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Hygrothermomechanical Fiber Composite Fatigue: Computational Simulation

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COMPUTATIONAL SIMULATION

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SUMMARY

The technology of advanced fiber composites has matured to the point where these composites are prime contenders for various structural applications. One of the major design considerations for prolonged service of these composites is fatigue due to cyclic hygral (moisture), thermal, and mechanical (hygrothermomechanical) loading conditions. Recent research activities at the NASA Lewis Research Center have led to the development of formal procedures for predicting, using computational simulation, fatigue in fiber composites due to cyclic hygrothermomechanical loading conditions. These formal procedures have subsequently been programmed into a computer module and embedded into the Integrated Composites Analyzer (ICAN) computer code. The objective of this paper is to present and describe results obtained using the augmented ICAN computer code.

INTRODUCTION

While the age of fiber composite materials is upon us, the ability to accurately predict their performance, in terms of life, is yet to come. As composites emerge in the design of critical components subject to harsh operating conditions, so emerge new parameters which must be considered in this life prediction. In view of the difficulty in obtaining measured data required to design these components, one must often rely upon computational simulation. In the last decade, NASA Lewis has been very active in the area of composite computational simulation.

Research in the area of composite mechanics has culminated in a publicly available computer code, ICAN (Integrated Composites ANalyzer (ref. 1)). The code incorporates micromechanic and macromechanic equations along with laminate theory to analyze/design multilayered fiber composites. Input variables include constituent material properties, fabrication process factors, and geometry. The output variables are the various ply and composite properties, composite structural response, and composite stress analysis results with details on failure. Prior to its public release, considerable effort was expended toward the validation of ICAN (ref. 2). Recently, ICAN has been used to analyze various composite structures for aerospace applications (ref. 3, for example).

Most recently, research has been directed toward developing methodology to predict life and/or durability of composite structural components in an aerospace propulsion environment. As such, the current methodologies have been extended to simulate and account for the combined cyclic characteristics of temperature, moisture, and applied mechanical loading conditions which exist in this type of environment. The term, hygrothermomechanical, applies to these combined characteristics. The methodologies developed to analyze the hygrothermomechanical fatigue of fiber composites will be discussed as well as their application to three typical laminate configurations used in aerospace propulsion systems.

HYGROTHERMOMECHANICAL FATIGUE SIMULATION

The method to predict the hygrothermomechanical fatigue response of fiber composites is a two step procedure. The initial step consists of determining the composite ply strength associated with each type of cyclic load: mechanical, thermal and hygral. The next step is to determine the effect of combined cyclic loading. With these considerations, criteria can be established to assess the durability of the fiber composite using measures such as margin of safety and/or residual strength margin. Each step will now be discussed in detail.

Fatigue Simulation

Durability and damage tolerance is generally assessed by determining the stress that the composite can carry relative to the in-situ composite strength. Simplified methods have been developed to determine the ply strength of composites subject to various types of cyclic loading. For instance, equation (1) is used to determine the ply strength, $S_{\ell cyc}$, due to a particular component of the applied mechanical load.

$$\frac{S_{\ell cyc}}{S_{\ell o}} = \left[\frac{T_{GW} - T}{T_{GD} - T_o}\right]^{1/2} - B \log N \tag{1}$$

The value of $S_{\ell cyc}$ is associated with the initial defect/growth caused by the cyclic mechanical load which is assumed to be of constant stress amplitude. This defect usually results in a failure mode characterized by transply cracking or delamination. The hygrothermal effects are accounted for in the equation which is readily applicable once all the variables are known. The service temperature, T, and number of cycles, N, are known from the design requirements. The reference temperature, T_O, usually is taken to be room temperature. The dry glass transition temperature, T_{GD}, is a material characteristic of the polymer matrix. The wet glass transition temperature, T_{GW}, can be estimated from equation (2) (ref. 4) where M is the amount of moisture in the composite, expressed as a percentage of weight.

$$T_{GW} = (0.005M^2 - 0.1M + 1)\ T_{GD} \tag{2}$$

While equation (1) applies to composite laminates without defects, i.e., no holes or cut-outs, the same equation can be applied to laminates with defects as discussed in reference 5 using the stress concentration factors. The variable, B, is known as the cyclic stress degradation coefficient and will be discussed shortly.

