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Durability/Life of Fiber Composites in Hygrothermomechanical Environments

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DURABILITY/LIFE OF FIBER COMPOSITES IN HYGROTHERMOMECHANICAL ENVIRONMENTS

by

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ABSTRACT

Statistical analysis and multiple regression were used to determine and quantify the significant hygrothermomechanical (HGTM) variables which influence the tensile durability/life (cyclic loading, fatigue) of boron-fiber/epoxy-matrix (B/E) and high-modulus-fiber/epoxy-matrix (HMS/E) composites. The use of the multiple regression analysis reduced the variables from fifteen, assumed initially, to six or less with a probability of greater than 0.999. The reduced variables were used to derive predictive models for compression and intralaminar shear durability/life of B/E and HMS/E composites assuming isoparametric fatigue behavior. The predictive models were subsequently "generalized" to predict the durability/life of graphite-fiber/resin-matrix composites. The "generalized" model is of simple form, predicts conservative values compared with measured data and should be adequate for use in preliminary designs.

NOMENCLATURE

B	unknown coefficients to be evaluated
M	moisture
N	number of loading cycles (fatigue) to fracture
S	strength (durability/life), general

S_ℓ	uniaxial strength specified direction and sense via appropriate subscripts
S_0	reference strength
T_{GW}	glass transition temperature wet resin
T_{GO}	glass transition temperature reference conditions, normal room temperature dry
T_p	preconditioning temperature
t_p	duration of preconditioning
T_T	test or use temperature
T_{to}	reference conditions temperature, normally room temperature
V	product T_p x tp

SUBSCRIPTS

C	compression
S	shear
T	tension
1,2,3	directions: 1-along the fiber, 2-transverse to the fiber, 3-through the thickness

CONVERSION FACTORS

1 ksi	6.89 MPa
1° C	5/9 (°F-32)

INTRODUCTION

A major concern in the fiber composites community over the last several years has been the accurate prediction, and/or even a good approximation, of the durability and/or life of fiber composite structures in service environments (refs. 1 and 2). Service environments of major concern are: temperature, moisture, mechanical loads (static and cyclic) and various combinations of these, or more concisely "Hygrothermomechanical". In response to this concern recent research effort at Lewis Research Center is directed towards the development of the methodology required to predict the life and/or durability of composite structural components in turbojet engine service environments. This paper describes that part of the research effort which is to develop predictively-correct models for determining the hygrothermomechanical effects on composite strength. The predictively correct models are first derived empirically using statistical methods and available hygrothermomechanical (HGTM) data from reference 1. These data are for unidirectional tension-tension fatigue for boron/epoxy (B/E) and high-modulus-graphite/epoxy (HMS/E). The empirical models are then extended to other unidirectional cyclic loading conditions (fatigue) for the same two composite systems assuming isoparametric fatigue behavior. Subsequently, the models are "generalized" to graphite/epoxy (resin) systems using the HGTM theory described in reference 2. The "generalized" models are used to predict the HGTM life/durability of unidirectional and (±45) composites subjected to compression-compression fatigue. Finally, the predicted results are compared with measured data from reference 3 in order to assess the predictive capability of the "generalized" model. Durability/life as used herein means tensile, compression and shear fatigue strength in HGTM environments.

DURABILITY/LIFE PREDICTION MODELS FOR TENSILE CYCLIC LOADS

The procedure used to develop a predictive model consists of determining empirically the functional relationship of composite strength (σ), and the independent variables in the following equation:

$$\sigma = F(S_0, T_T, V, N, M) \tag{1}$$

where the independent variables are: S_0 is the reference strength, T_T is the test temperature, V is the preconditioning variable and is the product of the preconditioning temperature and the preconditioning duration time ($V = T_p t_p$). N represents the number of fatigue cycles to fracture and M the precent of moisture weight gain. The composite strength in equation (1) is expressed in terms of the independent variables by assuming a complete second degree polynomial (general quadratic) relationship. This general quadratic is

$$\begin{aligned} S = {} & B_0 + B_1 T_T + B_2 T^2{}_T + B_3 V + B_4 V^2 + B_5 T_T V \\ & + B_6 \mathrm{Log}_{10} N + B_7 (\mathrm{Log}_{10} N)^2 + B_8 T_T \mathrm{Log}_{10} N \\ & + B_9 V \mathrm{Log}_{10} N + B_{10} M + B_{11} M^2 + B_{12} T_T M \\ & + B_{13} VM + B_{14} M \mathrm{Log}_{10} N \qquad (2) \end{aligned}$$

