test. The test specimen is loaded to a predetermined strain level. The strain is then held constant to allow for stress relaxation. This sequence is repeated and the end points of the maximum relaxation events are joined to form the equilibrium curve for a given temperature. This is schematically shown in Fig. 2.

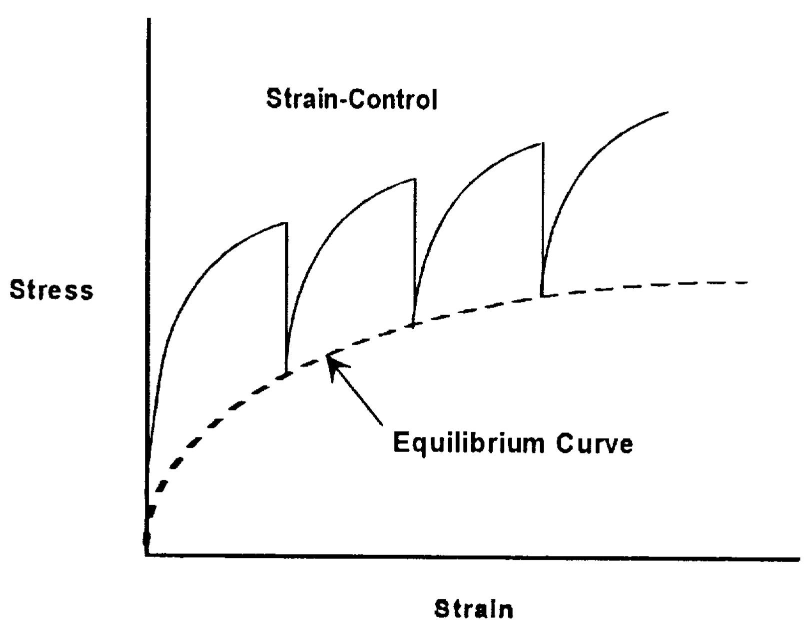

Figure 2 - Determination of equilibrium stress-strain response

CONSTANTS FOR THE EISENBERG-YEN MODEL

The constants k and p for the Eisenberg-Yen model are derived as shown by the schematic diagram in Figs. 3 and 4. The solid line on the stress-strain plot in Fig. 3 is a constant load rate test. The distance between the equilibrium curve and the constant load rate curve is the overstress, R. The amount of overstress is then plotted against the instantaneous strain rate as shown in Fig. 4. The k and p are then determined from the intercept and slope.

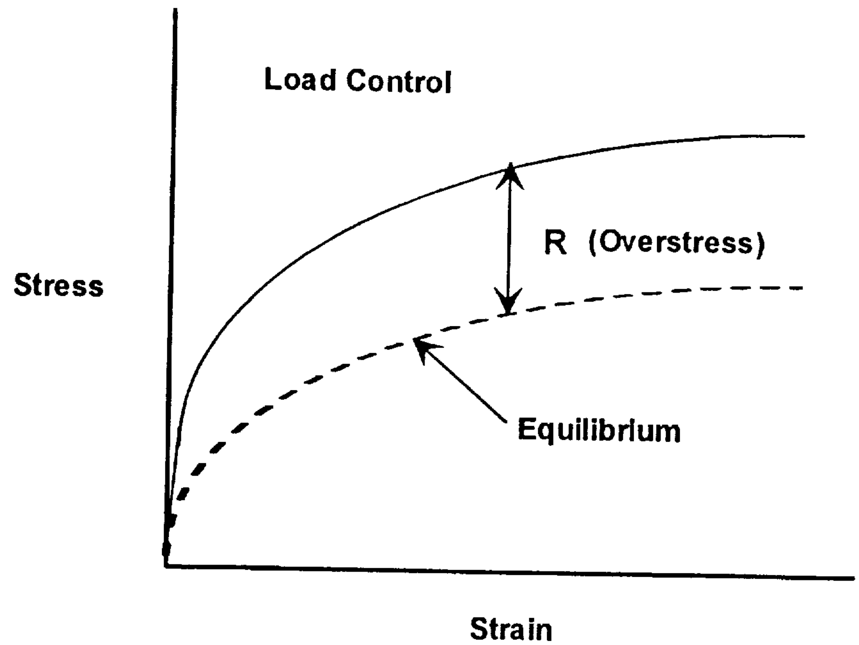

Figure 3 - Determination of overstress, R.

