Prediction of Micro-crack Densities in IM7/977-2 Polymer Composite Laminates under Mechanical Loading at Room and Cryogenic Temperatures

Xiaofeng Su, Frank Abdi
Alpha STAR Corporation, Long Beach, CA
and
Ran Y. Kim
University of Dayton Research Institute, Dayton, OH

ABSTRACT

Monotonic and cyclic mechanical properties of a quasi-isotropic laminate, IM7/977-2, at room and cryogenic temperatures were investigated through a numerical procedure. A micro mechanics model, the equivalent constraint model (ECM), was incorporated in the progressive failure finite element analyzer (GENOA) to address the initiation and evolution of micro cracks in polymer matrix during the entire fatigue process. The degradation of the laminate stiffness due to micro crack multiplication was also evaluated using this numerical method. The simulation results agreed with the test observation reasonably well. This capability can be used as first level verification in the building block strategy approach.

INTRODUCTION

Cryogenic polymer composite propellant tanks are widely employed in Reusable Space Vehicles due to their lightweight. However, leakage tends to occur when micro-damages exceed tolerable levels, which may cause catastrophic tank failure. Micro-cracks, formed in the polymer matrix during manufacturing and service, significantly contribute to the leakage of composite propellant tanks. Therefore, predicting micro-crack formation and development in cryogenic tanks is of great importance to tank design.

Methods for calculating stress fields in cracked laminates are the variational approach (Hashin, 1986 [1]), the shear lag method (Laws and Dvorak, 1988 [2]; and Han and Hahn, 1989 [3]), approximate elasticity (Nuismer and Tan, 1988 [4]) and internal variable models (Allen at al, 1987 [5]). The shear lag method is an efficient and simple means of calculating stresses in laminate fibers and matrix. It has also been extended to micro-crack density prediction in laminates. Zhang et al (1992) [6] developed an equivalent constraint model (ECM), which predicts the reduction in stiffness properties due to transverse ply cracks as well as the initiation and growth of matrix cracking with increasing the mechanical load. In their study, an improved two-dimensional (2-D) shear lag analysis was used to determine the stress distribution in the cracked laminates.

In order to predict micro-crack densities in structures, the equivalent constraint model was incorporated in a progressive failure life prediction analyzer (GENOA) that integrates commercial FEA, micro mechanics and damage tracking algorithms for this study. Stress and strain fields calculated using finite element analyzer were transferred into the ECM. Within the ECM, the average stress and strain fields in each constituent were used to calculate the micro-crack formation and development described by the magnitudes of micro-crack density. Combination of the FEM and ECM enables the entire profile of the crack density distribution through a polymer composite structure to be defined during the loading process. At each location of the structure, the crack density was obtained at the ply level in the laminate.

In this paper, this numerical method was employed to assess the mechanical properties of a polymer composite laminate under monotonic and fatigue cyclic loadings at both room and cryogenic temperatures. The simulation results were verified against the Air Force test data (Donaldson, Kim and Trejo [7]).

METHODOLOGY

The micro mechanics model, ECM, is embedded in the progressive failure FEM to perform macro-micro failure analysis for a structure. Prediction of the crack density in a structure includes three parts: 1) the onset of cracks in the structure, 2) the multiplication of cracks through the entire structure, and 3) the degradation of composite properties due to the existence of cracks at each location. This method assumes that the micro-crack spacing is uniform in the ECM. Only transverse cracking as shown in Figure 1 is considered in the ECM. Longitudinal cracking involves the fiber failure, which is the macro-fracture of the entire ECM.

Onset of Cracks in the Matrix*:* The onset of cracks in the matrix is predicted by the transverse tensile failure criterion. It occurs when

$$\sigma_{22} \geq \sigma_{22T} \tag{1}$$

In Equation 1, σ_{22} is the ply transverse tensile stress and σ_{22T} is the ply transverse tensile strength.