where the B's are unknown coefficients and are evaluated from experimental data (ref. 1) using the least squares method. The data selected are for B/E and HMS/E unidirectional composites which were tested in longitudinal (0^0) and transverse (90^0) tension using three replicates. The test conditions included: (1) steady state humidity; (2) thermal humidity; (3) accelerated weathering; (4) steady state thermal; and (5) cyclic thermal and ambient. About 150 data points were used in each evaluation (B/E -0°, and 90°; HMS/E -0° and 90°) or about 10 data points per unknown (B) coefficient. A summary description of the data used in the least square method is given in the appendix. The least squares method minimizes the square of the residuals between the approximating function (eq. (2)) and the measured data. The result is a set of linear algebraic equations which are solved simultaneously for the unknown coefficients (ref. 4). For this case, equation (2) was applied about 150 times (once per test point) to evaluate the B's for each set of data points: B/E - 0^o and 90^o, HMS/E - 0^o and 90^o. The solutions were obtained using an available program available at Lewis (ref. 5).

The results obtained from the least squares method for the B's for all four cases are summarized in table 1. The collective goodness-of-fit as determined by the program is indicated by the last entry in the table (R^2, percent). The fit was best for the 90^o B/E ($R^2 = 86.0$) and the lowest for the 90^o HMS/E ($R^2 = 65$). Substituting the values of the B's in equation (2) and solving for each test point yielded results which were within ten percent of the measured value in general. There were a few predicted values for the 90^o HMS/E composite which differ by about 20 percent from the measured value and one by about 40 percent. An independent program was also used to double check the values of the B's. The results of the independent program were identical to those from the available program.

Some insight can be obtained of the influence of the various variables (B's) on durability/life by examining corresponding columns in table 1. As can be seen the values for the B's have minus or plus signs. There are also a few with zero value. The interpretation is as follows: a minus sign indicates a degradation effect of the variable associated with this B on the unidirectional strength. A plus sign indicates enhancement and zero indicates no effect. For example, there is no coupling between preconditioning and cyclic loading ((VN) = B_9 = 0) for the 90^o strengths for both B/E and the HMS/E composites. There is also no coupling between moisture and cyclic load ((MN) = B_{14} = 0) for these same strengths. The moisture degrades the strength of the 0^o and 90^o composites of the B/E composites and of the

90^0 of the HMS/E composite but not that of the 0^0 HMS/E. Cyclic loading degrades the strength of the 0^0 and the 90^0 B/E composites and the 0^0 HMS/E composite but not that of the 90^0 HMS/E composite.

The significance of the various independent variables as reflected in the (B's) to the composite durability/life was evaluated using multiple regression analysis. The multiple regression used is a part of the available program (ref. 5). The results of the analysis for the B/E composite durability/life are summarized in table 2 for probability levels of greater than 0.900 and greater than 0.999. It is interesting to note that the number of nonzero coefficients (B's) was reduced from fifteen to four for the 0^0 strength and to five for the 90^0 strength with a probability of greater than 0.999. Also, it is interesting to note that the reference strength S_0 (B_0) value is about 1330 MPa (193 ksi) for the 0^0 strength and about 69 MPa (10 ksi) for the 90^0 strength. These are in close agreement with literature values for these strengths of 1300 MPa (188 ksi) and 62 MPa (9.0 ksi) respectively, (ref. 6). The regression analysis results for the HMS/E composites are summarized in table 3. For the case of probability of greater than 0.999, there are six coefficients remaining for the 0^0 strength and only four for the 90^0 strength. The reference 0^0 strength S_0 (B_0) is about 610 MPa (89 ksi) and the 90^0 is 83 MPa (12 ksi). These compare to literature values of about 830 MPa (120) and 83 MPa (12), respectively (reference 6).

The desired equations for a probability of greater than 0.999 are obtained by substituting the remaining B's from the corresponding columns (tables 2 and 3) in equation (2). The results and a brief discussion of their implications are:

Boron/Epoxy - Longitudinal Tension (first with the B's and then with the corresponding values).

$$\left.\begin{aligned} S_{\ell 11T} &= S_0 + B_2 T_T^2 + B_8 T_T \mathrm{Log}_{10} N + B_{12} T_T M \\ S_{\ell 11T} &= 193 - 3.96\times10^{-5} T_T^2 - 7.91\times10^{-3} T_T \mathrm{Log}_{10} N + 4.14\times10^{-2} T_T M \end{aligned}\right\} \quad (3)$$

Therefore, this strength depends on test temperature (T_T), on coupled test temperature and load cycles ($T_T N$), and on coupled test temperature and moisture ($T_T M$). Equation (3) indicates that the longitudinal tensile strength of B/E composites is not degraded by cyclic loading or moisture when these are applied independent of temperature.

Boron/Epoxy - Transverse Tension

$$\left.\begin{aligned} S_{\ell 22T} &= S_0 + B_2 T_T^2 + B_6 \mathrm{Log}_{10} N + B_{11} M^2 + B_{12} T_T M \\ S_{\ell 22T} &= 9.64 - 5.84\times10^{-6} T_T^2 - 0.593 \mathrm{Log}_{10} N + 5.33 M^2 - 6.71\times10^{-3} T_T M \end{aligned}\right\} \quad (4)$$

This strength is degraded by temperature, cyclic loading and coupled temperature/moisture. Interestingly, it is enhanced by moisture when applied independently.