When exposed to thermal cycles, composites often experience the phenomenon known as microcracking or transply cracking. Designers are therefore interested in the number of cycles, N_T, to cause the initial crack. For this purpose, the same variables in equation (1) can be rearranged to predict N_T in equation (3).

$$\mathrm{Log}\ N_T = \frac{1}{B_T}\left[\left(\frac{T_{GW} - T}{T_{GD} - T_o}\right)^{1/2} - \frac{\sigma_{\ell cyc}}{S_{\ell o}}\right] \tag{3}$$

To be used in this context, not only must the designer supply the various temperatures (T, T_O, T_{GW}, and T_{GD}), the coefficient B, and the ply transverse strength, $S_{\ell O}$, but also the cyclic temperature amplitude, ΔT, and the ply stress which results from it ($\sigma_{\ell cyc}$). Space does not permit further discussion on this method; however, a step-by-step procedure for applying this equation is given in reference 5. The point worth mentioning is that the equation considers all ranges of temperature amplitude as shown in figure 1.

If on the other hand, one is merely interested in the resulting stress from a discrete number of thermal cycles, then equation (3) can be arranged into the same format as equation (1) where the strength, $S_{\ell cyc}$, is calculated. Likewise, composites can experience exposure to a cyclic hygral environment whereby a structure is repeatedly saturated and dried out. While the effects of the hygral environment on composites have not conclusively been presented in the literature, an analogous form of equation (1) can be applied to determine the resulting composite strength, for the case of hygral loading.

Therefore, equation (1) can be used to determine the composite ply strength resulting from all the independent cyclic loads: mechanical, thermal, and hygral. The distinguishing variable in this equation is the coefficient, B, which is an empirical value indicative of the rate at which the composite material degrades with each cycle. As such, B is a function of the composite material system used, primarily affected by the composite strength (ref. 6). A previous research program at NASA Lewis determined the value of B for a graphite/epoxy system to be about 0.1 for a mechanical cyclic load (ref. 6). Note that this coefficient will change for each type of cyclic load.

The relationship of these variables and application of these equations is concisely summarized in figure 2. Here the results of equation (3) are plotted as the number of thermal cycles to failure for a $[0/90_3]_s$ graphite/epoxy laminate. Since B is not known for all conditions, a range is used to examine the effect it will have on the composite. The life, in terms of thermal cycles, is very sensitive to B. Note, also that this figure shows the sensitivity of N in relation to the composite strength, $S_{\ell O}$, in the equations. The point to note here, is that often the composite strength (either given as a material property or determined by micromechanics) can be either a conservative or inflated (ref. 1) value (compared to the actual in-situ value) depending on the source used to obtain it. Therefore, due to its sensitivity, predictions for life can only be as accurate as the composite strength provided.

These equations and relationships have been programmed as modules in the ICAN computer code. Since the code contains a resident data base, housing constituent material properties, the user need only provide as input the laminate configuration, material system, etc., as described in reference 1. As part of the output, tables containing the prediction of thermal cycles, N, as a function of the coefficient, B, are printed out.

Hygrothermomechanical Effects

In many situations, a composite structure may experience only one of the cyclic loads mentioned. However, in an aerospace propulsion system, a composite structure will be subject to all of those conditions. Since very little experimental data is available in this regime, computational simulation is used to understand and predict composite behavior and response. In addition, since many of these components are critical (life-limiting) items relative to the entire structure, reliable life prediction is an important issue.

Figure 3 contains the equations previously cited, and their incorporation into a unified equation for the combined cyclic loading stress. The equation includes mechanical load cycling, thermal cycling, and hygral cycling. Note that the equation predicts a stress on a ply-by-ply basis, for a particular component of the cyclic load and for constant amplitude of each of the cyclic loads. The composite strength predicted in step 1 is now used in the hygrothermomechanical equation. The equation can be applied to a variety of conditions: (1) variable cyclic amplitude can be handled by applying the equation to each amplitude and summing the corresponding terms, or (2) combined mechanical stress states can be handled by using available combined stress failure criteria (ref. 1). With the hygrothermomechanical composite stress (σ_C), a relationship can be established to assess the durability of the composite. In equation (4), the durability is assessed in terms of the remaining strength ratio after degradation due to the specified number of cycles.

$$MOS_{11} = 1 - \left(\frac{\sigma_{C11}}{S_{\ell 11T}}\right) \tag{4}$$

Here the remaining strength ratio is being calculated with respect to the longitudinal direction. The longitudinal composite stress, σ_{C11}, is determined by the hygrothermomechanical equation. The ratio, $\sigma_{C11}/S_{\ell 11T}$, subtracted from 1 yields a margin of safety (MOS) or remaining strength margin which will aid a designer in making a life prediction.