Multiplication of Cracks in the Matrix*:* The multiplication of matrix cracks is defined by the progressively increasing crack density and is predicted by the assumption that the energy released due to damage in the matrix forms new crack areas. Therefore, the crack density at each load level is derived based on the energy release rate equation, which is established by the damage energy release rate (*derr*) equal to the first partial derivative of the potential energy with respect to crack areas. At each load level,

$$derr = \alpha \frac{\partial (P - U)}{\partial (C_d \times A_e)} \tag{2}$$

where P is the external work done by the applied forces and U is the strain energy. C_d is the crack density and A_e is the cracked area. In finite element analysis, A_e is the damaged element area, and the partial derivative becomes the finite differential. α is a conversion factor relating *derr* to the strain energy release rate which is used instead of *derr* in Equation 2 in classical fracture mechanics. A value of 10 was utilized in this study. By this approach, we are able to calculate the crack density from the material strength and modulus instead of the fracture toughness. The definition of *derr* is

$$derr = \frac{1}{2V_d} \int_{V_d} \sigma_m^2 \times (1 - v_f) \times D / E_m dv \tag{3}$$

where σ_m and E_m are the matrix strength and modulus, respectively. v_f is the fiber volume fraction. D is the damage factor of the matrix adopted as the degradation factor of the lamina stiffness in the transverse direction (Λ_{22} in Equation 6). V_d is the damage volume that is computed from

$$V_d = A_e \times t \tag{4}$$

t is the laminate thickness.

The crack density C_d can be obtained by combining Equations 2 and 3.

Degradation of Composite Properties due to Existence of Cracks*:* The degradation of composite properties due to the existence of cracks is calculated by the Equivalent Constraint Model developed by Zhang et al [6]. An iterative process was introduced in the GENOA/ECM model to consider stress redistribution resulting from the damage in the matrix. In each iteration, the crack densities and the corresponding degradation of composite properties are re-calculated. The iteration reaches convergence when crack densities through the structure reach saturation under the current load level. New cracks may occur when the load moves to the next level.

The degraded lamina stiffness can be written as follows:

$$\begin{bmatrix} Q_{11}^d & Q_{12}^d & 0 \\ Q_{12}^d & Q_{22}^d & 0 \\ 0 & 0 & Q_{66}^d \end{bmatrix} = \begin{bmatrix} Q_{11}^o & Q_{12}^o & 0 \\ Q_{12}^o & Q_{22}^o & 0 \\ 0 & 0 & Q_{66}^o \end{bmatrix} - \begin{bmatrix} Q_{12}^{o^2} / Q_{22}^o \times \Lambda_{22} & Q_{12}^o \times \Lambda_{22} & 0 \\ Q_{12}^o \times \Lambda_{22} & Q_{22}^o \times \Lambda_{22} & 0 \\ 0 & 0 & Q_{66}^o \times \Lambda_{66} \end{bmatrix} \tag{5}$$

where Q_{ij}^o and Q_{ij}^d are original and degraded stiffness, respectively. The subscripts 1 and 2 represent, respectively, the ply longitudinal (fiber) and transverse directions. Λ_{22} and Λ_{66} are degradation factors, defined in the following equations

$$\Lambda_{22} = 1 - \frac{\phi_1 + \phi_2 C_d \tan(\lambda_1 / C_d)}{\phi_1 + \phi_3 C_d \tan(\lambda_1 / C_d)} \tag{6}$$

$$\Lambda_{66} = 1 - \frac{\Gamma_1 + \Gamma_2 C_d \tan(\lambda_2 / C_d)}{\Gamma_1 + \Gamma_3 C_d \tan(\lambda_2 / C_d)} \tag{7}$$

The parameters ϕ_1, ϕ_2, ϕ_3, λ_1, Γ_1, Γ_2, Γ_3, and λ_2 are related to lamina properties and the laminate configuration. Their expressions are defined in Reference 6. The ply degradation factors, Λ_{22} and Λ_{66}, concern not only the properties of the current ply but those of other plies in the laminate.