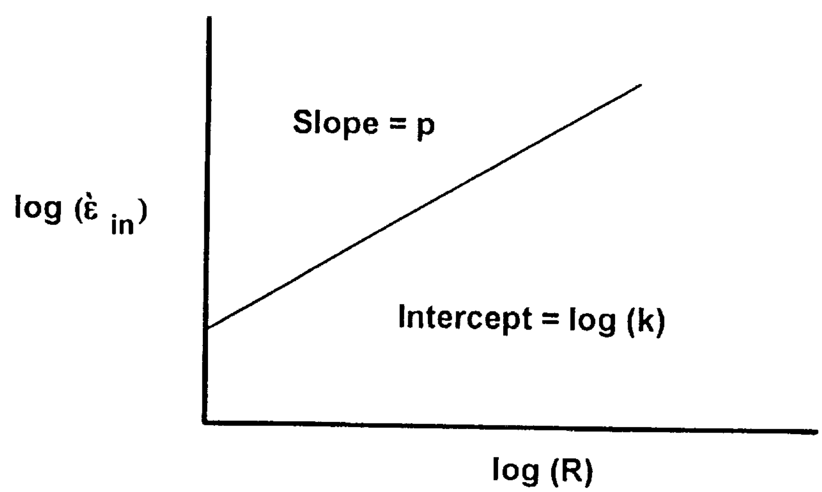

Figure 4 - Determination of the constants k and p.

MODEL CHECK ON THE MATRIX MATERIAL

Figure 5 shows an example of the model fit to the matrix data alone. These material constants will be used in all subsequent predictions.

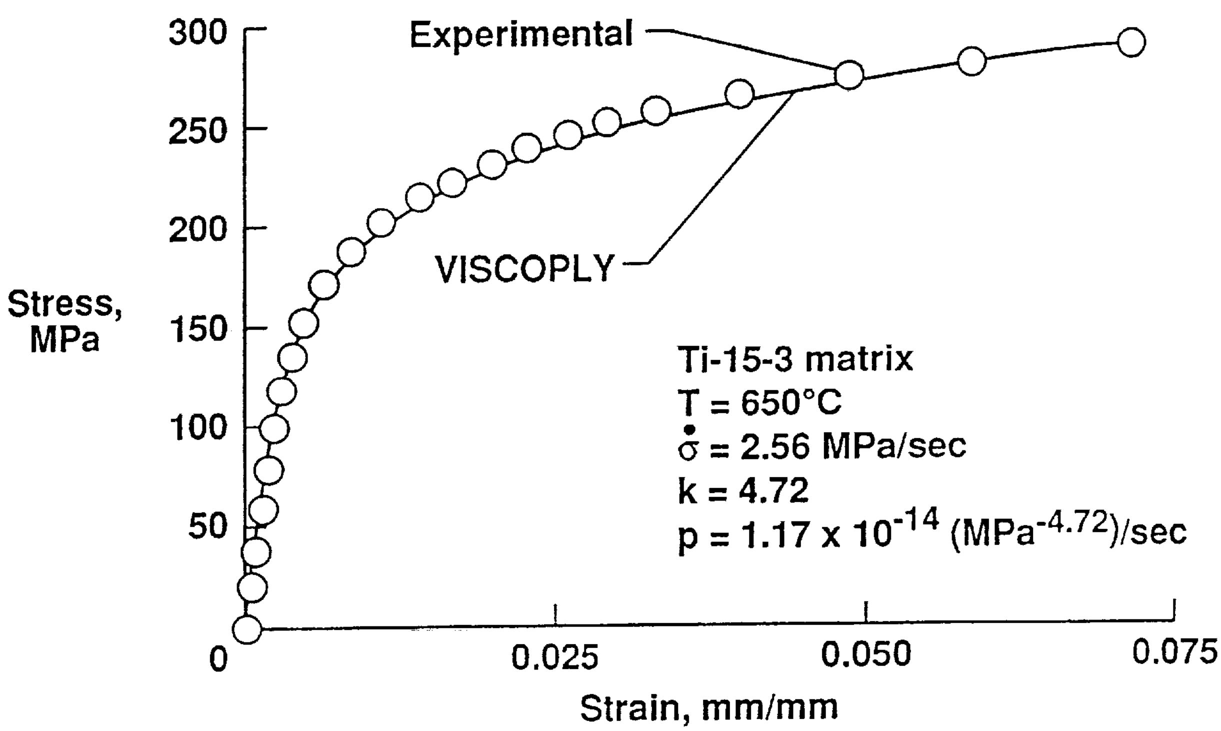

Figure 5 - Best fit approximation to the experimental data.