The margin of safety relationship is also included as a module in the ICAN code. The composite stresses are predicted for all modes: longitudinal, transverse, and shear allowing the designer to readily determine the MOS for each mode.

APPLICATION

Three laminate configurations were selected to demonstrate the computational simulation described above. The laminate configurations are representative of typical aeropropulsion structures and include: (1) a quasi-isotropic, $[0/\pm45/90]_s$, (2) pressure vessel type - $[\pm10/90_4]_s$ and, (3) engine blade type, $[0_3/\pm30]_s$. All the analyses were conducted using a T300 graphite/934 resin system with 0.62 fiber volume ratio.

One of the objectives of the simulation is to determine the number of cycles to initiate transply cracking as was previously mentioned. Although not discussed in this paper, another term can easily be added to the hygrothermo-mechanical equation, and that is one of a steady state or static load. With this in mind, each of the laminate configurations was analyzed with various combinations of mechanical, thermal, and hygral loads. The analysis was based upon the assumption that the degradation coefficients associated with these various loading conditions are equal, i.e., $B_L = B_T = B_M = 0.1$. The results are shown in table I and include the prediction of cycles to initiate transply cracking (microcracking) given the various loading conditions. It can be seen that: (1) the mechanical load with residual stress is the most critical condition, (2) 1 percent moisture (hygral) cycling, alone, is insignificant and can be neglected, and (3) the blade configuration is not likely to exhibit transply cracks under any cyclic condition since the structure itself is usually not in service that long. In the absence of experimental data, this simulation yields, at the very least, a life prediction in terms of number of cycles which can be used for, and in, a preliminary design analysis.

In another application, the durability of a composite in a hygrothermo-mechanical environment is determined. Each laminate configuration was analyzed accordingly. There were four thermal conditions: (1) the use temperature (taken as room temperature) to establish a reference, (2) the residual effects of curing were taken into account using a cure temperature of 177 °C (350 °F), (3) an elevated temperature of 121 °C (250 °F) is on one end of a thermal cycle, and (4) on the other end, the cryogenic temperature of -184 °C (-300 °F) was considered. The composites were analyzed as dry - 0 percent and wet - 1 percent moisture by weight. Static longitudinal and transverse loads equal to 50 and 75 percent of the failure loads were applied. Finally, a tensile mechanical cyclic load ranging from 0 to 50 percent of the composite failure load was applied for 100, 1000, 5000, and 10 000 cycles.

The conditions were chosen to adequately simulate the environment that any of these laminates could encounter as typical aerospace structures. Although a complex loading condition, the user-friendly input format of ICAN permits this data to be entered easily and quickly. Due to space limitations, only one laminate, the pressure vessel type ($[\pm10/90_4]s$), will be discussed. The results can be presented in two forms: bar charts and endurance limit (S-N) type curves. Although ICAN does not include a self-contained graphics capability, the data is readily retrievable from the output and plotted herein using the RS/1 software package.

For the purpose of discussion, the loading environment consisting of a static load equal to 50 percent of the static failure load and a cyclic load equal to 50 percent of the static failure load has been chosen. It is worth noting that this combined loading of 50 percent for each, should induce a single cycle failure. However, this is not the case since the static failure is determined using a combined stress criterion which uses the squares of the ratios. The calculated MOS for the various modes is plotted as a function of the prescribed number of cycles, 0 and 1 percent moisture and various temperatures. Figure 4 shows the results for the reference temperature which is 21 °C (70 °F). These results can be interpreted in the following manner. First, only data points which cross the zero axis indicate a ply failure in that particular mode. Hence, the 90° ply in a dry condition will fail in a transverse mode very quickly under the prescribed conditions. Note that with the presence of 1 percent moisture, this transverse mode would not be the dominant failure mode. Instead, the 10° ply is most likely to fail first in a longitudinal mode. This definitely demonstrates the sensitivity of transply cracking to environmental conditions and the advantage of having the computational simulation procedure described.

