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ICAN Sensitivity Analysis

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SUMMARY

A computer program called ICAN (Integrated Composite Analyzer) was used to predict the properties of high-temperature polymer matrix composites. ICAN is a collection of NASA Lewis Research Center-developed computer codes designed to carry out analysis of multilayered fiber composites. The material properties used as input to the program were those of the thermoset polyimide resin PMR-15 and the carbon fiber Celion 6000. The sensitivity of the predicted composite properties to variations in the resin and fiber properties was examined. In addition, the predicted results were compared with experimental data. In most cases, the effect of changes in resin and fiber properties on composite properties was reasonable. However, the variations in the composite strengths with the moisture content of the PMR-15 resin were inconsistent. The ICAN-predicted composite moduli agreed fairly well with experimental values, but the predicted composite strengths were generally lower than experimental values.

INTRODUCTION

Much research has been, and is being, carried out to derive models that are suited to deal with the characteristic mechanical behavior of a composite, including anisotropy, viscoelasticity, and deterioration phenomena like debonding or delamination. One of the modeling programs that has been developed at the NASA Lewis Research Center is the ICAN program. The acronym ICAN stands for Integrated Composite Analyzer. ICAN is used for linear elastic materials.

Resin and fiber properties are used in ICAN to calculate ply properties. Composite properties are calculated from ply properties and the ply layup. Some of the material properties cannot be measured accurately and are based on reasonable guesses. One way to evaluate the effect of these parameters is to perform a sensitivity analysis.

The purpose of this work is twofold. The first purpose is to examine the sensitivity of composite properties predicted by ICAN to variations in material properties and the ply layup. The second purpose of this work is to see how well the predicted values agree with experimental values.

ICAN PROGRAM

ICAN is a multilevel analyzer used to predict the structural response of multilayered fiber composites and used for designing structural components of multilayered fiber composites. ICAN is a combination of two other NASA Lewis Research Center-developed programs, namely MFCA (Multilayered Filamentary Composite Analyzer), which performs the laminate analysis accounting for the interply layer effects through the laminate theory , and INHYD (Intraply Hybrid Composite Design), which predicts the hygral, thermal, and the mechanical properties of the composite layers. ICAN performs micromechanics, macromechanics, and laminate analysis including the hygrothermal response of the fiber composite. The properties of the fibers and the resins are contained in a data base that the program accesses. The following sections discuss the data input to the ICAN program and the output that is obtained when the ICAN program is run.

Input

Fiber and matrix properties needed to run the ICAN program are stored in a data base. The user, however, has to supply some other information to make the data input complete. This section deals with the type of data required to simulate the properties of any given composite.

User-supplied data input. - The user of the ICAN program has to supply the following data to the program in an interactive mode in the order in which they appear:

1. The title of the input data set, up to 80 characters long. The nature of the simulation could be described here.

2. The number of layers/plies in the composite.

3. The number of loading conditions that are to be analyzed. To be able to continue with the data entry, at least one loading condition must be specified.

4. The number of material systems that are in the composite. The program can analyze a hybrid composite; therefore if more than one resin or more than one fiber is used in the composite, it has to be stated.

5. The detailed ply information for each ply has to be entered:

    a. Material system identification
    b. Use temperature
    c. Cure temperature
    d. Moisture content
    e. Ply orientation
    f. Ply thickness

The preceding information can be entered all at once on one line separated by a space.

6. If the ply layup is symmetric, then after typing in the necessary ply information for the first half of the layup, you just have to answer yes to the question, Is your layup symmetric (Y/N)? for the computer to supply the duplicate ply properties for the next half of the composite.

7. The material systems identification.

8. The code name for the materials in the composite. Each fiber and neat resin has a designated code name in the data base. One has to know what code name to use for the fibers or the matrix (matrices) beforehand.

9. The fiber volume ratio and the void volume ratio.

10. The loading conditions:

    a. The angle between load axes and structural axes
    b. Inplane loads
    c. Bending loads
    d. Transverse loads

Data base. - As stated earlier, the properties of the fiber and the matrix are in a data base that the program accesses when needed by using their code names. The code names of the materials used to form the composite must be known in advance before running the ICAN program. Example of the kind of data contained in the data base are shown in tables I and II for the fiber and the matrix used in this work, respectively. The code name for Celion 6000 is CEL6 and that for PMR-15 is PMRP.

Output

After running the ICAN program, the following results can be obtained all at once or individually:

1. Input data echo, an example of which is shown in table III
2. Summary of the input data
3. Constituent and ply properties. This includes the constituent properties if moisture or temperature effect is taken into account.
4. Stress/strain relations
5. Composite three-dimensional and two-dimensional properties
6. Composite constitutive relations
7. Reduced bending and axial stiffness
8. Data for finite element method analysis
9. Displacement/force relations
10. Ply properties and responses
11. Poisson's ratio mismatch
12. Free-edge stresses
13. Microstresses and influence coefficients
14. Stress concentration factors
15. Delamination around a hole
16. Stress/strain influence coefficients
17. Laminate failure stress analysis and summary of failure modes

Typical ply properties that ICAN can output are shown in table IV. If the composite is not unidirectional, the ICAN program can only calculate shear and elastic moduli, Poisson's ratio, density, thickness, stress-strain relations about the material axes, moisture diffusivities, moisture expansion coefficients, coefficient of thermal expansion, and heat capacity. The ICAN program cannot directly calculate the strengths of a composite, such as flexural, tensile, or compressive strength, if the composite is not unidirectional.

SENSITIVITY ANALYSIS APPROACH

The idea behind this sensitivity analysis is to vary a particular property, say the tensile strength of the fiber, and see whether there is any significant effect on other properties such as the tensile strength of the composite. Celion 6000 was the fiber chosen for this simulation. The matrix was PMR-15.

Table V shows the initial conditions used in the simulation. This first run was done using these conditions and varying the fiber volume ratio from 0.3 to 0.75. With each fiber volume ratio the moisture content of the composite was varied from 0 to 3 percent. Three percent was considered a reasonable maximum amount of moisture pickup by the composite. This part of the analysis was carried out assuming a void content of zero. For the rest of the analysis the following properties were varied at various fiber volume ratios and moisture content:

1. Void content of the composite (0 to 10 percent)
2. Use temperature (-250, -150, 70, 150, 250 °F)
3. The following fiber and matrix properties were varied from 40 percent below to 40 percent above each value contained in the data base.
   a. Compressive and tensile strengths
   b. Tensile modulus and shear modulus(fiber only)
   c. Thermal expansion coefficient (CTE) and Poisson's ratio

The effect of varying each of the preceding properties of the matrix and the fibers on the following composite properties was studied:

1. Elastic and shear moduli (longitudinal and transverse)
2. Poisson's ratio (12 and 23)
3. CTE (11 and 23)
4. Tensile and compressive strengths
5. Interlaminar shear strength
6. Flexural strength (12 and 23)

RESULTS AND DISCUSSION

Sensitivity Criterion

A criterion was established in order to consistently determine if a given laminate property is sensitive to changes in a particular parameter such as the void content of the composite or the fiber tensile strength. The percentage change of the independent variable was related to the percentage change in the resulting laminate property and if this relationship fell within an arbitrarily chosen guideline, then the property of the laminate was regarded as either slightly, moderately, or highly sensitive. For example, in the ICAN data base the fiber tensile modulus for Celion 6000 is listed as 34 Msi. We wish to determine whether the composite longitudinal tensile modulus is sensitive to the changes in the fiber tensile modulus. With the value contained in the ICAN data base for the fiber tensile modulus, ICAN predicts a value of 10.3 Msi for the composite longitudinal tensile modulus. If the fiber tensile modulus is reduced by 40 percent to 20.4 Msi, ICAN predicts a laminate tensile modulus of 6.45 Msi. So a 40 percent decrease in the fiber tensile modulus causes a 38.8 percent decrease in the laminate tensile modulus for a conversion of 96.8 percent (= 38.8/40×100). This is regarded as a high sensitivity and is indicated by the letter "H" in table VI.

The criteria established for the analysis are as follows: S, slightly sensitive (1 to 9 percent conversion); L, low sensitivity (10 to 24 percent); M, moderate sensitivity (25 to 50 percent); H, high sensitivity (51 to 100 percent). In most cases, the slightly sensitive parameters can be regarded as not sensitive, since the changes in the resulting laminate property are very small, within the error of mechanical test measurements. Table VI shows the results of the ICAN sensitivity analysis. The trends, designated as increase or decrease, are also shown. For example, the transverse tensile strength of a unidirectional composite increases with moisture content to a point and then it starts decreasing.

Longitudinal Tensile Modulus

Figure 1 shows a typical composite geometry. The longitudinal tensile modulus (LTM) of the composite is strongly influenced by the ply angle. Figure 2 shows the variation of the longitudinal tensile modulus with ply angle. As the ply angle increases, the LTM decreases and reaches a minimum value of 1.2 Msi at an angle of about 60° and remains constant thereafter for the rest of the ply angle studied. Figure 2 also shows that the plot for the transverse tensile modulus with ply angle is a mirror image of the plot of the LTM about a ply angle of 45°. Changes in the moisture content of the composite have little effect on LTM. LTM is slightly influenced by the fiber volume ratio.