PREDICTION OF MATRIX RESPONSE

Figure 6 shows a comparison of measured and predicted time-dependent matrix response to a loading and relaxation test. Very good agreement between the model and experimental results was found.

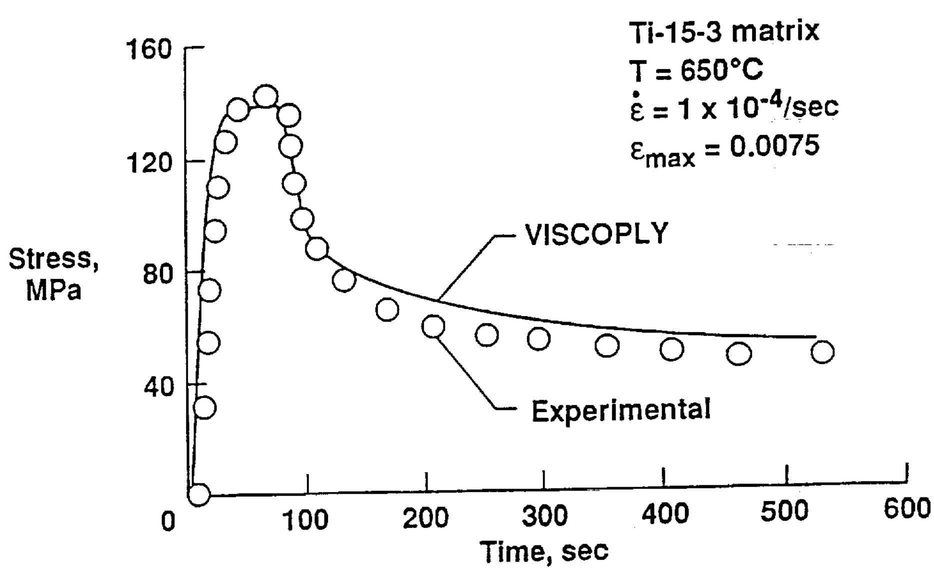

Figure 6 - Prediction of time-dependent matrix response.

PREDICTION OF A UNIDIRECTIONAL COMPOSITE RESPONSE

The predicting loading - unloading response of a unidirectional composite at elevated temperature is shown in Fig. 7. The VISCOPLY prediction was based only on those parameters determined from the constituent tests. As seen in the figure, VISCOPLY captured the essence of loading, unloading, and the permanent deformation of the composite.

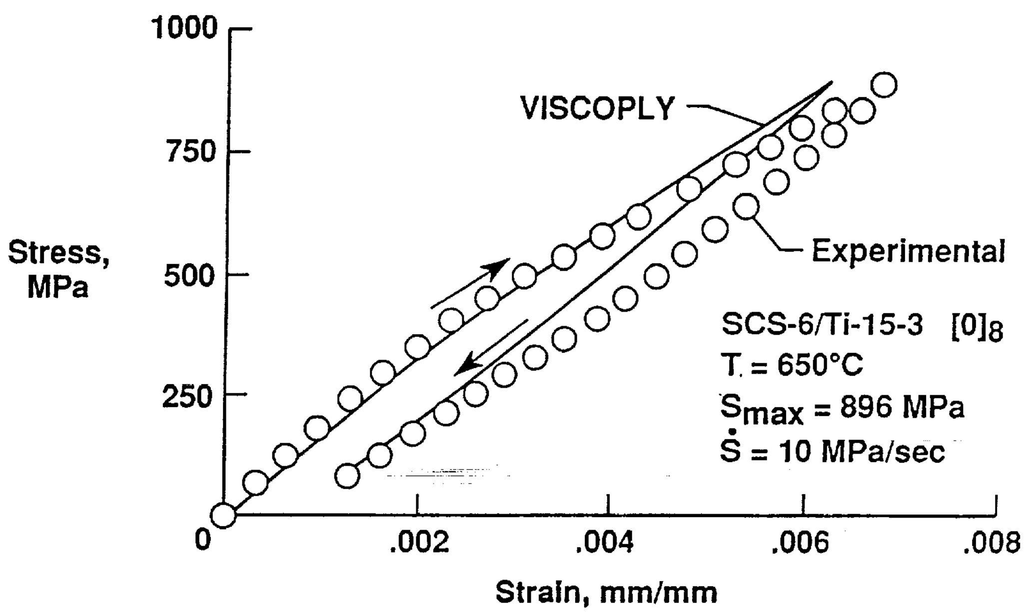

Figure 7 - Prediction of composite response.