In figure 5, the results of the fabrication process, namely the residual stresses resulting from the cure temperature, are accounted for. The results indicate that the 90° ply fails in a transverse mode sometime within the first 100 cycles for a dry specimen. In the presence of moisture, the laminate is more durable in that it does not experience failure until 1000 cycles.

The same trend is observed in figure 6 when the laminate is exposed to a high temperature, 121 °C (250 °F). Under these conditions, moisture has very little effect on the behavior of the composite and the most likely ply to fail is once again the 90° ply at approximately 1000 cycles.

The results of the last thermal condition, cryogenic temperature of -184 °C (-300 °F), are shown in figure 7. As was observed at the high temperature, moisture has very little effect on the composite behavior. Once again, the 90° ply is the most likely to fail in a transverse mode around 1000 cycles. In terms of durability, given the prescribed condition and all thermal ranges, this laminate configuration is a poor design with respect to a prescribed life of 10 000 cycles.

The results can also be conveyed as bar charts as shown in figure 8, which are the same results that were displayed in figure 7. In this format, one can eliminate unsafe designs with a cursory glance. It may be argued that all of the results presented are intuitive when one considers the laminate configuration chosen and the loading conditions applied. However, these methods do much more than yield a prediction. They point out the complex interdependency and sensitivity of the factors involved and suggest a design life, in terms of cycles, which designers are most interested in.

CONCLUSIONS

These methods lend themselves efficiently to a parametric study. As is often the case, due to lack of a complete set of constituent material properties or limited knowledge on the actual environment, a parametric study is conducted before the actual structural analysis. The results obtained demonstrate that it is now possible to quantify hygrothermomechanical fatigue in fiber composites accounting for: (1) the effects of constituents, (2) individual loading conditions, and (3) combinations of loading conditions, including uniaxial and biaxial loads using only one computer code. Further, it is possible to identify the participating micromechanistic failure modes due to fatigue; thereby establishing guidelines for the selection of composite constituents for a specified fatigue life.

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TABLE I. - CYCLES TO INITIATE TRANSPLY CRACKING DEPEND ON LAMINATE CONFIGURATION AND TYPE OF LOADING CONDITIONS (AS GRAPHITE-FIBER/EPOXY AT 0.62 FVR)

Load condition	Laminate configuration			Comments
	$[0/\pm45/90]_s$	$[\pm10/90_4]_s$	$[0_3/\pm30]_s$	
Applied stress, N_L	36 500	4220	$>100\times10^6$	σ_{cxx} = 207 MPa[a]
Applied stress and residual stress,[b] N_L	1	1	$>100\times10^6$	σ_{cxx} = 207 MPa + σ_R
Elevated temperature cycling,[c] N_T	76 620	234 060	987 000	T = 121 °C (250 °F)
Cryogenic temperature cycling,[c] N_T	180	275 260	$>100\times10^6$	T = -184 °C (-300 °F)
Moisture cycling,[d] N_M	$>100\times10^6$	$>100\times10^6$	$>100\times10^6$	M = 1 percent

[a]30 ksi
[b]Cure temperature, 177 °C (350 °F).
[c]Cyclic temperatures are from room temperature to T.
[d]Cyclic moisture is from dry to M.