The computational procedure in crack density prediction is illustrated in Figure 2.

FINITE ELEMENT MODEL

The finite element idealization of the test coupon illustrated in Figure 3 was used to simulate the monotonic and cyclic responses of the quasi-isotropic laminate at room and cryogenic temperatures. It should be noted that only the gauge length of the specimen was considered. The prescribed loading and boundary conditions provided the required uniform strain field in the test coupon model.

COMPOSITE SYSTEM

The composite system consisted of IM7 graphite fiber and 977-2 polymer matrix configured as a quasi-isotropic laminate, $[0/45/90/-45]_S$. The constituent properties were given in Table 1.

Table 1 Major constituent properties

Mat.	Modulus (msi)		Strength (ksi)		Poisson Ratio	
	RT	Cryo	RT	Cryo	RT	Cryo
IM7	37.8	38.5	650	580	0.22	0.22
977-2	0.4	1.2	8	6	0.42	0.42

Fiber properties in Table 1 were presented in the longitudinal direction. Matrix was assumed to be isotropic. The fiber volume fraction was 60%.

The fatigue degradations of the matrix in the form of fatigue strength-cycle (SN) curves are illustrated in Figure 4.

RESULTS

The monotonic and cyclic responses of the quasi-isotropic IM7/977-2 laminate at both room and liquid Nitrogen temperatures were predicted and verified with the Air force test results [7]. For the fatigue cyclic case, the micro crack evolution and corresponding laminate stiffness degradation were also computed.

The simulation stiffness and strengths of the laminate under monotonic loading were compared with the test data. The consistency was good as shown in Table 2. The laminate at cryogenic temperature (liquid Nitrogen) was stiffer but weaker than it at room temperature.

Figure 5 illustrates the comparison of simulation and test fatigue lives of the laminate at various stress levels. It can be seen that the numerical results fell within scattered test data at each stress level. The laminate fatigue S-N curve at cryogenic temperature (liquid Nitrogen) was stabilized at higher stress level than it did at room temperature.

Crack density development in the angled plies of the laminate in the case of the maximum cyclic stress 96.5 ksi are illustrated in Figure 6 and Figure 7. Micro cracks in the matrix at cryogenic temperature multiplied more rapidly than those at room temperature as shown in both simulation and test observations. Considering the scattering nature of test data, it is safe to say that the crack densities of simulation agreed reasonably well with the test results.

The laminate stiffness at both room and cryogenic temperatures degraded due to the existence of micro cracks in the polymer matrix, which is shown in Figure 8 and Figure 9 at various cyclic stress levels. The stiffness degradations of the laminate were not significant because the fiber stiffness was dominant in this quasi-isotropic laminate.

Table 2 Comparison between the simulation monotonic laminate properties and the test data

Temperature	Strength (ksi)		Stiffness (msi)	
	Test	Simulation	Test	Simulation
Room Temp.	131.8	138.5	8.76	8.63
Liquid Nitrogen	115.8	122.8	10.45	10.6

CONCLUSION

Numerical results of the laminate monotonic and fatigue cyclic responses as well as micro crack development in the matrix agreed well with the Air force test results [7]. Combination of the ECM with the GENOA progressive failure finite element analyzer allows the unit cell model to be used at the structural level Thus, it is a powerful tool for the permeability and damage tolerance design of polymer composite cryogenic propellant tanks.