HMS/Epoxy - Longitudinal Tension

$$\left.\begin{aligned} S_{\ell 11T} &= S_0 + B_1 T_T + B_5 T_T V + B_6 \mathrm{Log}_{10} N + B_{10} M + B_{12} T_T M \\ S_{\ell 11T} &= 89.0 + 4.68 \times 10^{-2} T_T - 4.98 \times 10^{-7} T_T V - 6.15 \mathrm{Log}_{10} N + 89.4 M - 0.16 T_T M \end{aligned}\right\} \quad (5)$$

The longitudinal tensile strength of HMS/E graphite composites is degraded by coupled temperature with preconditioning ($T_T V$), cyclic loading (N), and coupled temperature with moisture ($T_T M$). It is enhanced when subjected to either temperature or moisture individually. Equation (5) shows decoupling between hygrothermal effect (T_T or M) with cyclic loading (N). The decoupling with moisture may have resulted from the suspected drying during elevated temperature testing (private communication, author, ref. 1).

HMS/Epoxy - Transverse Tension

$$S_{\ell 22T} = S_0 + B_1 T_T + B_3 V + B_5 T_T V$$

$$= 11.8 - 1.32 \times 10^{-2} T_T - 4.98 \times 10^{-4} V + 6.64 \times 10^{-7} T_T V \quad (6)$$

The transverse tensile durability/life of HMS/E composites is degraded by temperature (T_T) preconditioning (V), and is enhanced by the coupled test temperature with preconditioning. It is independent of moisture (M) and cyclic loading (N). This implies that test temperature and preconditioning dominate the transverse durability/life of HMS/E composites. Equation (6) cannot be construed to imply that the moisture and cyclic loading have no effect on this durability. However, this equation does imply that there is no coupling between test temperature (T_T) with cyclic loading (N) or moisture (M) with cyclic loading (N), or more concisely, the environmental (hygrothermal) effects are decoupled from the cyclic loading, as was the case in equation (5). The decoupling with moisture could be due to suspected drying as mentioned previously.

The important conclusions from the preceding discussion are: (1) The durability/life of fiber resin composites can be determined from available data using the well-known least squares method; and (2) the variables which influence the durability/life significantly can be determined with specified confidence level using multiple regression analysis. For the case described herein: (1) the number of significant variables was reduced from fifteen to six or less; (2) the reference strengths (S_0) approached ambient conditions statis value; and (3) the hygrothermal effects are decoupled with cyclic loading for HMS/E composites (keeping in mind that this may be due to suspected drying during elevated temperature testing).

EXTENSIONS TO PREDICTIVE MODELS FOR OTHER CYCLIC LOADS

The predictive models for durability/life under tensile cyclic loads determined in the previous section can be extended to compressive and shear cyclic loads by making a key assumption. "There is an isoparametric relationship for cyclic loading and/or coupled environmental effects as follows:

(1) Longitudinal tension and longitudinal compression

(2) Transverse tension and transverse compression

(3) Transverse tension and intralaminar shear."

This key assumption is reasonable for the following reasons: (1) longitudinal tension and longitudinal compression are primarily fiber dominated properties; (2) transverse tension, transverse compression and intralaminar shear are matrix dominated properties; and (3) permits the values for the reference strength (S_0) and the test temperature coefficient (B_2) to be different for the same composite system. The desired equations for the B/E composite are:

Longitudinal Compression (equation (3)):

$$S_{\ell 11C} = S_o + B_2 T_T^2 - 7.91\times10^{-3} T_T \mathrm{Log}_{10} N + 4.14\times10^{-2} T_T M \qquad (7)$$

Transverse Compression (equation (4)):

$$S_{\ell 22C} = S_o + B_2 T_T^2 - 0.593 \mathrm{Log}_{10} N + 5.33 M^2 - 6.71\times10^{-3} T_T M \qquad (8)$$

Intralaminar Shear (equation 4)):

$$S_{\ell 12S} = S_o + B_2 T_T^2 - 0.593 \mathrm{Log}_{10} N + 5.33 M^2 - 6.71\times10^{-3} T_T M \qquad (9)$$

The unknowns S_o and B_2 in equation (7), (8) and (9) are evaluated from know S_ℓ's at two different T_T values, that is, $T_T \neq 0$; but $V=M=N=0$. Using appropriate data from reference 1 to evaluate S_o and B_2 equations (7), (8) and (9) become:

<u>Boron/Epoxy</u> - Longitudinal and transverse compression and sheer, respectively

$$S_{\ell 11C} = 345 - 3.34\times10^{-4} T_T^2 - 7.91\times10^{-3} T_T \mathrm{Log}_{10} N + 4.14\times10^{-2} T_T M \qquad (10)$$

$$S_{\ell 22C} = 44.7 - 3.63\times10^{-5}T_T^2 - 0.593\text{Log}_{10}N + 5.33M^2 - 6.71\times10^{-3}T_TM \qquad (11)$$

$$S_{\ell 12S} = 12.8 - 1.09\times10^{-5}T_T^2 - 0.593\text{Log}_{10}N + 5.33M^2 - 6.71\times10^{-3}T_TM \qquad (12)$$

Three important points are worth noting in equations (10), (11) and (12). These are: (1) The values for S_0 are about the same for typical room temperature strengths available in the literature. Typical values are 2480 MPa (360 ksi), 310 MPa (45 ksi), and 120 MPa (17 ksi), respectively. (2) the values for the B_2's (T_T^2 coefficients) are of about one order of magnitude higher, than the corresponding values in equations (3) and (4). (3) and more important the durability/life predicted by these equations needs to be verified experimentally.

Following the procedure described above, using equations (5) and (6), and using appropriate values from reference 1, the predictive equations for longitudinal compression, transverse compression and intralaminar shear for HMS/E composite are:

HMS/Epoxy - Longitudinal Compression

$$S_{\ell 11C} = 126 - 5.36\times10^{-2}T_T - 4.98\times10^{-7}T_TV - 6.15\ \text{Log}_{10}N + 89.4M - 0.16\ T_TM \qquad (13)$$

HMS/Epoxy - Transverse Compression

$$S_{\ell 22C} = 59.5 - 5.00\times10^{-2}T_T - 4.98\times10^{-4}V - 6.64\times10^{-7}T_TV \qquad (14)$$

HMS/Epoxy - Intralaminar Shear

$$S_{\ell 12S} = 17.4 - 1.32\times10^{-2}T_T - 4.98\times10^{-4}V - 6.64\times10^{-7}T_TV \quad (15)$$

Typical literature values for S_0, at room temperature dry, are 830 MPa (120 ksi), 240 MPa (35 ksi), and 69 MPa (10 ksi), respectively. The test temperature (T_T) coefficients are of the same magnitude as those in equations (5) and (6). However, the sign in equation (13) is reversed from that in equation (5). This may be interpreted to indicate that the strength enhancement in equation (5) is in part due to the amelioration of residual longitudinal compression stress in the graphite fibers. Equations (13), (14), and (15) also need experimental verification as was the case for equations (10), (11), and (12).

The important conclusion from the afore discussion is that the fitted equations for the tensile durability/life in conjunction with the isoparametric relationship can be used to derive predictive equations for compression and intralaminar shear. The predictive equations thus derived, however, still need experimental verification mainly, due to lack of experimental data, and can only be used as a guide at this time.

GENERALIZATION FOR DURABILITY/LIFE TO GRAPHITE/EPOXY COMPOSITES

The multiple regression analysis results showed that the hygrothermal environmental effects and cyclic loading were decoupled for the graphite HMS/E composite system, as was described previously. This information together with the observation that the hygrothermal environment affects only resin properties (ref. 2) can be used to derive a "generalized" predictive equation for the durability/life of graphite-fiber/epoxy-matrix composites. The desired equation is (assuming negligible drying effect on moisture/cyclic load coupling at elevated temperature).

$$S = \left[\frac{T_{GW} - T_T}{T_{GO} - T_{TO}}\right]^{1/2} S_0 - B\,\mathrm{LOG}_{10}N \qquad (16)$$

The first term in equation (16) is that derived in reference 2 expressed in the present notation and represents the coupled hygrothermal degradation effects.

The second term is the cyclic loading (fatigue) effect adopted from the multiple regression analysis in view of the decoupled relationship described previously. The notation in equation (16) is as follows:

T_{GW}	denotes the glass transition temperature of the resin at that moisture content
T_T	denotes test or use temperature at which S is to be predicted
T_{GO}	denotes the glass transition temperature at which S_0 was measured
T_{TO}	denotes the test temperature at which S_0 was measured
S_0	denotes reference durability/life
B	is a coefficient to be determined for the specific composite system and for the specific strength
N	is the number of loading cycles as previously described.

Equation (16) is general; it is not limited to any one resin system; and the user has the option to generate his own experimental data to evaluate the participating variables. Procedures for evaluating the participating variables in equation (16), application of this equation to available experimental data and comparisons between predicted and experimental data are described in some detail below.