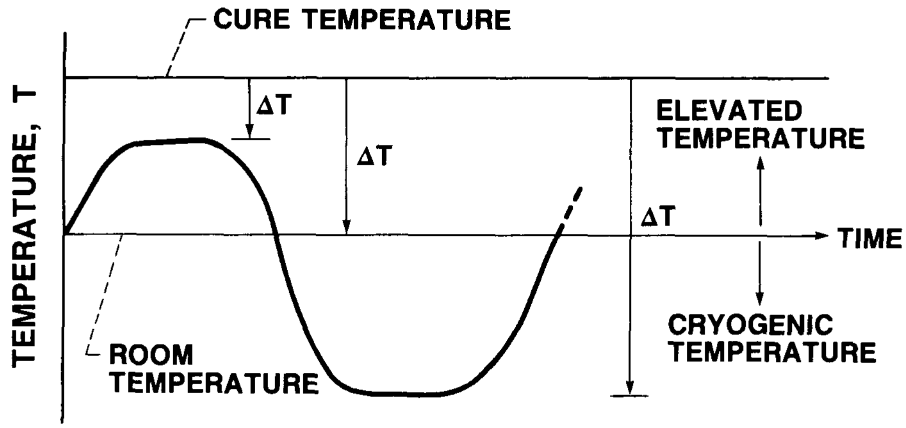


FIGURE 1. - TEMPERATURE RANGES CONSIDERED IN DETERMINING THE THERMAL FATIGUE AND CYCLES TO INITIAL CRACKING.

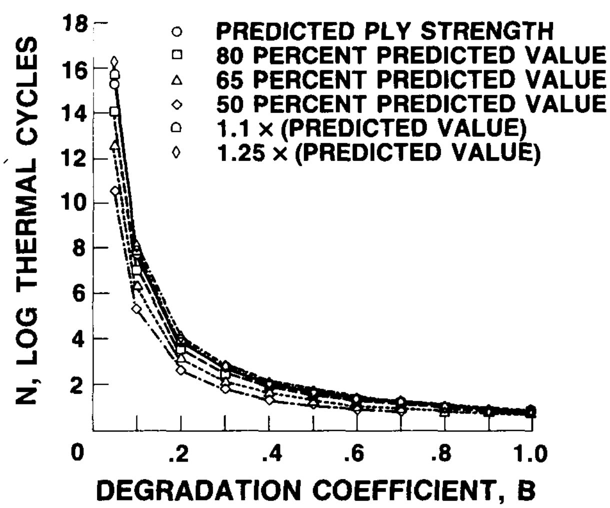
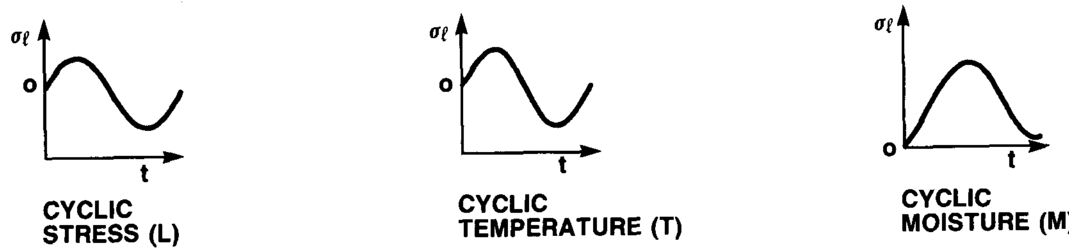


FIGURE 2. - THERMAL CYCLES TO FAILURE, SENSITIVITY TO DEGRADATION COEFFICIENT AND TO IN SITU PLY STRENGTH OF A $(0/90_3)_S$ T300 GRAPHITE FIBER/EPOXY LAMINATE AT AN ELEVATED TEMPERATURE. (T = 175 ^{0}F (79 ^{0}C).)



$$\left(\frac{S_{\ell cyc}}{S_{\ell o}}\right) = F_{HT} - B_L \operatorname{Log} N_L \qquad \left(\frac{S_{\ell cyc}}{S_{\ell o}}\right) = F_{HT} - B_T \operatorname{Log} N_T \qquad \left(\frac{S_{\ell cyc}}{S_{\ell o}}\right) = F_{HT} - B_M \operatorname{Log} N_M$$

$$\text{WHERE } F_{HT} = \left[\frac{T_{GW} - T}{T_{GD} - T_o}\right]^{1/2}$$

$$\Downarrow$$

$$\left(\frac{\sigma_{\ell cyc}}{S_{\ell cyc}}\right)_L + \left(\frac{\sigma_{\ell cyc}}{S_{\ell cyc}}\right)_T + \left(\frac{\sigma_{\ell cyc}}{S_{\ell cyc}}\right)_M < 1/K_T$$

WHERE
K_T = STRESS CONCENTRATION FACTOR

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FIGURE 3. - COMBINED HYGROTHERMOMECHANICAL CYCLIC LOADING EQUATION.