LTM is not sensitive to the use temperature. The longitudinal tensile modulus remains the same at cryogenic temperatures, such as -250 °F, as at a very high temperature of 250 °F even in the presence of moisture. Figure 3 shows the effect of fiber tensile modulus on LTM at various fiber volume ratios. The LTM is very sensitive to the changes in the fiber tensile modulus but less sensitive to the changes in the matrix tensile modulus because the tensile modulus of the fiber is far greater than that of the matrix. A 20 percent increase in the fiber tensile modulus causes the same percentage increase in the longitudinal tensile/modulus of the composite. Changes in the composite LTM caused by the changes in the matrix tensile modulus are not significant.

Transverse Tensile Modulus

The transverse tensile modulus of the composite is very sensitive to changes in the tensile modulus of the matrix, moderately sensitive to fiber volume ratio, and slightly sensitive to moisture content. The transverse tensile modulus is also sensitive to changes in the ply angle (see fig. 2) and slightly sensitive to the use temperature. Figure 4 shows the relationship between the transverse tensile modulus of the laminate and the fiber volume ratio at various moisture contents. At zero percent moisture content, as the fiber volume ratio increases from 0.3 to 0.75, the transverse tensile modulus increases from 0.81 Msi to 1.39 Msi. Figure 5 shows the relationship between the transverse tensile modulus of the composite and the matrix tensile modulus at various fiber volume ratios. As the tensile modulus of the matrix increases, the transverse tensile modulus of the laminate increases.

Composite Shear Modulus

The longitudinal shear modulus is influenced a great deal by the fiber volume, the ply angle, and the matrix tensile modulus. Figure 6 shows the effect of the fiber volume ratio on the longitudinal shear modulus of the composite at various moisture contents. In figure 6, the laminate longitudinal shear modulus increases with increasing fiber volume ratio. In figure 7, the longitudinal shear modulus increases monotonically with increasing ply angle. The laminate longitudinal shear modulus is moderately influenced by the use temperature and by the matrix Poisson's ratio. It is highly sensitive to changes in matrix tensile modulus (see fig. 8) and moderately sensitive to changes in fiber shear modulus (see fig. 9).

In figure 7, the transverse shear modulus increases with increasing ply angle to a maximum value at an angle of 45° and then it decreases. The transverse shear modulus is symmetric about a ply angle of 45°. The transverse shear modulus is highly sensitive to changes in the fiber volume ratio and in the matrix tensile modulus and moderately sensitive to changes in the matrix Poisson's ratio. The moisture content of the composite has very little effect on both the transverse and longitudinal shear modulus.

Laminate Poisson's Ratio

The longitudinal Poisson's ratio of the composite is highly influenced by the ply-angle and the matrix Poisson's ratio. It is moderately influenced by the fiber volume ratio and the fiber Poisson's ratio. As shown in figure 10, the laminate longitudinal Poisson's ratio reaches a maximum at about 20°. In figure 11, the longitudinal Poisson's ratio increases from 0.288 to 0.336 when the fiber Poisson's ratio changes from 0.12 to 0.28 at a fiber volume ratio of 0.3. However, at higher fiber volume ratios, the influence of the fiber Poisson's ratio becomes greater. At a fiber volume ratio of 0.65, the laminate Poisson's ratio increases from 0.204 to 0.308 when the fiber Poisson's ratio changes from 0.12 to 0.28.

The transverse Poisson's ratio is also influenced by the fiber volume ratio, the ply angle, the matrix Poisson's ratio, and the void content. The fiber volume ratio, the void content, and the ply angle have a decreasing effect on this ratio. The matrix Poisson's ratio has an increasing effect on this ratio. Figure 10 shows the relationship between the laminate transverse Poisson's ratio and the ply layup angle. This Poisson's ratio reaches a minimum at about 70° and then it begins to increase as the angle increases.

Coefficient of Thermal Expansion (CTE)

The longitudinal CTE is highly sensitive to the fiber volume ratio, the void content, the ply angle, the CTE of the fiber, the tensile modulus of the fiber, the CTE of the matrix, and the tensile modulus of the matrix; and it is slightly influenced by the moisture content of the composite. Figure 12 shows the laminate longitudinal CTE versus the void content and the moisture content. In figure 13, the CTE increases as the ply angle increases. Figures 14 and 15 show the effect of the fiber CTE and the matrix CTE on the laminate longitudinal CTE, respectively, at three different fiber volume ratios. The longitudinal CTE decreases sharply at lower fiber volume ratio as the fiber tensile modulus is increased. However, at higher fiber volume ratios the rate of change of the laminate CTE is lower. The plots of longitudinal CTE versus fiber tensile modulus at various fiber volume ratios in figure 16 show the same behavior.

The transverse CTE is very sensitive to the fiber volume ratio, the ply layup, and the matrix CTE. It is moderately sensitive to the moisture content of the composite and the use temperature. In figure 13, the value of the transverse CTE decreases with increasing ply angle.

Heat Capacity

The only parameter that significantly affects the heat capacity is the use temperature. As the use temperature increases the heat capacity increases. The fiber volume ratio and the moisture content do have a little influence on the heat capacity of the composite.

Heat Conductivity

The only parameters that influence the longitudinal heat conductivity of the composite are the fiber volume ratio and the ply angle. The transverse heat conductivity is influenced by the fiber volume ratio, the use temperature, and the ply angle. However, it is moderately affected by the moisture and the void content of the composite. Figure 17 shows the effect of ply angle on the heat conductivity.

Tensile Strength

The longitudinal tensile strength of the composite is sensitive to the fiber volume ratio and the fiber tensile strength and very slightly sensitive to both the tensile moduli of the fiber and the matrix. Figure 18 shows the effect of the fiber volume ratio on the composite longitudinal strengths. Figure 19 also shows the effect of the fiber tensile strength on the laminate longitudinal tensile strength.

The transverse tensile strength is also sensitive to the fiber volume ratio, the use temperature, and the tensile strength of the matrix. Figure 20 shows the relationship between the transverse tensile strength with the matrix tensile strength. The moisture content of the composite has little effect on the transverse tensile strength. However, the presence of a small amount of moisture causes the transverse tensile strength to increase. For a fiber ratio of 0.6 and a zero moisture content, ICAN predicts a transverse tensile strength of 5.06 ksi. But for the same fiber volume and a moisture content of 0.05 percent, the transverse tensile strength of the composite becomes 8.08 ksi. When the moisture content is increased to 0.5 percent, the transverse tensile strength decreases to 7.88 ksi. Thereafter, any subsequent increase in the moisture content causes the tensile strength to decrease slightly. The same phenomenon was observed for the flexural strength (see the section on flexural strength), the interlaminar shear strength, and the compressive strength. These results indicate that the manner in which ICAN handles the presence of moisture in composites needs to be examined.

Compressive Strength

The longitudinal compressive strength is highly sensitive to the void content and the use temperature. It is moderately sensitive to the fiber volume ratio (see fig. 18) and slightly sensitive to the moisture content and the compressive strength of the matrix. Figure 21 shows the relationship between the longitudinal compressive strength of the composite and the void content. As the void content of the composite increases, the longitudinal compressive strength decreases. The same trend has been reported by other researchers (ref. 4). When the void content of the composite with 0.55 fiber volume ratio and zero percent moisture is zero, the longitudinal compressive strength is 97.45 ksi. When the void content increases to 4 percent, the longitudinal compressive strength reduces to 68.92 ksi; and when the void content is 10 percent, it reduces further to 48.62 ksi. The longitudinal compressive strength increases with increasing use temperature. In figure 22, at 70 °F, the compressive strength of the composite decreases very sharply to a minimum, as shown by the big dip in the plot. Thereafter, it begins to increase with increasing use temperature. This sharp drop in the longitudinal compressive strength may be due to the way this property is computed by ICAN. The longitudinal compressive strength is computed in ICAN on the basis of three different criteria, namely rule of mixture, fiber microbuckling, and delamination. The minimum of these three computed values is returned as the longitudinal value. The transverse compressive strength, is however, influenced by the fiber volume ratio, the use temperature, and the compressive strength of the matrix and it is slightly sensitive to the changes in the moisture content.

Flexural Strength

The longitudinal flexural strength is influenced by the void content and the use temperature, whereas the transverse flexural strength is affected by the changes in the fiber volume ratio (see fig. 18), the use temperature, and the tensile strength of the matrix. Figures 23 to 25 show the dependence of the longitudinal flexural strength on the use temperature, the void content, and the fiber tensile strength, respectively. In figure 23, the longitudinal flexural strength shows the same sharp drop at the use temperature of 70 °F as does the longitudinal compressive strength. This only happens when the moisture content of the composite is zero. When the moisture content is increased to 1 percent, the flexural strength decreases with increasing use temperature. This phenomenon occurs in all composites regardless of the fiber volume ratio. The dependence of longitudinal flexural strength on moisture content is shown in figure 26. The addition of as little as 0.05 percent moisture causes the longitudinal flexural strength to increase appreciably. However, as the amount of moisture is increased, the flexural strength decreases.