The glass transition temperature of the wet resin can be determined from the graphical information in figure 1 (ref. 7). For other resins (wet/dry) similar graphs can be constructed using standard methods for determining the glass transition temperature (ref. 8). Comparisons of predicted and measured hygrothermal effects on transverse compression, transverse tension, and intralaminar shear strengths are summarized in figure 2. Several composite systems tested at a variety of hygrothermal environments are included. Measured data used in the statistical analysis as well as measured data which will be used subsequently for evaluating B in equation (16) are included. The agreement is excellent. This excellent agreement further substantiates the predictive capability of equation (16) for hygrothermal effects.

The coefficient B in equation (16) is evaluated herein using the hygrothermomechanical (HGTM) data in reference 3. Solving equation (16) for B yields

$$\frac{B}{S_0} = \left[\mathrm{LOG}_{10} N\right]^{-1} \left\{ \left[\frac{T_{GW} - T_T}{T_{GO} - T_{TO}}\right]^{1/2} - \frac{S}{S_0} \right\} \qquad (17)$$

where S is the durability/life (fracture stress) corresponding to HGTM conditions represented by N, T_{GW} and T_T. Using the unidirectional cyclic data in reference 3 for longitudinal compression, transverse compression and the $(\pm 45^0)_s$ data for intralaminar shear in equation (17) yields values for B/S_0 ranging from 0.02 to 0.13 or in equation form

$$0.02 \leq B/S_0 \leq 0.13 \qquad (18)$$

where the 0.02 values are predominantly for longitudinal compression. The majority of the values for B/S_0 were about 0.1. Since the majority of the

B/S_0 values were about 0.1 and since a value of 0.1 was determined for glass-fiber/epoxy composites (ref. 9), it is recommended that a value of 0.1 be used for B/S_0 for all uniaxial strengths of graphite-fiber/resin-matrix composites. This simplifies the equation and should be more than adequate for preliminary design use. Normalizing equation (16) with respect to S_0 and using 0.1 for B/S_0 results in

$$\frac{S}{S_0} = \left\{ \left[\frac{T_{GW} - T_T}{T_{GO} - T_{TO}} \right]^{1/2} - 0.10 \, \mathrm{LOG}_{10} N \right\} \tag{19}$$

as the desired "generalized" predictive model for the durability/life of graphite-fiber/resin-matrix composites. Equation (19) represents a family of straight lines. For example the number of cycles at room temperature dry conditions and S equal to zero is 10^{10} or 10 billion.

The parallel lines predicted by equation (19) and the experimental data of reference (3) are shown in figure 3. The point of major importance to be noted in this figure is that the measured data at fracture is above the predicted lines. This illustrates the conservativeness of the "generalized" predictive model equation (19) and provides credence for its use in preliminary designs in general. The equation can be used in more specific designs in AS/E composites with 1.1 percent moisture up to 93.3° R (200° F).

The important observation from the above discussion is that a "generalized" predictive model for predicting the unaxial durability/life of graphite-fiber/resin-matrix composites has been derived. This model has simple form, predicts conservative values, and should be adequate for use in preliminary designs. The model provides the user with options to adapt it to his own specific case. The authors have not applied this predictive model to other fiber/resin composite systems, as yet. However, there is no apparent reason why it would not apply so long as the hygrothermal behavior is decoupled, or lightly coupled, with cyclic loading for these other composites.

SUMMARY OF RESULTS

The significant results of an investigation to assess the durability/life (fatigue strength) of fiber/resin-matrix composites and derive requisite predictive models are as follows:

1. Statistical analysis (least squares method and multiple regression) was used to determine the significance of hygrothermomechanical (HGTM) variables on tensile composite strength (durability/life) of boron/epoxy (B/E) and high-modulus-graphite/epoxy (HMS/E) composites.
2. The multiple regression analysis reduced the number of HGTM variables from fifteen assumed in the initial curve fit model to six or less with a probability of 0.999 or greater.
3. The multiple regression results showed that the hygrothermal variables are decoupled from the cyclic load variables though the decoupling with moisture may have been due to suspected drying during elevated temperature testing.
4. Predictive models derived for the tensile durability/life were used in conjunction with assumed isoparametric relationships to derive predictive models for the compression and shear durability/life of B/E and HMS/E composites.
5. A "generalized" predictive model was derived for the durability/life of graphite-fiber/resin-matrix (Gr/R) composites to be used mainly in preliminary designs.

6. The "generalized" predictive model for the Gr/R composites is of simple form and predicts conservative values when compared with available measured data for AS/E composites with 1.1 percent moisture up to 93° C (200° F).

APPENDIX - SUMMARY DESCRIPTION OF DATA USED IN THE LEAST SQUARES METHOD

Data used: From parts I and II (ref. 1)

Test Descriptions: Tensile and Fatigue

Materials used: (1) Avco 5505/Boron and (2) Hercules 3002M/ Courtalds HMS Graphite

Preconditioning:

(1) Specimens with no preconditioning (served as baseline data).

(2) Steady state humidity - Included 500 and 1000 hr. exposure to 98 percent relative humidity (RH) at 120°F.