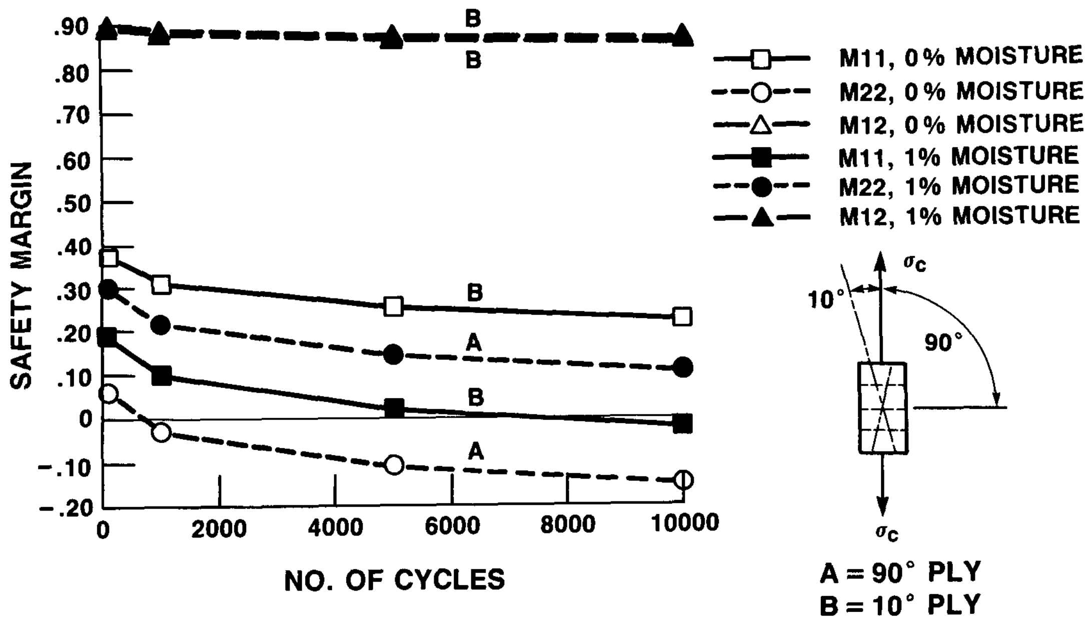

FIGURE 4. - REMAINING FATIGUE STRESS MARGIN FOR A T300/934 $[\pm 10/90_4]_S$ LAMINATE SUBJECTED TO A 50% STATIC LOAD AND A 50% CYCLIC LOAD AT REFERENCE TEMPERATURE.