The transverse flexural strength is sensitive to the fiber volume ratio, the use temperature (see fig. 23), and the matrix tensile strength. The matrix compressive strength has a moderate effect on the transverse flexural strength. The flexural strength is also dependent on the void content, which can cause a change in the failure mechanism from tensile to compressive as the void content increases.

Interlaminar Shear Strength (ILSS)

This property of the composite is sensitive to the changes in the void content, the use temperature, and the fiber volume ratio. In figure 18, as the fiber volume ratio increases, the interlaminar shear strength of the composite decreases. In figure 22, the ILSS decreases with increasing use temperature. The presence of voids causes the interlaminar shear strength to decrease as shown in figure 27. The ILSS depends slightly on the moisture content. When a small amount of moisture is present in the composite, the ILSS increases noticeably, as compared with when no moisture is present at all. Any additional amount of moisture causes the ILSS to increase, but the rate of increase is not as large.

Comparison of Some ICAN Results

Calculated values from the ICAN analysis and the reported values in the literature for HT-S/PMR-15 composite properties are tabulated in table VII. A ply thickness of 0.008 in. and use and cure temperatures of 70 and 600 °F, respectively, were used. The ICAN program predicts lower composite properties than those reported in the literature with exception of the tensile strength and the flexural modulus for the unidirectional composite with configuration $[0]_6$. ICAN's prediction for flexural modulus is almost the same as that reported in the literature. The prediction for the tensile strength is a little higher. For the $[90]_6$ laminate, ICAN's prediction for the tensile modulus agrees with the experimental value. The agreement between the predicted CTE and the reported CTE (ref. 3) is also very good.

Figures 28 and 29 show the strength of AS/PMR-15 unidirectional composite as a function of fiber content and void content, respectively. A laminate configuration of $[0]_{12}$, a ply thickness of 0.008 in., a use temperature of 70 °F, and a cure temperature of 600 °F were used in the ICAN analysis. In these graphs the ICAN-predicted values are plotted in addition to the experimental values reported by Bowles and Frimpong (ref. 2). The ICAN values are generally lower than the experimental values. The differences may be due to the assumptions employed in the modeling. Besides, the flexural strength should increase with increasing fiber content. The data obtained from the ICAN analysis show no trend with fiber content.

Greszczuk (ref. 4) developed two mathematical models for calculating the effect of voids on interlaminar shear strength. He modeled the effects of spherical voids and cylindrical voids. Although evidence from optical microscopy indicates that the voids studied in reference 2 were cylindrical in shape, the data that were measured agreed with the predictions of the spherical model. The ICAN program utilizes a relationship similar to the model for cylindrical voids that is presented in reference 4. The differences between the measured and predicted ILSS values presented in figure 28 are probably due to interfacial bonding effects.

CONCLUSIONS

A sensitivity analysis of the properties of a Celion 6000/PMR-15 composite to matrix and fiber properties was performed using the ICAN analysis. It was determined that one or more matrix properties do affect the composite properties. Likewise, some properties of the composite are sensitive to changes in the fiber properties. In most cases the effect of changes in resin and fiber properties on composite properties were reasonable. Variations in composite strengths with the moisture content of the PMR-15 resin were found to be inconsistent. Comparison of the ICAN-predicted properties with experimental data suggested lower values are predicted by ICAN for composite strengths. However, predictions of composite moduli agreed fairly well with experimental values.

RECOMMENDATION

The results, particularly the large increase in strength at low moisture levels, do not seem reasonable. The manner in which moisture effects are handled by the ICAN code should be examined. It also appears that ICAN consistently predicts lower values than the experimental values. More work needs to be done on either the data base or the actual program codes to ensure that values predicted by ICAN are closer to experimental values. Modification to the program codes is needed to allow the strengths of composites other than unidirectional composites to be computed and printed.

REFERENCES

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3. Serafini, T.T.: High-Temperature Resins. Handbook of Composites. G. Lubin, ed., Van Nostrand, 1982, pp. 89-114.

4. Greszczuk, L.B.: Effect of Voids on Strength Properties of Filamentary Composites. Reinforced Plastics International, Society of the Plastics Industry, Reinforced Plastics Division, Annual Technical Conference, 22nd; Proceedings, Society of the Plastic Industry, New York, 1967, pp. 20-A.1-20-A.10.

TABLE I. - PROPERTIES OF THE CELION 6000 FILAMENT USED IN THIS WORK AND CONTAINED IN THE ICAN DATA BASE

Number of filament per end	6000
Filament equivalent diameter, 10^{-3}	0.280
Density, 10^{-1} lb/in.^{3}	0.640
Elastic modulus, 10^7 psi:	
(1,1)	3.40
(2,2) or (3,3)	0.20
Poisson's ratio:	
(1,2) or (1,3)	0.20
(2,3)	0.25
Shear modulus, 10^6 psi:	
(1,2) or (1,3)	1.30
(2,3)	0.70
Thermal expansion coefficient, 10^6 in./in./°F	
(1,1)	-0.55
(2,2)	5.60
Heat conductivity:	
(1,1)	3.33
(2,2)	0.333
Heat capacity	0.17
Strengths, 10^6 psi:	
Tensile	0.47
Compressive	0.40

TABLE II. - PROPERTIES OF PMR-15 USED IN THIS WORK AND CONTAINED IN ICAN DATA BASE

Density, lb/in.^{3}	0.044
Elastic modulus, 10^6 psi	0.47
Poisson's ratio	0.36
CTE, 10^{-4} in./in./°F	0.28
Heat conductivity, 10^{-3}	8.681
Heat capacity	0.25
Strengths, 10^3 psi:	
Tensile	8.10
Compressive	16.50
Shear	8.10
Strains, 10^{-1}:	
Tensile	0.183
Compressive	0.350
Shear	0.50
Torsional	0.50
Void conductivity	0.225
Dry glass transition temperature, °F	626.0

TABLE III. - ICAN INPUT DATA SET FOR CELION 6000/PMR-15

```
1
                ICAN
        INPUT DATA ECHO

MATRIX CTE
     T
     F
     F
     F
     T
     PLY       1      1     70.00  600.00    0.000    0.000 0.00750
     PLY       2      1     70.00  600.00    0.000    0.000 0.00750
     PLY       3      1     70.00  600.00    0.000    0.000 0.00750
     PLY       4      1     70.00  600.00    0.000    0.000 0.00750
     PLY       5      1     70.00  600.00    0.000    0.000 0.00750
     PLY       6      1     70.00  600.00    0.000    0.000 0.00750
   MATCRD       1CEL6MRP   0.3000  0.0000CEL6PMRP0.0        0.3000  0.0000
     PLOAD   0.00   0.00     0.00    0.00
     PLOAD   0.00   0.00     0.00
     PLOAD   0.00   0.00     0.00    0.00
   OPTION      5
   OPTION      7
1
SUMMARY OF INPUT DATA

MATRIX CTE


- - -      CASE   CONTROL   DECK       - - -
NUMBER OF LAYERS              NL  =    6
NUMBER OF LOADING CONDITIONS NLC  =    1
NUMBER OF MATERIAL SYSTEMS   NMS  =    1

  COMSAT     CSANB     BIDE     RINDV     NONUDF
    T          F         F        F         T
```

- - - LAMINATE CONFIGURATION - - -

PLY	NO	MID	DELTAT	DELTAM	THETA	T-NESS
PLY	1	1	-530.000	0.0%	0.0	0.008
PLY	2	1	-530.000	0.0%	0.0	0.008
PLY	3	1	-530.000	0.0%	0.0	0.008
PLY	4	1	-530.000	0.0%	0.0	0.008
PLY	5	1	-530.000	0.0%	0.0	0.008
PLY	6	1	-530.000	0.0%	0.0	0.008

TABLE IV. - TYPICAL PLY PROPERTIES THAT ICAN OUTPUTS

Fiber volume ratio - 0.300 Matrix volume ratio - 0.700 Void volume ratio - 0

1	Elastic moduli	EPC1	0.1053E+08
2		EPC2	0.8090E+06
3		EPC3	0.8090E+06
4	Shear moduli	GPC12	0.3291E+06
5		GPC23	0.2232E+06
6		GPC13	0.3291E+06
7	Poisson's ratio	NUPC12	0.3120E+00
8		NUPC23	0.5622E+00
9		NUPC13	0.3120E+00
10	Therm. exp. coef.	CTEPC1	-0.3286E-07
11		CTEPC2	0.1283E-04
12		CTEPC3	0.1283E-04
13	Density	RHOPC	0.5000E-01
14	Heat capacity	CPC	0.2193E+00
15	Heat conductivity	KPC1	0.1005E+01
16		KPC2	0.1412E-01
17		KPC3	0.1412E-01
18	Strengths	SPC1T	0.1455E+06
19		SPC1C	0.1096E+06
20		SPC2T	0.7792E+04
21		SPC2C	0.1587E+05
22		SPC12	0.7159E+04
23	Moist. diffusivity	DPC1	0.1400E-03
24		DPC2	0.9046E-04
25		DPC3	0.9046E-04
26	Moist. exp. coef.	BTAPC1	0.1250E-03
27		BTAPC2	0.2440E-02
28		BTAPC3	0.2440E-02
29	Flexural moduli	EPC1F	0.1053E+08
30		EPC2F	0.8090E+06
31	Strengths	SPC23	0.5593E+04
32		SPC1F	0.1563E+06
33		SPC2F	0.1307E+05
34		SPCSB	0.1074E+05
35	Ply thickness	TPC	0.5000E-02
36	Interply thickness	PLPC	0.1730E-03
37	Interfiber spacing	PLPCS	0.1730E-03