(3) Thermo-Humidity cycle - Total exposure time was 500 hr. Specimens exposed to 95 percent RH at 120°F except for 1-1/2 hrs. each working day. Then they were exposed to thermal shock for 1 hr. at -65°F followed by 1/2 hr. at 250°F.

(4) Steady state thermal - Exposure to 260°F and 350°F for 100 and 500 hrs.

(5) Accelerated weathering humidity cycle - Exposed five days/week and in two hour cycles. Each two hour cycle was divided into 102 minutes of exposure to light without water where the average temperature was 145°F, and 18 minutes of light with water spray of 12-15 psi. Specimens were undisturbed remaining two days of the week.

(6) Cyclic thermal - Thermal cycles of 100^{0}F to 260^{0}F and 100^{0}F to 350^{0}F for 500 and 1000 cycles. Rate was one cycle per hour.

Variables used:

From equation 1, the hygrothermomechanical (HGTM) variables are:

T_T = test temperature

N = fatigue cycles to failure

M = percent moisture weight gain

$V = T_p \times tp$

T_p = preconditioning temperature

t_p = duration of preconditioning

For:

(1) Steady state humidity -

T_p = 120^{0}F

Time = 500 or 1000 hour

M = 0.3 for 500 hr., 0.59 for 100 hr. for Boron 0^{0}.

0.355 for 500 hr., 0.72 for 1000 hr. for Boron 90^{0}.

0.343 for 500 hr., 0.653 for 1000 hr. for HMS 0^{0}.

0.357 for 500 hr., 0.589 for 1000 hr. for HMS 90^{0}.

(2) Hygrothermal

T_p = -65^{0}F.

time = 15 hours

M = 0.291 for 0^{0} Boron

0.331 for 90^{0} Boron

0.459 for 0^{0} HMS

0.640 for 90^{0} HMS

(3) Accelerated weathering -

$T_p = 145^{O}F$

time = 54 hours

$M = 0.064$ for Boron 0^{O}

0.029 for Boron 90^{O}

0.015 for HMS 0^{O}

0.126 for HMS 90^{O}

(4) Steady state thermal -

$T_p = 260^{O}F$ or $350^{O}F$

time = 100 hrs. or 500 hrs.

$M = 0.0$

(5) Cyclic thermal -

$T_p = 160^{O}F$ or $250^{O}F$ (used T)

time = 500 hrs. or 1000 hrs. (let 1 cycle = 1 hour)

$M = 0.0$

All temperatures (T_T, T_p) were converted from ^{O}F to ^{O}R by adding 460.0 and time was converted from hours to days by dividing by 24. The above scaling and the base ten logarithm of fatigue cycles were done before performing any statistical analysis.

<u>Ranges of values used for the HGTM variables:</u>

T_T	test temperature. Computations were done in ^{O}Rankine (^{O}F + 460). Values are: $530^{O}R$ ($70^{O}F$), $720^{O}R$ ($260^{O}F$), $810^{O}R$ ($350^{O}F$)
T_p	preconditioning temperature. Also converted to ^{O}R as was T_T. Values are: $580^{O}R$ ($120^{O}F$), $380^{O}R$ ($-65^{O}F$), $605^{O}R$ ($145^{O}F$), $620^{O}R$ ($160^{O}F$), $710^{O}R$ ($250^{O}F$), $720^{O}R$ ($260^{O}F$), $810^{O}R$ ($350^{O}F$)

time	duration of preconditioning. NEWRAP (ref. 5) have provisions for converting the input hours to days. Values are: 20.83 days (500 hrs.), 41.67 days (1000 hrs.), 0.63 days (15 hrs.), 2.25 days (54 hrs.), 4.17 days (100 hrs.)
V	product of T_p and time. Thus has units of ^{O}R-days. Values are: 12081.4^{O}R-days, 24168.2^{O}R-days, 245.7^{O}R-days, 1361.25^{O}R-days, 12914.6^{O}R-days, 3002.4^{O}R-days, 14997.6^{O}R-days, 3377.7^{O}R-days, 16872.3^{O}R-days, 25835.3^{O}R-days, 14789.3^{O}R-days, 29585.7^{O}R-days. $LOG_{10}N$ - base ten logarithm of the fatigue cycles. Is input into the programs as fatigue cycles. Provisions have been made in both programs to take the log of this number. There are no units and the values range from 0 to 7.
M	percent moisture weight gain. Is input as a percentage and has no units. Values range from 0.015 to 0.64.
T_T^2	Sample values: 280900$^{O}R^2$, 518499$^{O}R^2$, 656100$^{O}R^2$
V^2	Sample values: Minimum - 60368.5$^{O}R^2$-days Maximum - 875313644.5$^{O}R^2$-days
$(LOG_{10}N)^2$	Sample values: range from 0 to 49
M^2	Values: Minimum - $2.25\text{x}10^{-4}$ Maximum - 0.41 (Some are zero.)
T_tV	Values: Minimum - $1.302\text{x}10^5$ $^{O}R^2$ days Maximum - $2.396\text{x}10^7$ $^{O}R^2$days

$T_T \mathrm{Log}_{10} N$ Values:

Minimum - 530°R Maximum - 5.67×10^{3} °R Some are zero.