ACCOUNTING FOR INTERFACE FAILURES IN 90° PLIES

In the VISCOPLY program the transverse modulus of the fibers in the 90° plies is reduced to simulate the fiber/matrix interface failures that have been shown to occur at very small load levels. It was determined that by multiplying the transverse modulus by 0.1 gave the best fit to the experimental data as shown in Fig. 8. This factor will be used in all future predictions of composite response above the fiber/matrix separation stress level at all temperatures.

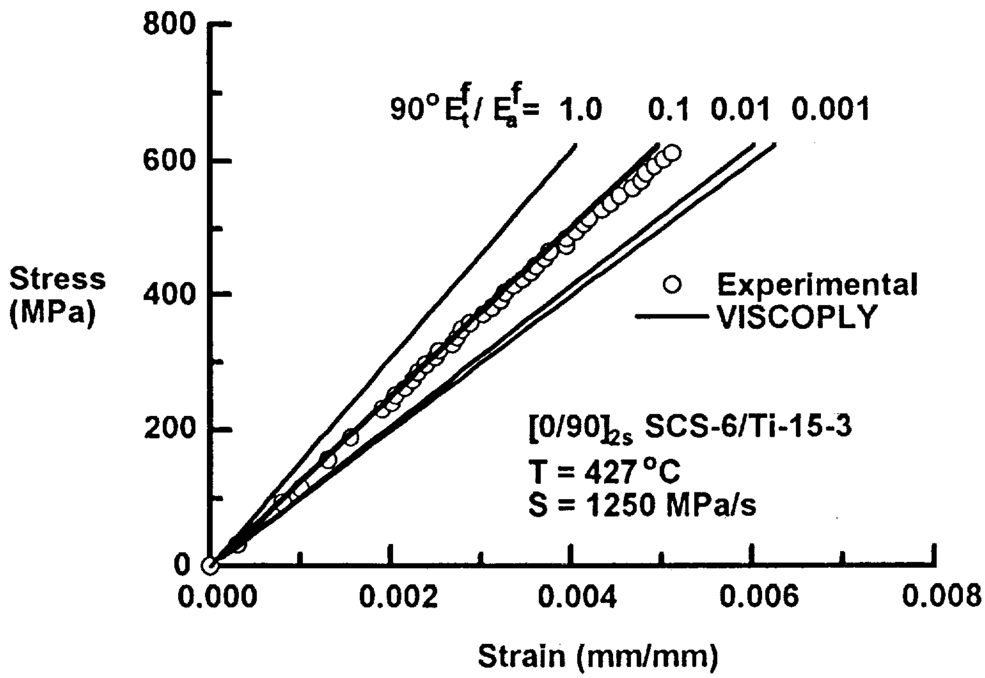

Figure 8 - Effect of reducing fiber transverse modulus on VISCOPLY predictions.

FLIGHT SIMULATION PROFILE

The flight profile shown in Fig. 9 was applied to actual specimens and the overall laminate stress-strain response was measured.