REFERENCE:

1. Hashin, Z., "*Analysis of Stiffness Reduction of Cracked Cross-Ply Laminates,*" Engng. Fracture Mech., Vol. 25, pp 771-778, 1986
2. Laws, N and Dvorak, G. J., "*Progressive transverse Cracking in Composite Laminates*," J. Composite Mater., Vol. 22, pp900-915, 1988
3. Han, Y.M. and Hahn, H.T., "*Ply Cracking and Property Degradations of Symmetric Balanced Laminates under General In-plane Loading,*" Composites Sci. and Technol., Vol. 35, pp337-397, 1989
4. Nuismer, R.J. and Tan, S.C., "Constitutive Relations of a Cracked Composite Lamina," J. Composite Mater., Vol. 22, pp306-321, 1988
5. Allen, D.H., Harris, C.E. and Groves, S.E., "*A Thermo-mechanical Constitutive Theory for Elastic Composites with Distributed Damage*," Int. J. Solids and Structures, Vol. 23, pp 1301-1338, 1987

6. Zhang, J., Fan, J., and Soutis, C., "*Analysis of Multiple Matrix Cracking in [±θm/90n]s Composite Laminates – Part 2: Development of Transverse Ply Cracks*," Composites, Vol. 23, No. 5, Sept. pp299 – 304, 1992.
7. Donaldson, S. L., Kim, R. Y. and Trejo, R. E., "*Damage Development in Laminates Mechanically Cycled at Cryogenic Temperature*," *43rd AIAA Structures, Structural Dynamics, and Materials Conference*, Palm Spring, CA, AIAA-2004-1774, April 2004.

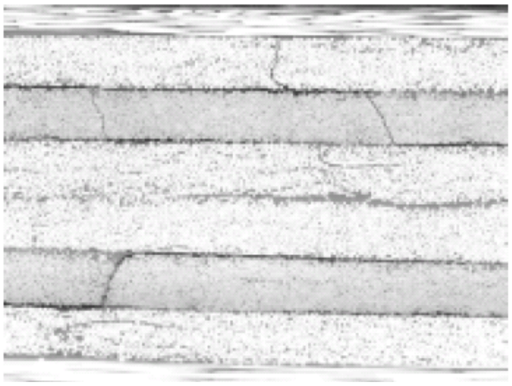

Figure 1 Typical micro cracks in the polymer matrix [7]