$V \mathrm{Log}_{10} N$ Values:

Minimum - 245.7°R days Maximum - 2.07×10^{5} °R days Some are zero.

$T_T M$ Values:

Minimum - 7.95°R Maximum - 518.4°R Some are zero.

VM Values:

Minimum - 3.685°R days Maximum - 18934.9°R days Some are zero.

$M \mathrm{Log}_{10} N$ Values:

Minimum - 0.015 Maximum - 4.48 Some are zero.

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TABLE 1.

SUMMARY OF COEFFICIENTS FOR TWO UNIDIRECTIONAL COMPOSITES

COEFFICIENT		BORON/EPOXY		HMS/EPOXY	
		0^0	90^0	0^0	90^0
(S_0)	B_0	114.54	5.43	-9.15	12.86
(T_T)	B_1	0.276	1.38×10^{-2}	0.333	-1.43×10^{-2}
(T_T^2)	B_2	-2.66×10^{-4}	-1.69×10^{-5}	-2.04×10^{-4}	1.70×10^{-6}
(V)	B_3	-1.32×10^{-3}	2.23×10^{-5}	1.05×10^{-3}	-5.27×10^{-4}
(V^2)	B_4	-1.44×10^{-8}	-2.37×10^{-9}	-7.51×10^{-9}	5.03×10^{-9}
(T_TV)	B_5	2.11×10^{-6}	4.44×10^{-8}	-1.48×10^{-6}	4.35×10^{-7}
(N)	B_6	-0.143	-0.866	-7.15	7.93×10^{-2}
(N^2)	B_7	-0.203	1.54×10^{-2}	0.515	2.04×10^{-2}
(T_TN)	B_8	-6.70×10^{-3}	3.12×10^{-4}	-2.08×10^{-3}	-7.14×10^{-9}
(VN)	B_9	4.61×10^{-5}	0	-5.33×10^{-5}	0
(M)	B_{10}	-14.08	-3.00	60.13	-14.36
(M^2)	B_{11}	-2.18	4.66	64.53	-6.77
(T_TM)	B_{12}	-5.98×10^{-2}	-4.54×10^{-3}	-0.153	1.70×10^{-2}
(VM)	B_{13}	1.42×10^{-3}	9.50×10^{-5}	-2.21×10^{-4}	2.42×10^{-4}
(MN)	B_{14}	0.394	0	-2.65	0
	$(R^2, \%)$	(70.3)	(86.0)	(78.6)	(65.2)

TABLE 2.

REGRESSION ANALYSIS RESULTS FOR BORON/EPOXY UNIDIRECTIONAL COMPOSITES

COEFFICIENT		STRENGTH/PROBABILITY			
		LONGITUDINAL (0^0)		TRANSVERSE (90^0)	
		>0.900	>0.999	>0.900	>0.999
(S_0)	B_0	114.45	193.07	9.67	9.64
(T_T)	B_1	0.271	....	....	....
(T_T^2)	B_2	-2.58×10^{-4}	-3.96×10^{-5}	-6.13×10^{-6}	-5.84×10^{-6}
(V)	B_3	-1.58×10^{-3}	....	....	....
(V^2)	B_4	....	....	-2.36×10^{-9}	....
(T_TV)	B_5	2.22×10^{-6}	....	8.22×10^{-8}	....
(N)	B_6	....	....	-0.570	-0.593
(N^2)	B_7	....	....	....	....
(T_TN)	B_8	7.08×10^{-3}	-7.91×10^{-3}	....	....
(VN)	B_9	....	....	....	....
(M)	B_{10}	....	....	....	....
(M^2)	B_{11}	....	....	7.18	5.33
(T_TM)	B_{12}	7.48×10^{-2}	4.14×10^{-2}	-8.39×10^{-3}	-6.71×10^{-3}
(VM)	B_{13}	1.18×10^{-3}	....	....	....
(MN)	B_{14}	....	....	....	....

TABLE 3.