TABLE V. - INITIAL CONDITIONS USED IN SIMULATION

Material	
Fiber	Celion 6000 (CEL6)
Resin	PMR-15 (PMRP)
Number of plies	6
Ply thickness, in.	0.0075
Cure temperature, °F	600
Use temperature, °F	70
Ply moisture content by weight, percent	0
Ply alignment (angle)	[0]
Fiber volume ratio	0.3
Void content	0
Axial load in x-direction, psi	0
Membrane load, psi	0
Bending load, psi	0

TABLE VI. - PARAMETERS INFLUENCING COMPOSITE PROPERTIES

Composite properties	Fiber volume	Moisture content	Void content	Use temper-ature	Ply angle	Fiber properties						Matrix properties				
						Tensile strength	Compress. strength	CTE (1)	Poisson's ratio(12)	Shear modulus	Tensile modulus(1)	Tensile strength	Compress. strength	CTE	Tensile modulus	Poisson's ratio
Elastic modulus (long.)	H,I	N	N	N	H,D	N	N	N	N	N	H,I	N	N	N	S,I	N
Elastic modulus (trans.)	M,I	L,D	N	S,D	H,I	N	N	N	N	N	N	N	N	N	H,I	N
Shear modulus (long.)	H,I	L,D	N	M,D	M,I	N	N	N	N	L,I	N	N	N	N	H,I	M,D
Shear modulus (trans.)	H,I	L,D	N	M,D	H,I,D	N	N	N	N	N	N	N	N	N	H,I	M,D
Poisson's ratio (long.)	M,D	N	N	N	H,I	N	N	N	L,I	N	N	N	N	N	N	H,I
Poisson's ratio (trans.)	H,D	N	H,D	N	H,D	N	N	N	N	N	S,I	N	N	N	S,I	H,I
Thermal exp. coeff. (long.)	H,D	L,I	H,D	N	H,I	N	N	H,I	N	N	H,D	N	N	H,I	H,I	N
Thermal exp. coeff. (trans.)	H,D	M,I	S,D	M,I	H,D	N	N	N	N	N	S,I	N	L,I	H,I	N	L,I
Heat capacity	L,I	L,I	S,D	H,I	N	N	N	N	N	N	N	N	N	N	N	N
Heat conductivity (long.)	H,I	N	N	N	H,D	N	N	N	N	N	N	N	N	N	N	N
Heat conductivity (trans.)	H,I	M,I	M,I	H,I	H,I	N	N	N	N	N	N	N	N	N	N	N
Tensile strength (long.)	H,I	N	N	N	NA	H,I	N	N	N	N	S,I	N	N	N	S,I	N
Tensile strength (trans.)	H,D	L,I,D	N	H,I	NA	N	N	N	N	N	N	H,I	N	N	S,I	N
Compressive strength (long.)	M,D	L,I,D	H,D	H,D	NA	N	N	N	N	S,I	N	N	L,I	N	S,I	N
Compressive strength (trans.)	H,D	L,I,D	N	H,D	NA	N	N	N	N	N	N	N	H,I	N	S,I	N
Flexural strength (long.)	S,I,D	L,I,D	H,D	H,D	NA	H,I	N	N	N	S,I	S,I	N	S,I	N	S,I	N
Flexural strength (trans.)	H,D	S,I,D	N	H,D	NA	N	N	N	N	N	N	H,I	M,I	N	S,I	N
Interlaminar shear strength	H,D	S,I,D	H,D	H,D	NA	N	N	N	N	S,I	N	N	N	N	S,I	N

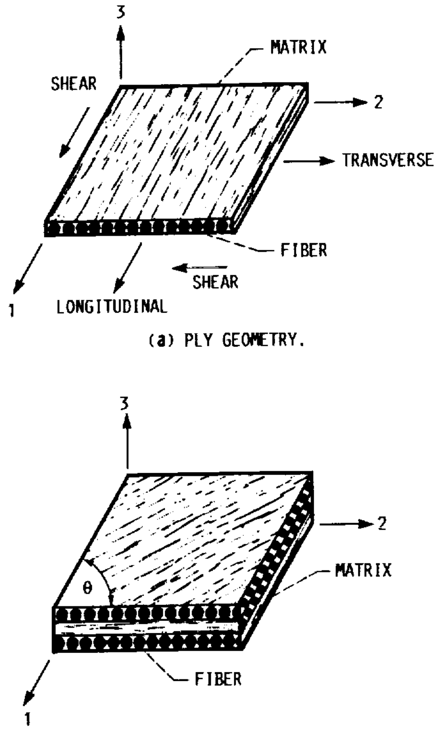
N - Not sensitive.
S - Slight sensitivity (1 to 9 percent).
L - Low sensitivity (10 to 24 percent).
M - Moderate sensitivity (25 to 50 percent).
H - High sensitivity (51 to 100 percent).
NA - Not available.

I - Composite property increases with increasing value of the variable.
D - Composite property decreases with increasing value of the variable.

TABLE VII. - COMPARISON OF HT-S/PMR-15 COMPOSITE PROPERTIES

Property	Laminate configuration			
	$[0]_6$		$[90]_6$	
	ICAN	LIT[a]	ICAN	LIT[a]
Tensile strength, ksi	194.8	180.0	5.55	9.74
Tensile modulus, msi	17.8	21.7	1.18	1.15
Compressive strength, ksi	96.0	135.0	11.3	34.0
Flexural strength, ksi	160.8	206.0	9.31	16.35
Flexural modulus	17.8	17.6	1.18	1.07
Short-beam ILSS, ksi	9.2	16.0	9.2	-----
CTE × 10^6, in./in./°F	-0.211	-----	13.96	14.5

[a]From reference 3.



(b) ANGLE-PLIED LAMINATE.

FIGURE 1. - TYPICAL COMPOSITE GEOMETRY.

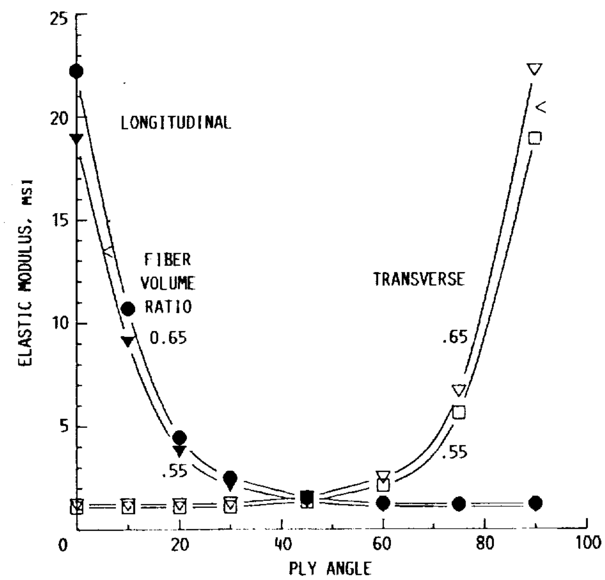


FIGURE 2. - ELASTIC MODULUS OF THE COMPOSITE VERSUS PLY ANGLE AT VARIOUS FIBER VOLUME RATIOS.

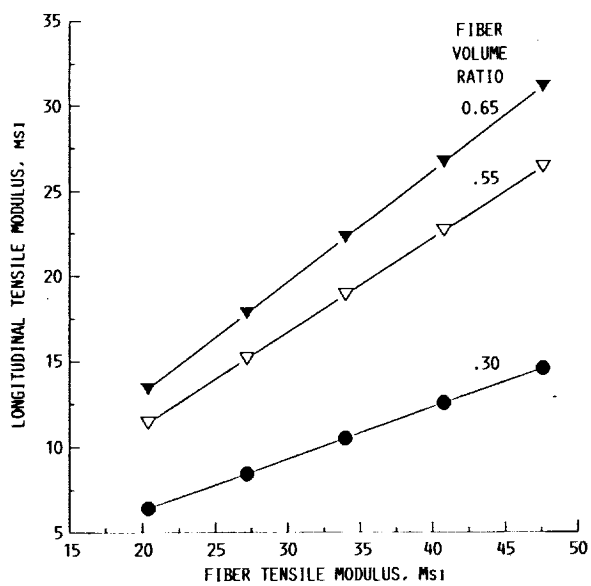


FIGURE 3. - EFFECT OF FIBER TENSILE MODULUS ON THE LONGITUDINAL TENSILE MODULUS OF THE COMPOSITE.