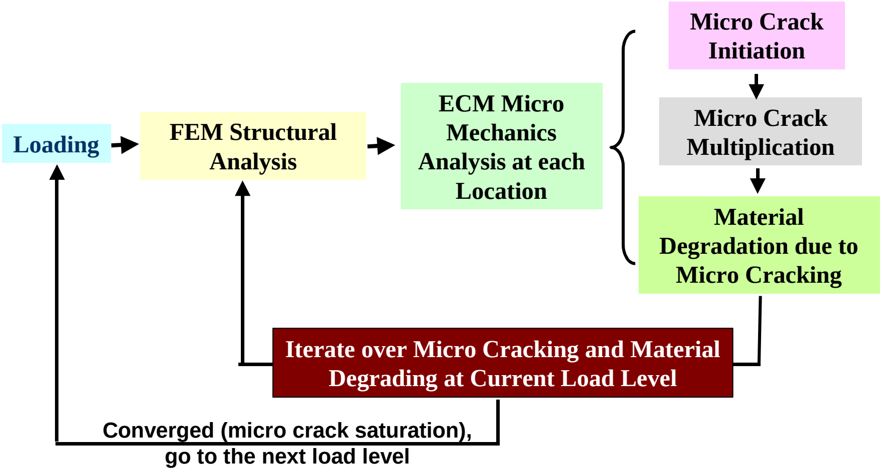

Figure 2 Computational procedure in crack density prediction

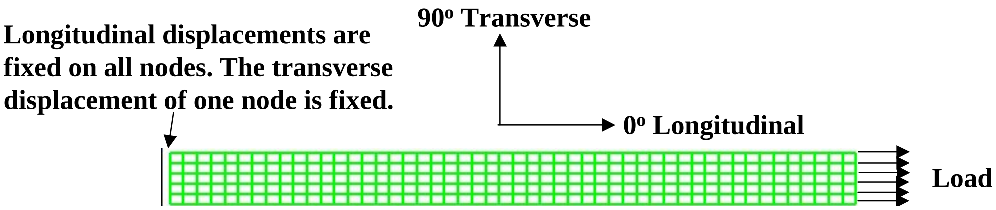

Figure 3 The finite element coupon model

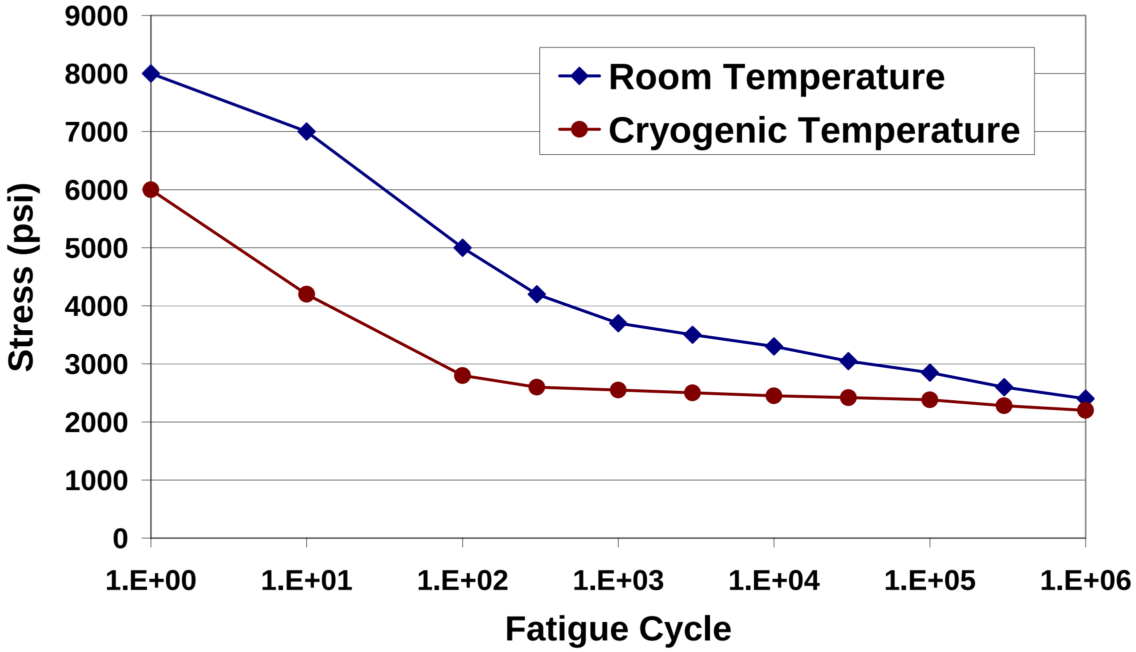

Figure 4 Fatigue strength –cycle (SN) curves of the matrix

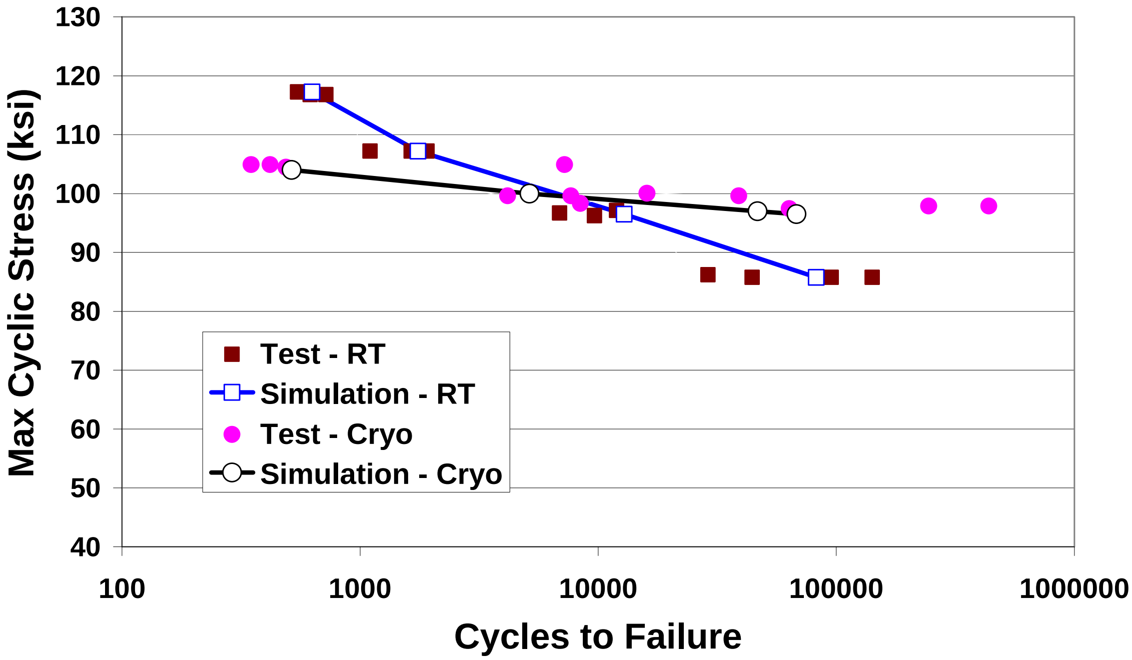