REGRESSION ANALYSIS RESULTS FOR HMS/EPOXY UNIDIRECTIONAL COMPOSITES

COEFFICIENT		STRENGTH/PROBABILITY			
		LONGITUDINAL (0°)		TRANSVERSE (90°)	
		>0.900	>0.999	>0.900	>0.999
(S_0)	B_0	-11.42	89.44	12.36	11.78
(T_T)	B_1	0.346	4.68×10^{-2}	-1.28×10^{-2}	-1.32×10^{-2}
(T_T^2)	B_2	-2.17×10^{-4}	....	....	....
(V)	B_3	8.71×10^{-4}	....	-4.67×10^{-4}	-4.98×10^{-4}
(V^2)	B_4	....	....	....	....
(T_TV)	B_5	-1.70×10^{-6}	-4.98×10^{-7}	5.29×10^{-7}	6.64×10^{-7}
(N)	B_6	-8.68	-6.15	....	....
(N^2)	B_7	-0.457	....	....	....
(T_TN)	B_8	....	....	3.66×10^{-4}	....
(VN)	B_9	....	....	....	....
(M)	B_{10}	95.28	89.42	-14.78	....
(M^2)	B_{11}	....	....	....	....
(T_TM)	B_{12}	-0.154	-0.160	1.64×10^{-2}	....
(VM)	B_{13}	....	....	2.49×10^{-4}	....
(MN)	B_{14}	-2.68	....	....	....

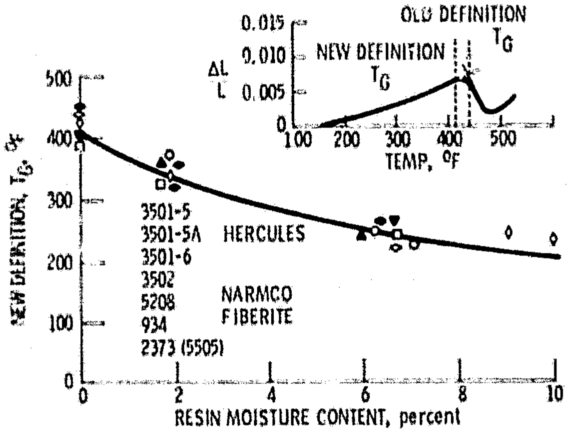

Figure 1. - Glass transition temperature, T_G, of wet resins.

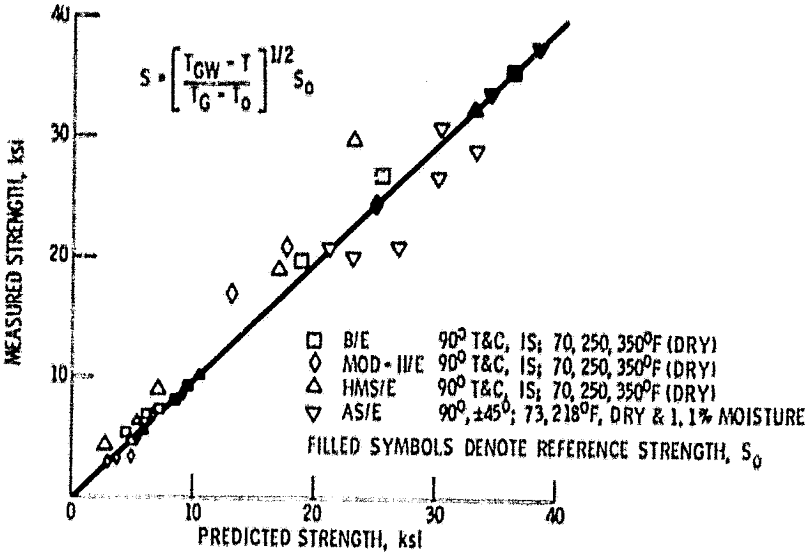

Figure 2. - Hygrothermal effects on strength predicted accurately.

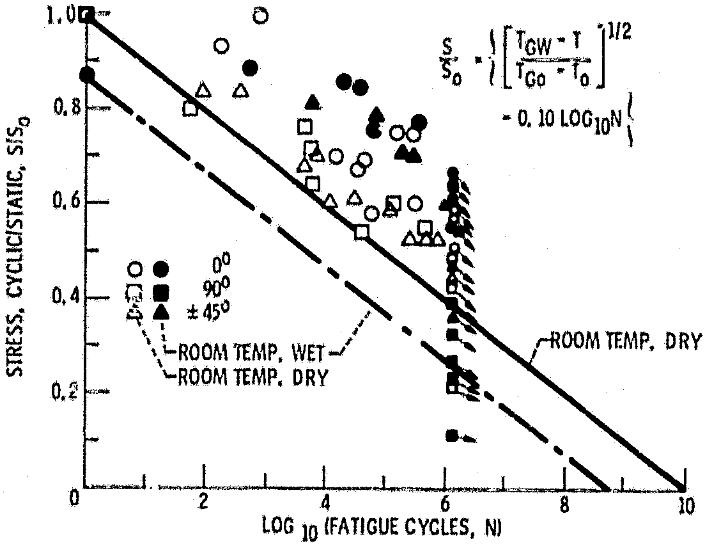

Figure 3. - Compressive life/durability, AS/E.