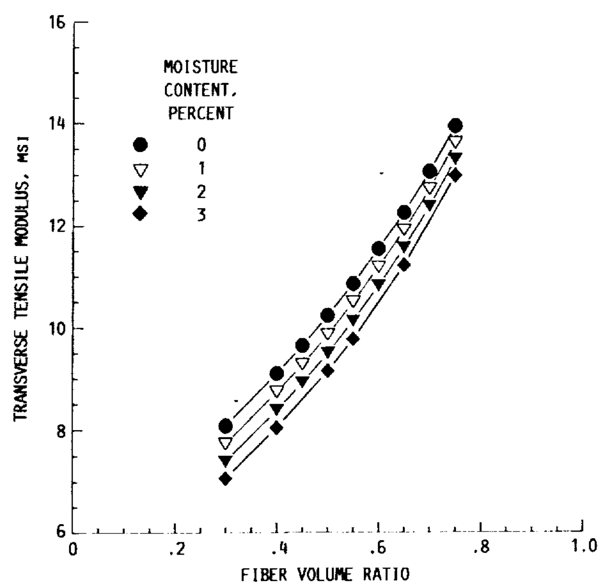


FIGURE 4. - TRANSVERSE TENSILE MODULUS OF THE COMPOSITE VERSUS THE FIBER VOLUME RATIO AT VARIOUS MOISTURE CONTENT.

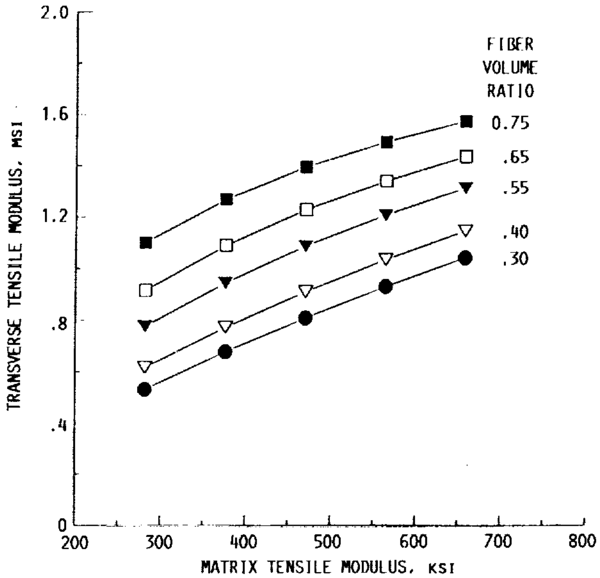


FIGURE 5. - TRANSVERSE TENSILE MODULUS OF THE COMPOSITE AS A FUNCTION OF THE MATRIX TENSILE MODULUS AND FIBER VOLUME RATIO.

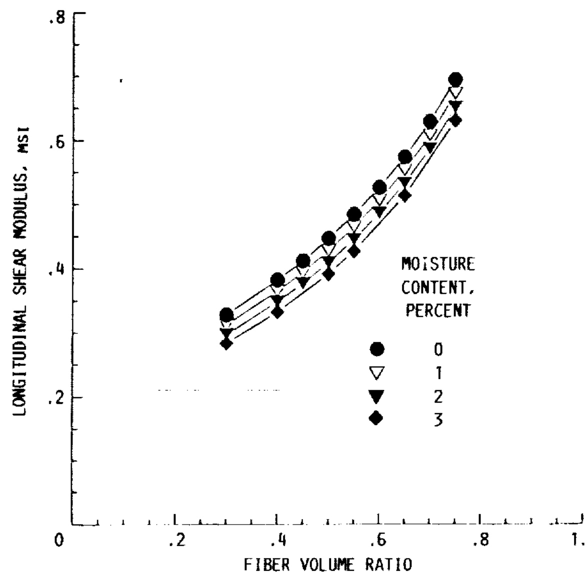


FIGURE 6. - VARIATION OF THE LONGITUDINAL SHEAR MODULUS OF THE COMPOSITE WITH FIBER VOLUME RATIO.

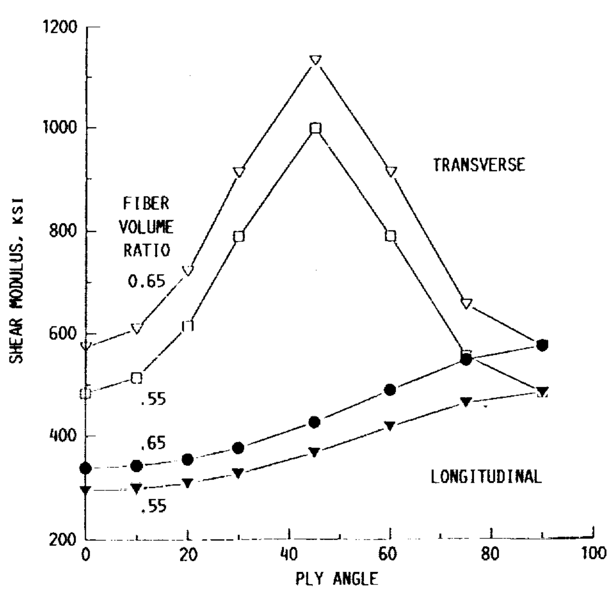


FIGURE 7. - SHEAR MODULUS OF THE COMPOSITE AS A FUNCTION OF PLY LAY-UP.

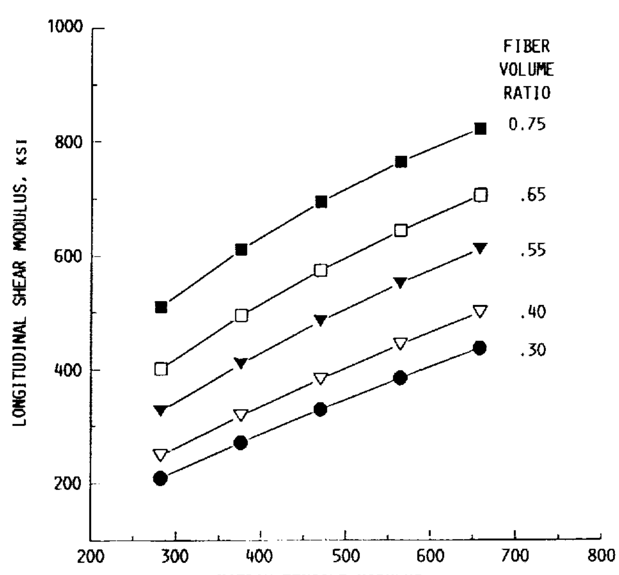


FIGURE 8. - PLOT OF THE COMPOSITE'S LONGITUDINAL SHEAR MODULUS VERSUS THE MATRIX TENSILE MODULUS.

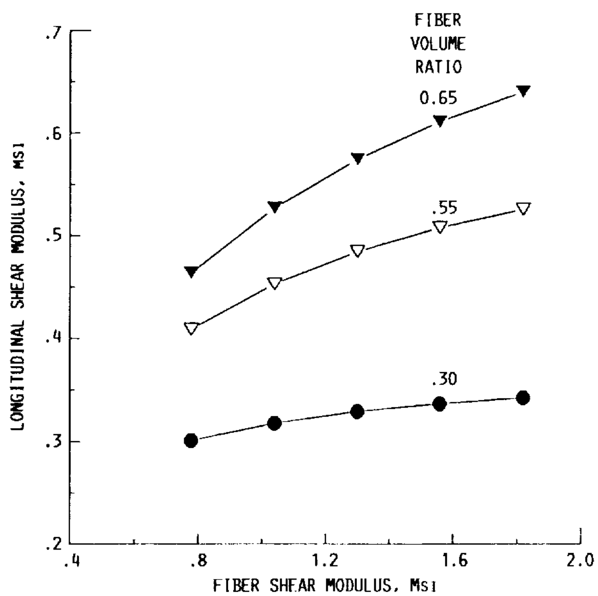


FIGURE 9. - PLOT OF THE LONGITUDINAL SHEAR MODULUS OF OF THE COMPOSITE VERSUS THE FIBER SHEAR MODULUS.

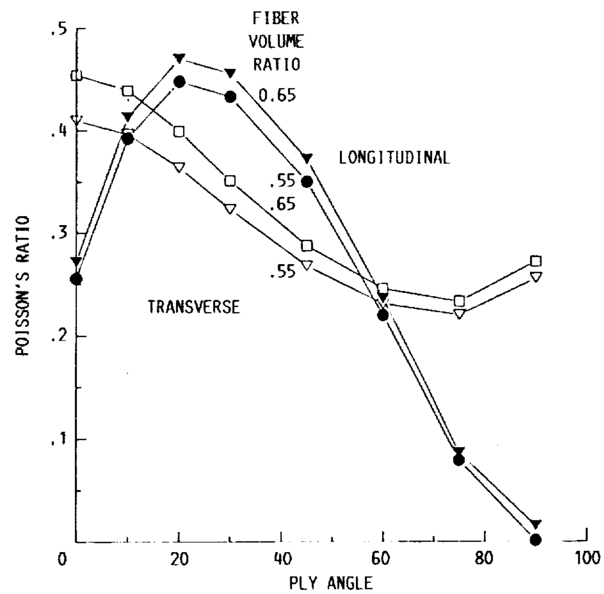


FIGURE 10. - POISSON'S RATIO OF THE COMPOSITE VERSUS PLY LAY-UP.