Figure 5 Comparison between the simulation and test fatigue lives of the laminate at room and cryogenic temperatures

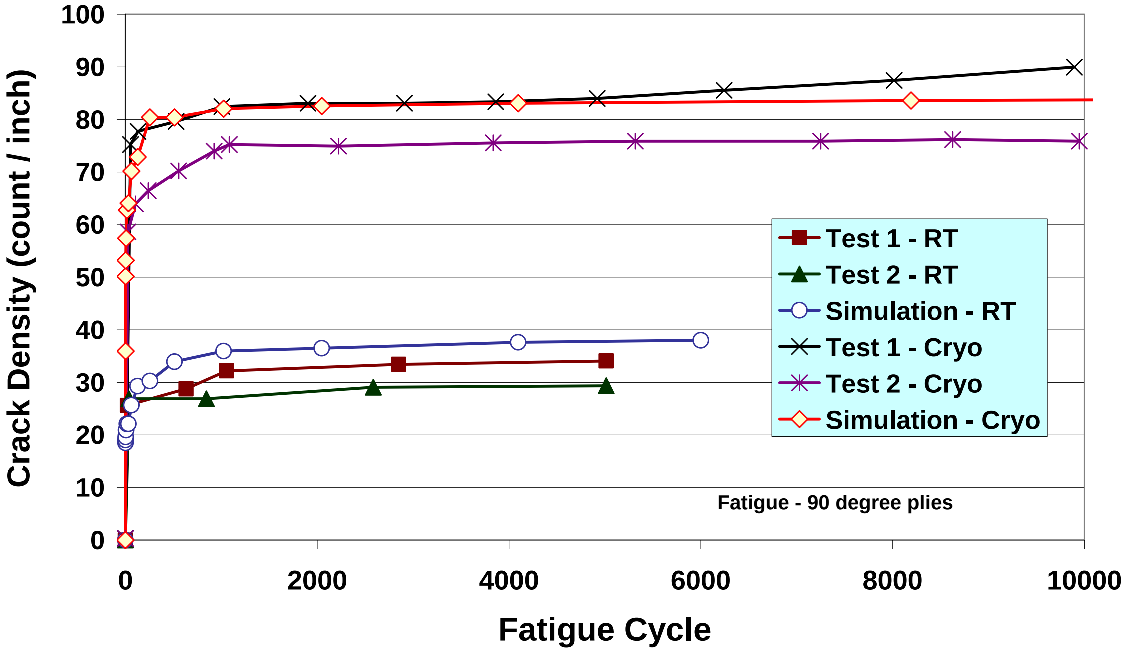

Figure 6 Crack density development in the 90 degree plies of the laminate tensioned in the 0 degree direction. Laminate configuration is [0/45/90/-45]s