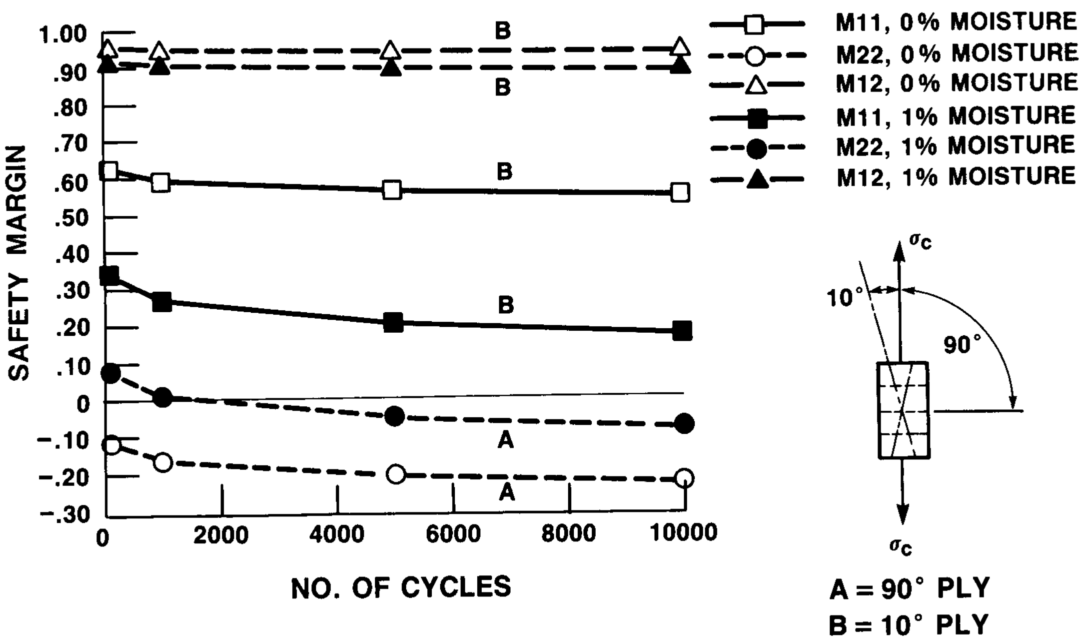

FIGURE 5. - REMAINING FATIGUE STRESS MARGIN FOR A T300/934 $[\pm 10/90_4]_S$ LAMINATE SUBJECTED TO A 50% STATIC LOAD AND A 50% CYCLIC LOAD WITH RESIDUAL THERMAL EFFECTS.

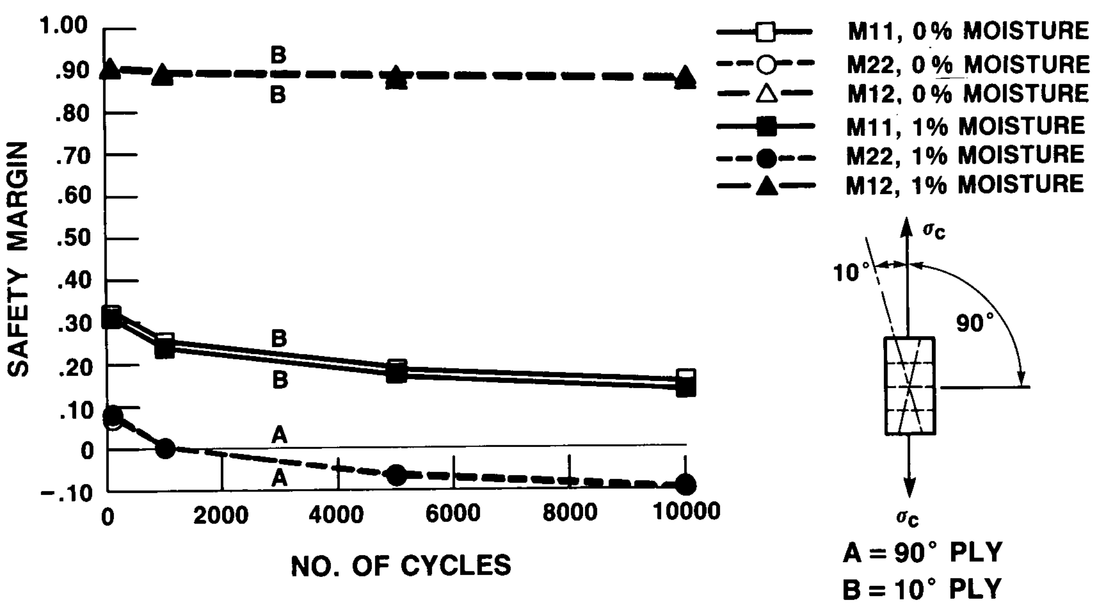

FIGURE 6. - REMAINING FATIGUE STRESS MARGIN FOR A T300/934 $[\pm 10/90_4]_S$ LAMINATE SUBJECTED TO A 50% STATIC LOAD AND A 50% CYCLIC LOAD AT AN ELEVATED TEMPERATURE.