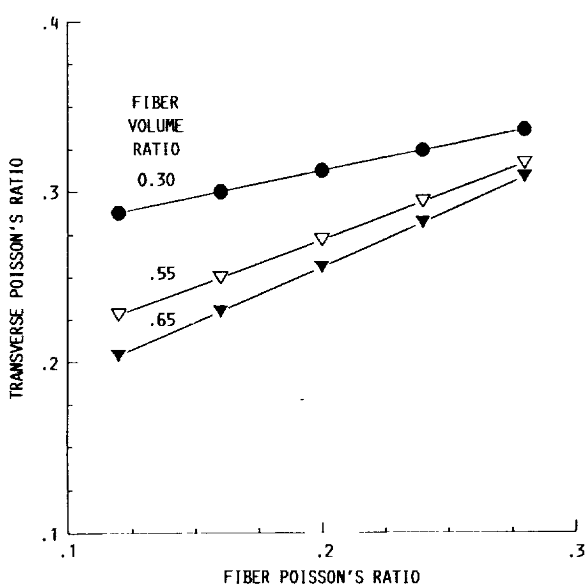


FIGURE 11. - TRANSVERSE POISSON'S RATIO OF THE COMPOSITE VERSUS FIBER POISSON'S RATIO.

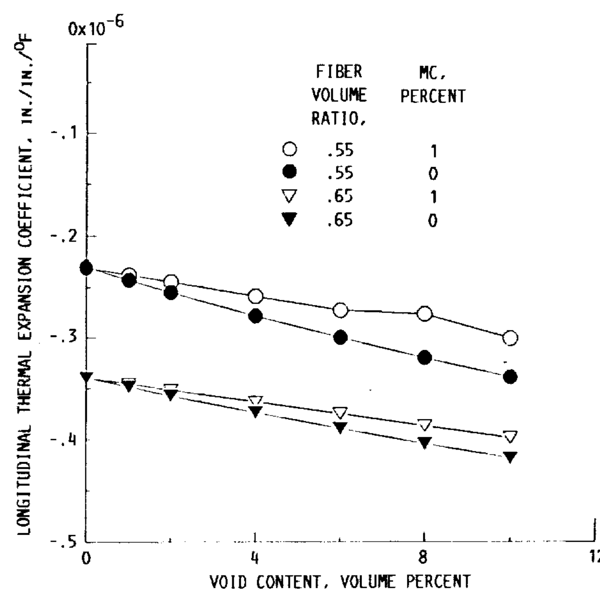


FIGURE 12. - LONGITUDINAL THERMAL EXPANSION COEFFICIENT OF THE COMPOSITE AS A FUNCTION OF VOID CONTENT AND MOISTURE CONTENT.

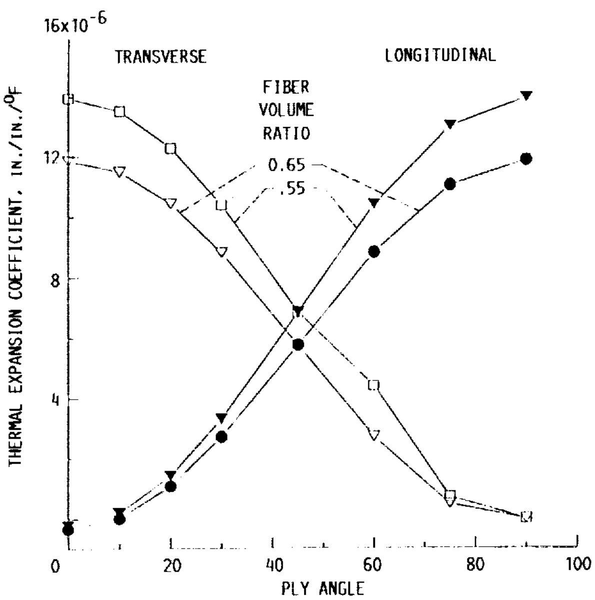


FIGURE 13. - THERMAL EXPANSION COEFFICIENT OF THE LAMINATE VERSUS PLY ANGLE.

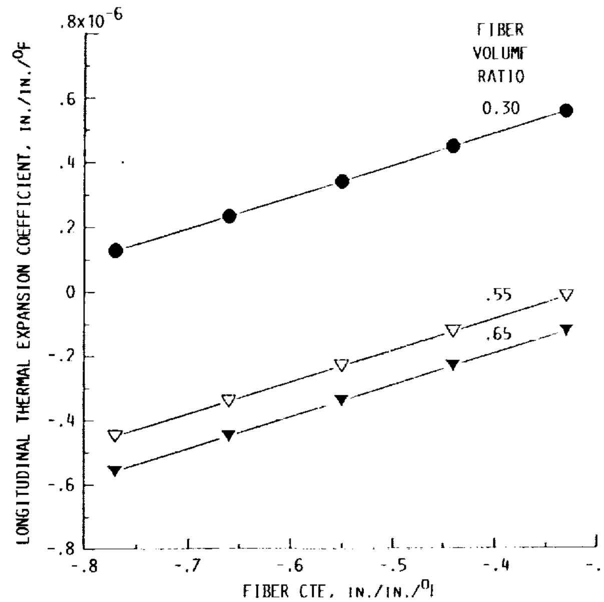


FIGURE 14. - COMPOSITE'S LONGITUDINAL THERMAL EXPANSION COEFFICIENT VERSUS THE FIBER THERMAL EXPANSION COEFFICIENT FOR DIFFERENT FIBER VOLUME RATIO (FIBER VOLUME RATIO).

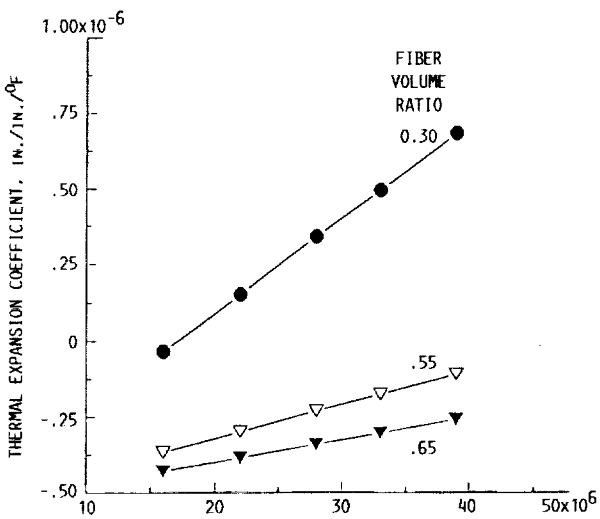


FIGURE 15. - LONGITUDINAL THERMAL EXPANSION COEFFICIENT OF THE COMPOSITE VERSUS THE MATRIX THERMAL EXPANSION COEFFICIENT FOR DIFFERENT FIBER CONTENTS.

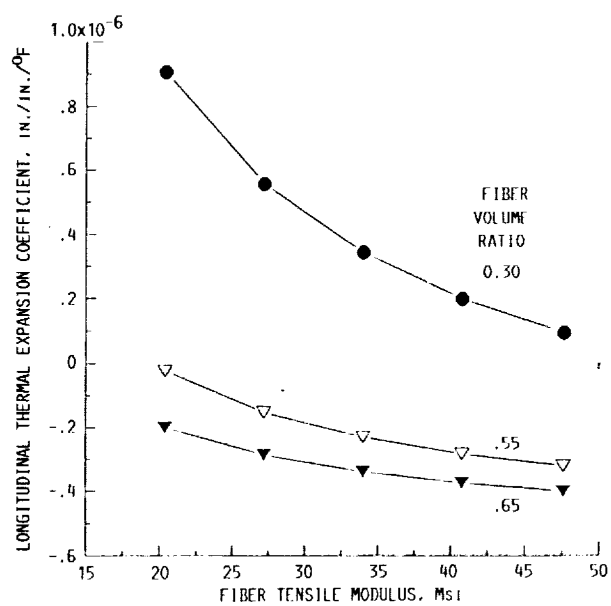


FIGURE 16. - LONGITUDINAL THERMAL EXPANSION COEFFICIENT OF THE COMPOSITE VERSUS THE FIBER TENSILE MODULUS.

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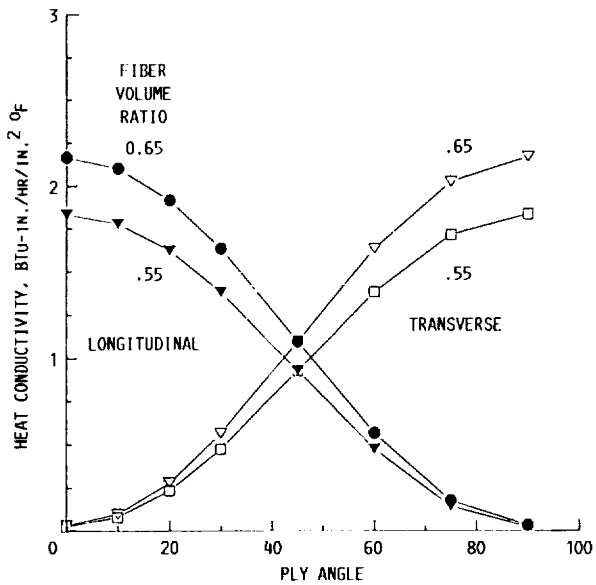

FIGURE 17. - PLOT OF THE HEAT CONDUCTIVITY OF THE LAMINATE VERSUS THE PLY ANGLE AT VARIOUS FIBER CONTENTS.