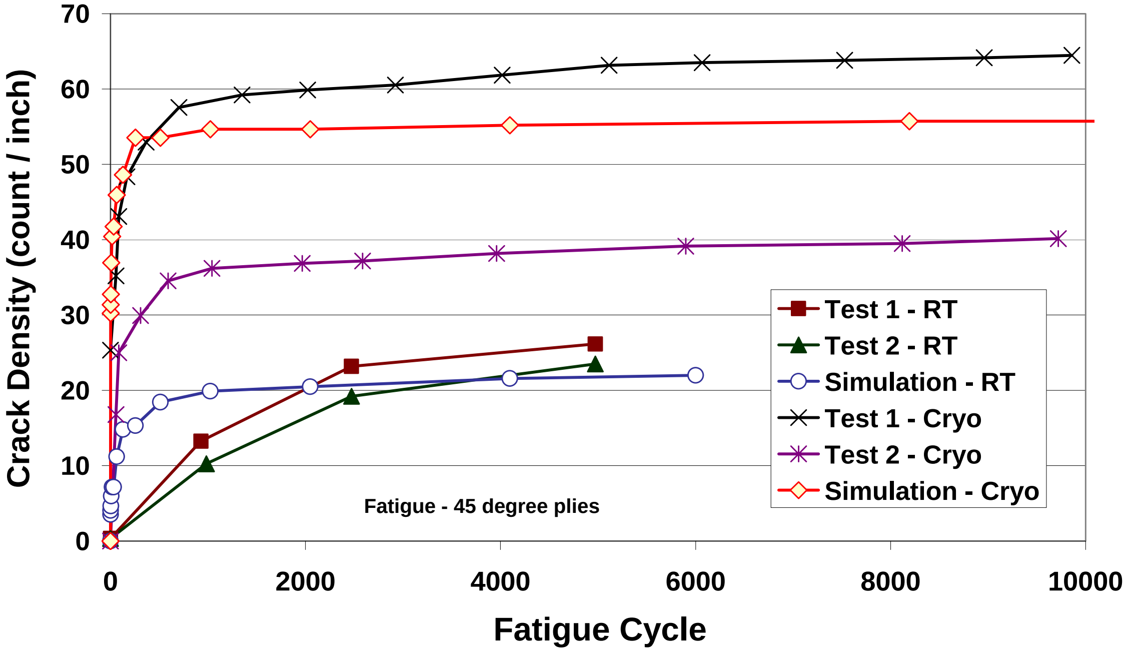

Figure 7 Crack density development in the 45 degree plies of the laminate tensioned in the 0 degree direction. Laminate configuration is [0/45/90/-45]s