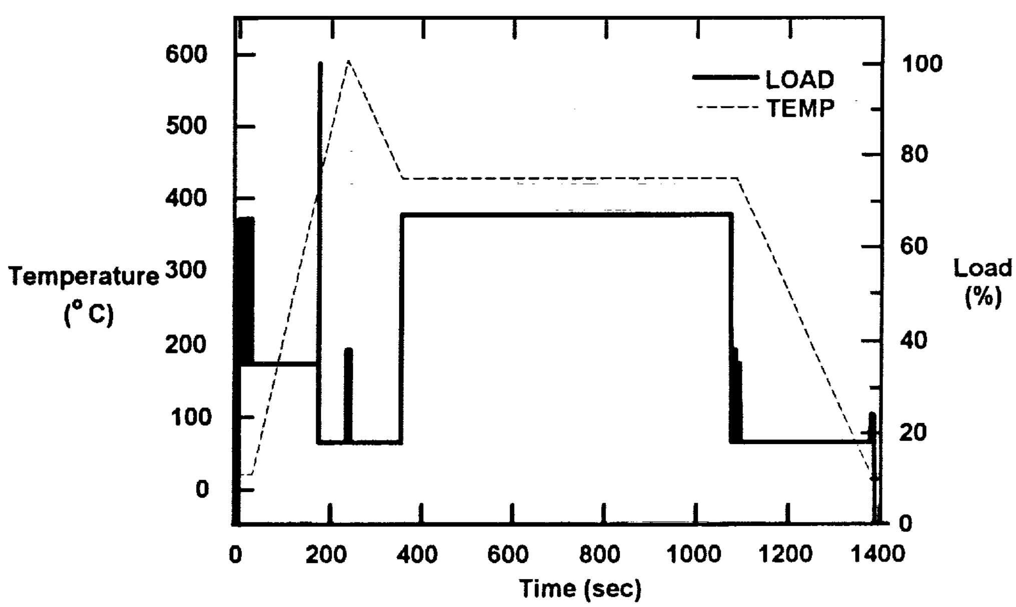

Figure 9 - Generic hypersonic flight profile.

PREDICTED LAMINATE STRESS-STRAIN RESPONSE TO THE FLIGHT PROFILE

As seen in Fig. 10, VISCOPLY accurately predicted the stress-strain response of the composite for the flight profile incorporating fiber/matrix interface failure of the 90° plies.

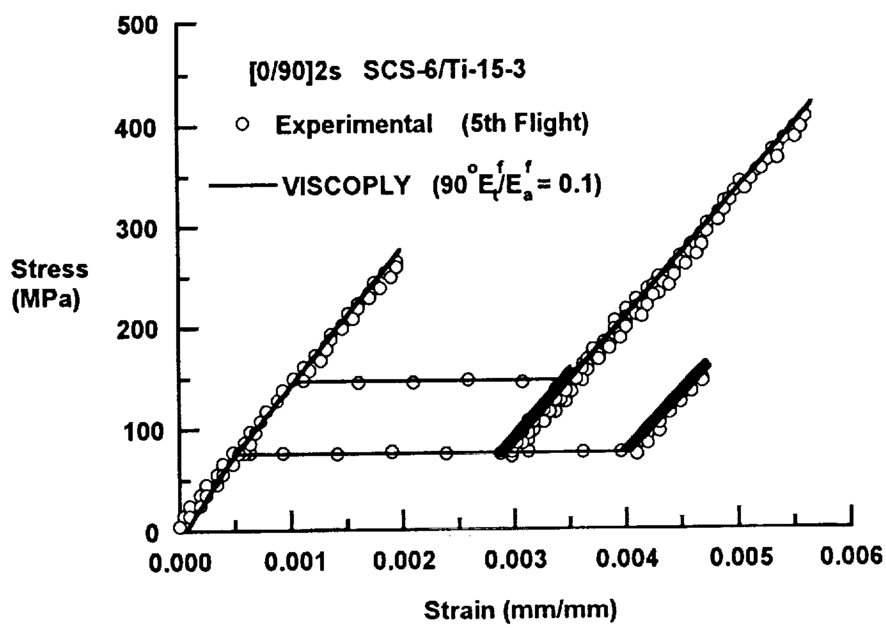

Figure 10 - Prediction of composite response under flight profile.

CONCLUSIONS

- Good characterization of constituent properties is required for accurate model predictions.
  - Matrix heat treatment should be the same as composite.
  - Rate-dependent and temperature-dependent constituent properties must be properly characterized.
- Fiber/matrix interface failure must be modeled for accurate predictions.
- VISCOPLY accurately predicted composite stress-strain response to cruise mission profile.
- VISCOPLY predictions of constituent behavior during mission profile are accurate and can be used in a failure criterion.

REFERENCES

1. Mirdamadi, M., Johnson, W. S., Bahei-El-Din, Y. A., and Castelli, M. G., *Analysis of Thermomechanical Fatigue of Unidirectional Titanium Metal Matrix Composites*, NASA TM 104105, July 1991.

2. Mirdamadi, M. and Johnson, W. S., *Stress-Strain Analysis of a $[0/90]_{2s}$ Titanium Matrix Laminate Subjected to a Generic Hypersonic Flight Profile*, NASA TM 107584, March 1992.