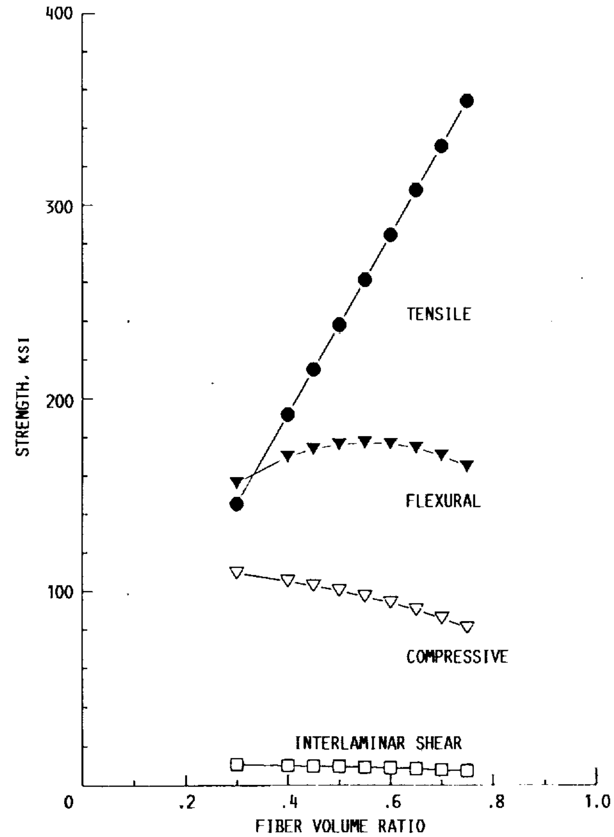

FIGURE 18. - LONGITUDINAL STRENGTH OF THE COMPOSITE VERSUS THE FIBER VOLUME RATIO.

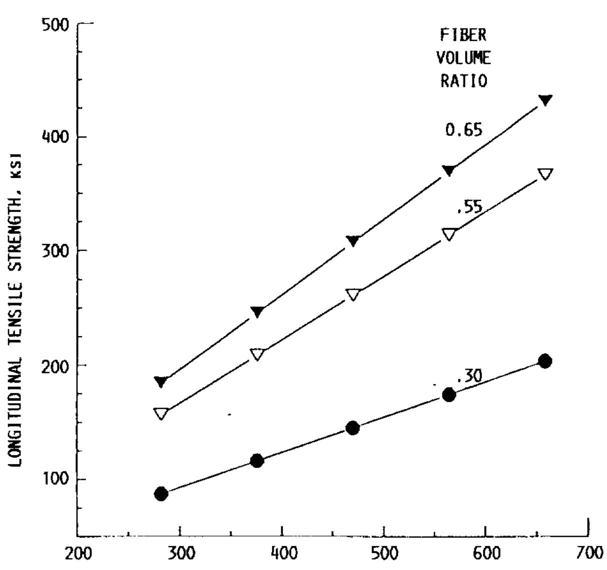

FIGURE 19. - LONGITUDINAL TENSILE STRENGTH OF THE COMPOSITE VERSUS FIBER TENSILE STRENGTH AT VARIOUS FIBER CONTENTS.

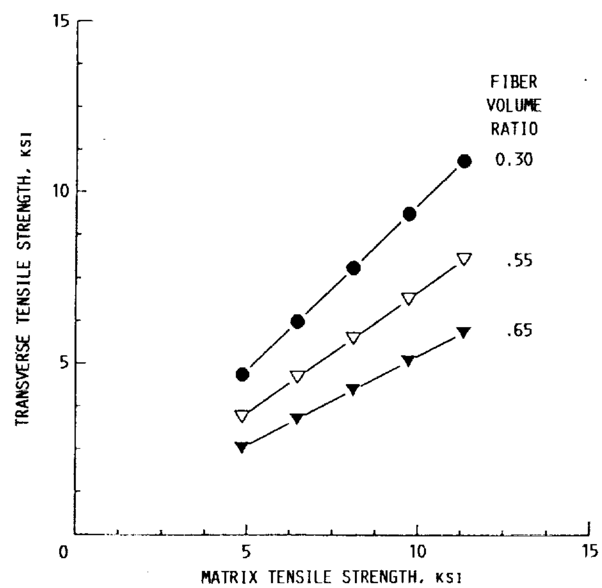

FIGURE 20. - TRANSVERSE TENSILE STRENGTH AS A FUNCTION OF THE MATRIX TENSILE STRENGTH AND FIBER VOLUME RATIO.

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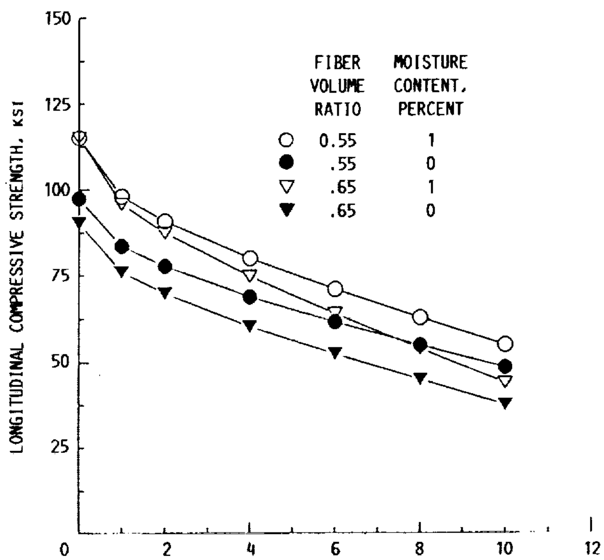

FIGURE 21. - VARIATION OF THE LONGITUDINAL COMPRESSIVE STRENGTH WITH THE VOID CONTENT OF THE COMPOSITE.

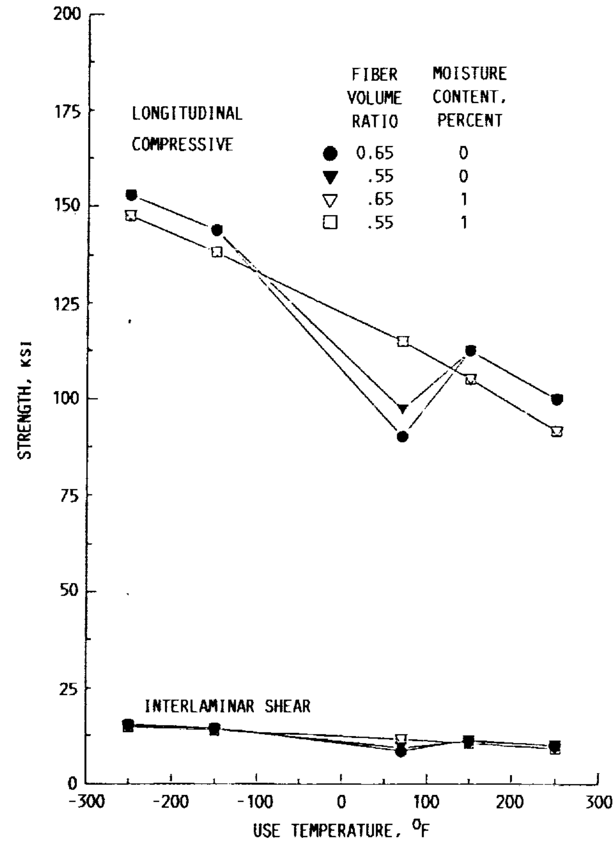

FIGURE 22. - STRENGTH OF THE COMPOSITE VERSUS THE USE TEMPERATURE AT DIFFERENT FIBER VOLUME RATIO AND MOISTURE CONTENT.

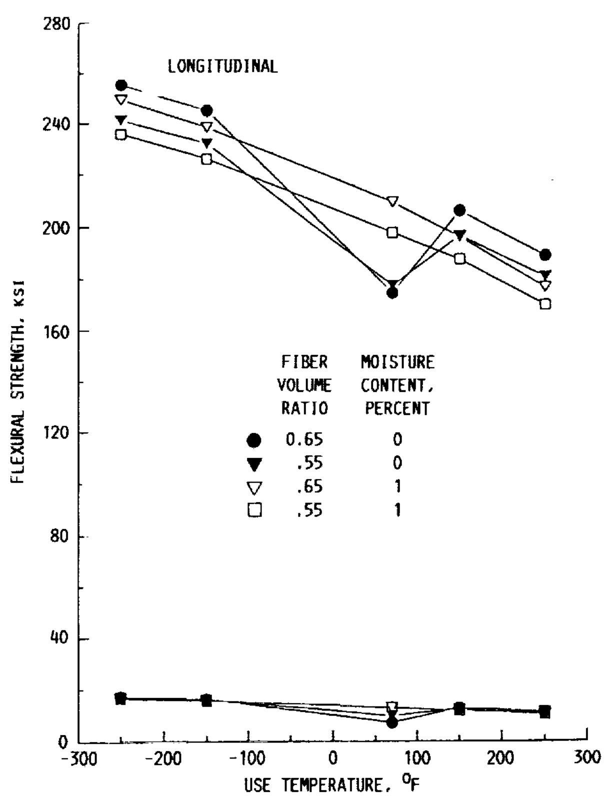

FIGURE 23. - LAMINATE FLEXURAL STRENGTH VERSUS THE USE TEMPERATURE AT DIFFERENT FIBER VOLUME RATIO AND MOISTURE CONTENT.