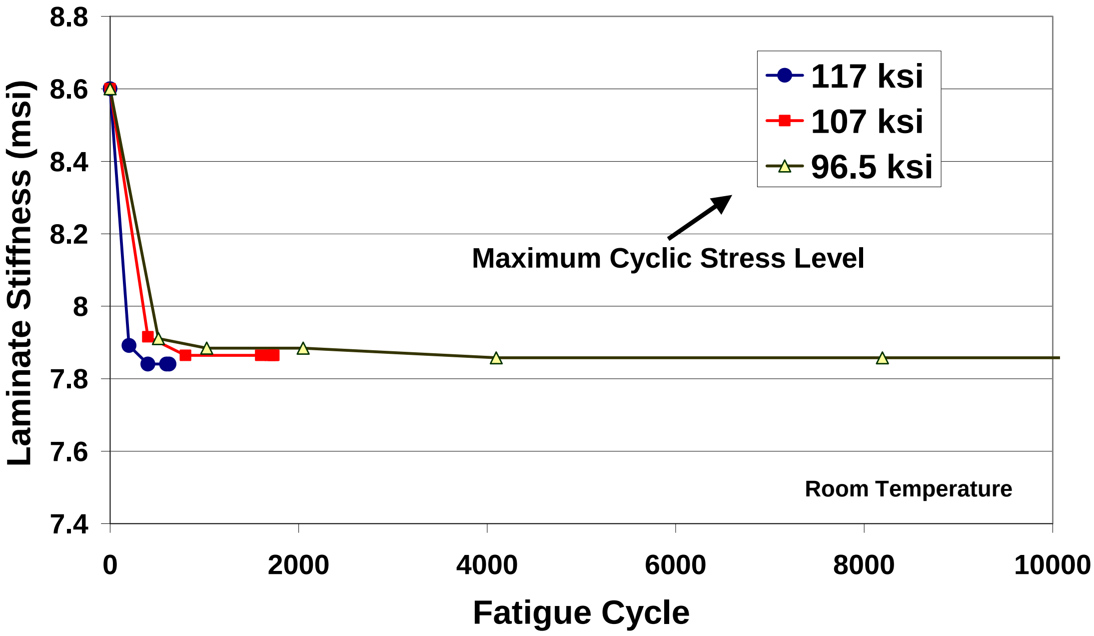

Figure 8 Degradations of the laminate stiffness due to micro crack development in the matrix during fatigue processes at various stress levels - room temperature

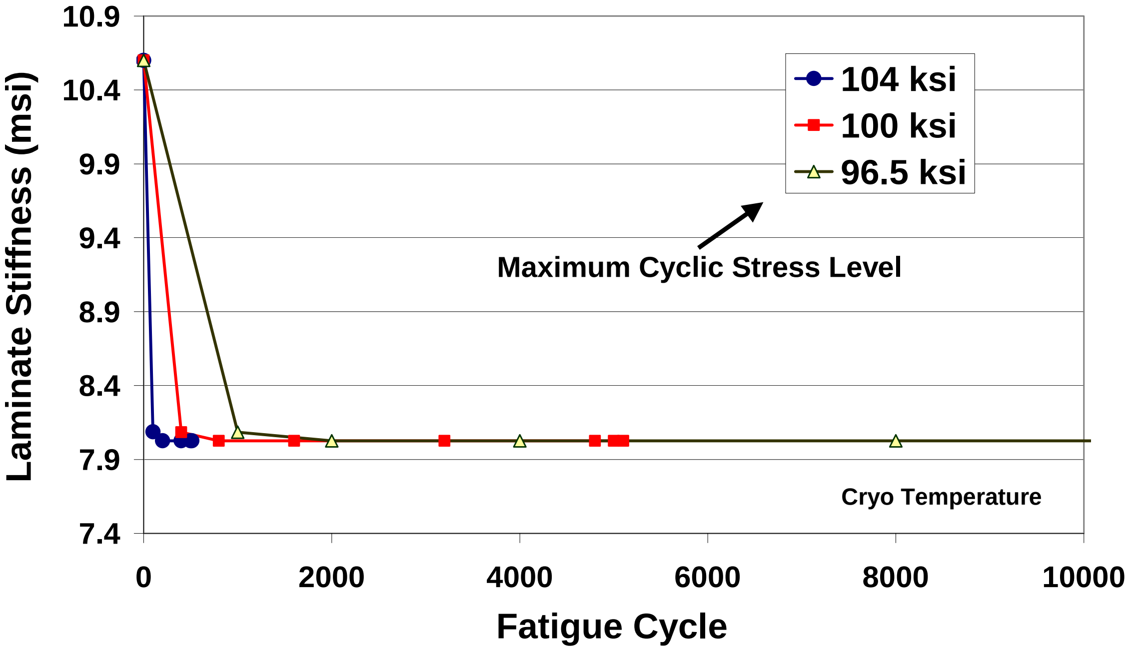

Figure 9 Degradations of the laminate stiffness due to micro crack development in the matrix during fatigue processes at various stress levels - cryogenic temperature