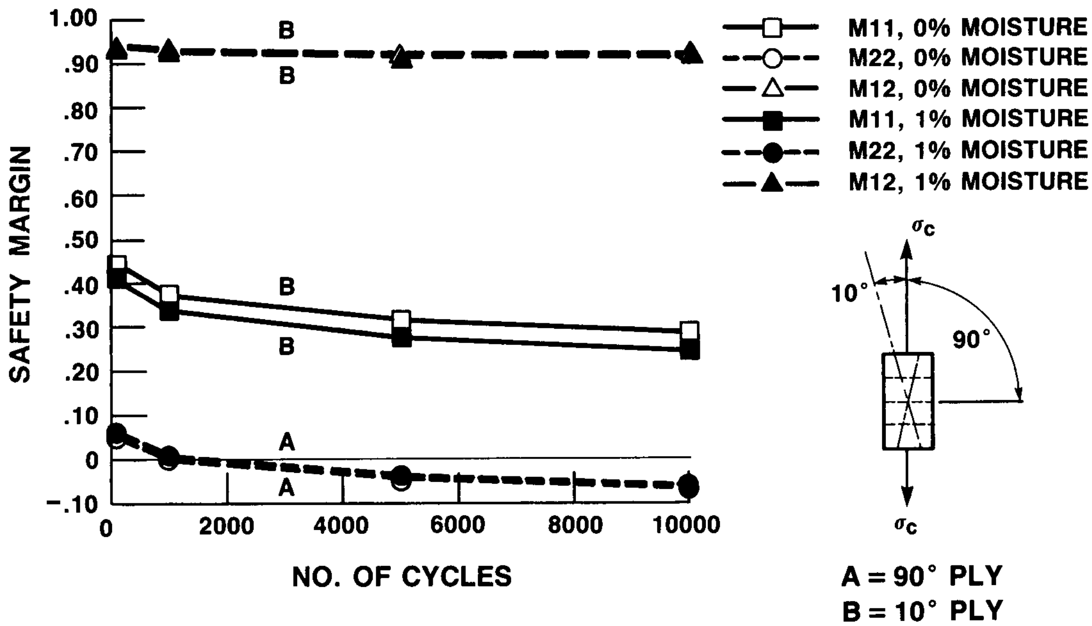

FIGURE 7. - REMAINING FATIGUE STRESS MARGIN FOR A T300/934 $[\pm 10/90_4]_S$ LAMINATE SUBJECTED TO A 50 PERCENT STATIC LOAD AND A 50 PERCENT CYCLIC LOAD AT A CRYOGENIC TEMPERATURE.

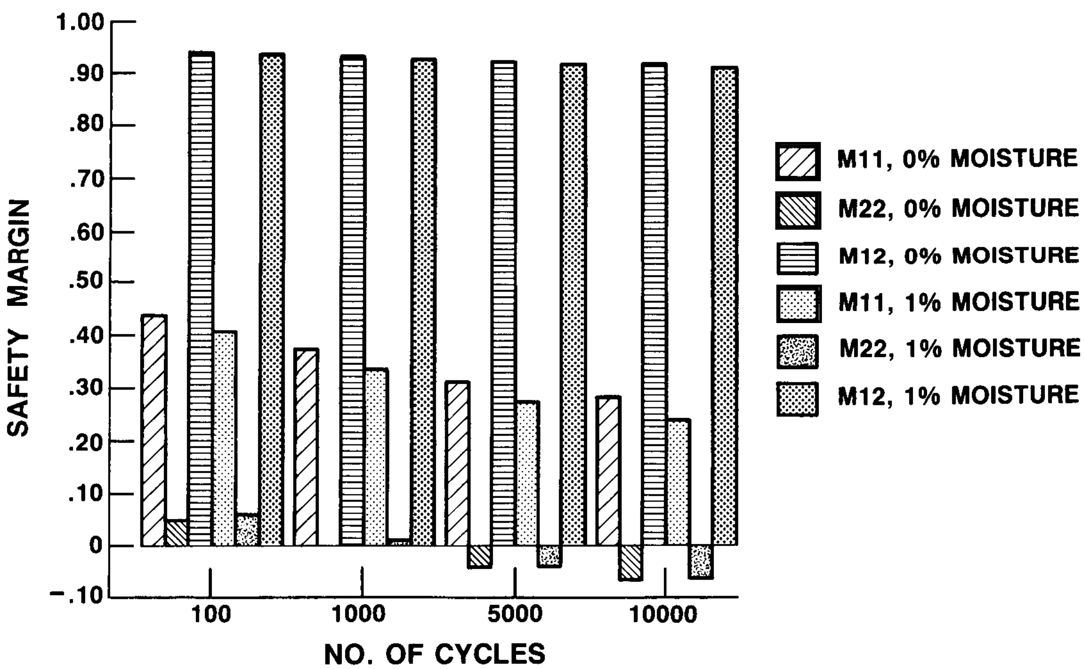

FIGURE 8. - RESULTS IN FIGURE 7 PLOTTED IN BAR-CHART FORMAT.

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16. Abstract

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