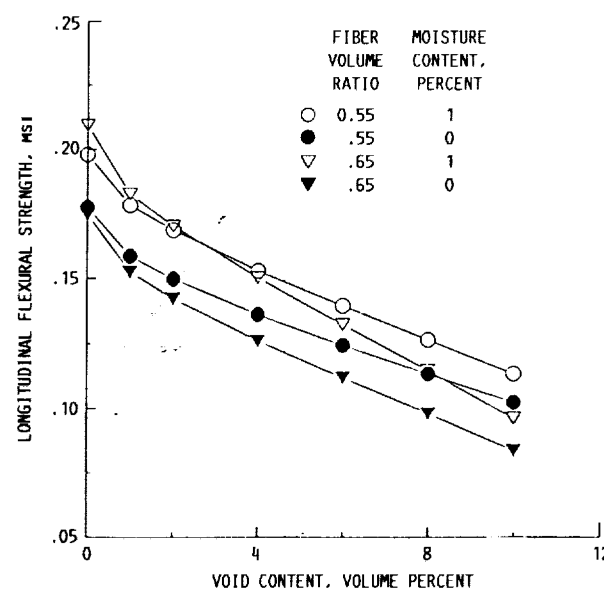

FIGURE 24. - LAMINATE LONGITUDINAL FLEXURAL STRENGTH VERSUS THE VOID CONTENT AT VARIOUS FIBER VOLUME RATIO AND MOISTURE CONTENT.

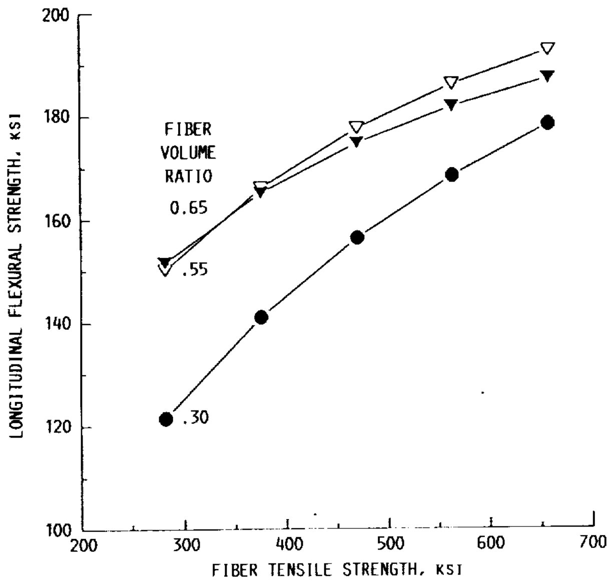

FIGURE 25. - LAMINATE LONGITUDINAL FLEXURAL STRENGTH VERSUS THE FIBER TENSILE STRENGTH FOR DIFFERENT FIBER CONTENTS.

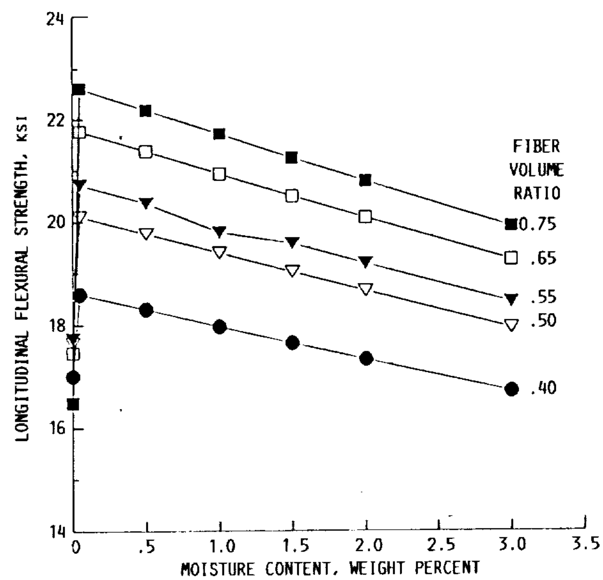

FIGURE 26. - DEPENDENCE OF THE LONGITUDINAL FLEXURAL STRENGTH OF THE COMPOSITE ON THE MOISTURE CONTENT.

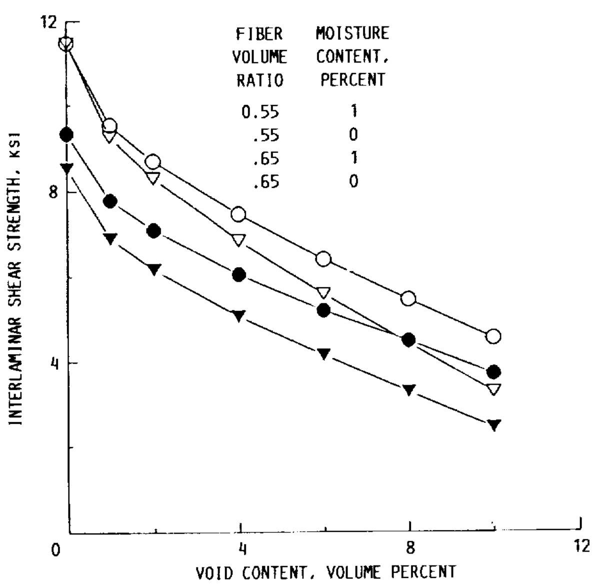

FIGURE 27. - VARIATION OF THE INTERLAMINAL SHEAR STRENGTH OF THE COMPOSITE WITH VOID CONTENT AND FIBER CONTENT.

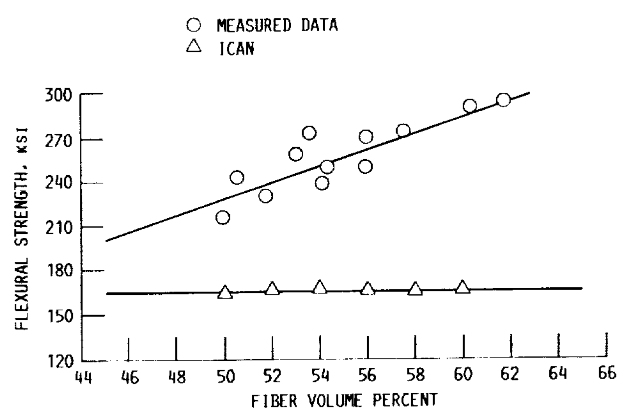

FIGURE 28. - LONGITUDINAL FLEXURAL STRENGTH AS A FUNCTION OF FIBER CONTENT FOR AS/PMR-15 UNIDIRECTIONAL COMPOSITE.

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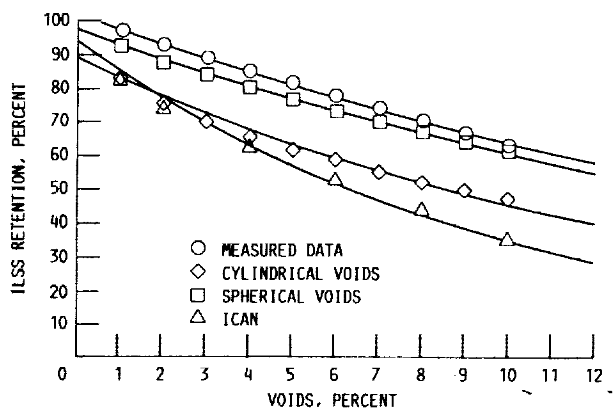

FIGURE 29. - INTERLAMINAR SHEAR STRENGTH AS A FUNCTION OF VOID CONTENT FOR 60 PERCENT FIBER VOLUME FRACTION OF AS/PMR-15 UNIDIRECTIONAL COMPOSITE.

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15. Supplementary Notes

16. Abstract

A computer program called ICAN (Integrated Composite Analyzer) was used to predict the properties of high-temperature polymer matrix composites. ICAN is a collection of NASA Lewis Research Center-developed computer codes designed to carry out analysis of multilayered fiber composites. The material properties used as input to the program were those of the thermoset polyimide resin PMR-15 and the carbon fiber Celion 6000. The sensitivity of the predicted composite properties to variations in the resin and fiber properties was examined. In addition, the predicted results were compared with experimental data. In most cases, the effect of changes in resin and fiber properties on composite properties was reasonable. However, the variations in the composite strengths with the moisture content of the PMR-15 resin were inconsistent. The ICAN-predicted composite moduli agreed fairly well with experimental values, but the predicted composite strengths were generally lower than experimental values.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Matrix; Graphite fiber composite; PMR-15; ICAN; Mechanics; Computer modeling; Strength; Composite properties	Unclassified – Unlimited Subject Category 24

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