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ICAN: A Versatile Code for Predicting Composite Properties

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ICAN: A VERSATILE CODE FOR PREDICTING COMPOSITE PROPERTIES

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SUMMARY

ICAN (Integrated Composites ANalyzer), a stand-alone computer code, incorporates micromechanics equations and laminate theory to analyze/design multilayered fiber composite structures. Procedures for both the implementation of new data in ICAN and the selection of appropriate measured data for comparison are described in detail. ICAN predictions and experimental data are summarized for: (1) composite systems subject to severe thermal environments, (2) woven fabric/cloth composites, and (3) select new composite systems including those made from high strain-to-fracture fibers. The comparisons demonstrate the versatility of ICAN as a reliable method for determining composite properties suitable for preliminary design.

INTRODUCTION

The difficulty in obtaining measured data required to design fiber composite components for aerospace structures is well known in the composites community. It is frequently necessary to base designs on very limited property data.

Recognizing this difficulty, fifteen years of evolutionary research on mechanics of composites has culminated in the stand-alone computer code ICAN (Integrated Composites ANalyzer) (ref. 1). ICAN incorporates micromechanics and macromechanics equations and laminate theory to analyze/design multilayered fiber composite structures.

Input parameters of this user friendly program include: selection of material system, fiber volume ratio, laminate configuration, fabrication factors, and environmental conditions. The ICAN output parameters include practically all composite hygral, thermal and mechanical properties that are needed in order to perform structural/stress analyses in the respective service environments. In this respect ICAN is an effective tool for the preliminary design of fibrous composite structures. ICAN has a resident data bank which houses the properties of a variety of constituent (fiber and matrix) materials with provisions to add new constituent materials as they become available. ICAN thus permits evaluating composites made from these new constituents at an early stage in their development.

To establish confidence in the composite properties predicted by ICAN, comparisons with experimental data are required for existing composite systems as well as new ones in nonhostile or extreme hygrothermal environments.

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Unfortunately, measured data for various properties in hostile and nonhostile environments are scattered in numerous publications including government, industry, and university reports. As a result, a continuing effort at NASA Lewis Research Center is devoted to periodic review of the published literature for measured data to establish additional capability and reliability in the ICAN predictions.

The objective of this paper is to describe procedures for both the implementation of new data in the data bank of ICAN and the selection of appropriate measured data for further comparison and verification. ICAN predictions and experimental data are summarized for composite systems in extreme thermal environments, woven fabric/cloth composites, and new composite systems with high strain-to-fracture fibers. These comparisons are presented to demonstrate the versatility of ICAN as a reliable method for determining a variety of composite properties suitable for preliminary designs.

ICAN: INTEGRATED COMPOSITES ANALYZER

A computer code, ICAN (Integrated Composites ANalyzer), has been developed to analyze/design fiber composite structures. The program includes composite mechanics theories which resulted from extensive research conducted over the past 15 yr at NASA Lewis. ICAN is a synergistic combination of two other NASA Lewis developed codes: MFCA (Multilayered Fiber Composites Analysis) and INHYD (Intraply Hybrid Composite Design).

MFCA (ref. 2) is efficient in predicting the structural response of multilayered fiber composites given the constituent material properties, fabrication process, and composite geometry. INHYD (ref. 3) incorporates several composite micromechanics theories, intraply hybrid composite theories, and a hygrothermomechanical theory to predict the mechanical, thermal, and hygral properties of intraply hybrid composites. ICAN utilizes the micromechanics design of INHYD and the laminate theory of MFCA to build a comprehensive analysis/design capability for structural composites. Features unique to ICAN include: (1) ply stress-strain influence coefficients, (2) microstresses and microstress influence coefficients, (3) stress-concentration factors at a circular hole, (4) predictions of probable delamination locations around a circular hole, (5) Poisson's ratio mismatch details near a straight free edge, (6) free edge stresses, (7) material cards for finite element analysis for NASTRAN (COSMIC and MSC) and MARC, (8) laminate failure stresses based upon first ply failure and fiber fracture criteria, with and without hygrothermal degradation, (9) transverse shear stresses and normal stresses, (10) explicit specification of intraply layers, and (11) delamination of these layers due to adjacent ply relative rotation.

In addition, ICAN possesses another unique feature in its resident data bank which houses the constituent (fiber/matrix) properties. The fiber is entered into the data bank as a four character coded name followed by the physical, elastic, thermal, and strength related properties. Likewise the matrix is entered with a four character coded name with the same properties and an additional card for miscellaneous properties. Years of literature searches and in-house experimental programs on materials characterization have resulted in the compilation of the existing data bank. Designed to be open-ended, the user has the ability to add new constituent materials to the data bank as they appear in the literature.

Input parameters of ICAN include: Selection of material system, fiber volume ratio, laminate configuration, fabrication factors, and environmental and loading conditions. A sample input data set is shown in figure 1 where the parameters are transparent to the user. Also shown, are the properties of the constituents (used in the sample) as they appear in the data bank.

The complete documentation of ICAN with compiled listing, user instructions, programmer's manual and sample cases for each option will be available in the near future (ref. 4). At that time, the program will be made available through COSMIC-Computer Software Management and Information Center, Suite 112, Barrow Hall, Athens, Georgia 30602.

COMPARISON STUDY

Periodic reviews are conducted of government, industry, and university publications to select relevant data for comparison with ICAN predictions. Data are considered to be relevant if (1) they are directly comparable to ICAN output/predictions and (2) sufficient information is provided on the experimental program to ensure adequate modeling with ICAN parameters.

Based upon these criteria, three cases (experimental investigations) have been selected for comparison and discussion herein. Case 1 studies the influence of the space environment on the behavior of various carbon-fiber-reinforced plastics. Case 2 investigates the mechanical properties of a fiberglass woven fabric prepreg system at cryogenic and other temperatures. And case 3 investigates the mechanical properties of materials for space applications. All the cases have two characteristics in common: (1) each deals with a material system which is new to the ICAN resident data bank, and (2) each material system is subject to a hostile environment.

The comparisons and discussion for each case are presented in the following format. First, the purpose of the experimental program is identified. Next, all pertinent information on the experimental procedure, the data generated, and the final results are summarized. Finally, the modeling with ICAN, the ICAN predictions, and comparison results are presented and discussed.

CASE 1: INFLUENCE OF SPACE ENVIRONMENT ON THE BEHAVIOR OF VARIOUS CARBON-FIBER-REINFORCED PLASTICS

The influence of the space environment on the behavior of carbon-fiber-reinforced plastics with ±45° ply orientations was reported by W. Hartung and H.W. Bergmann (ref. 5). They reported that graphite/epoxy and graphite/polyimide composites are prime material candidates for future spacecraft applications due to their low thermal expansion coefficients which keep deformations of structures to a minimum under thermal exposure. However, they were concerned that on a microscopic level thermal stresses of substantial magnitude existed, due to the large difference in the thermal expansion coefficients of the fiber and resin, when exposed to the alternating sun/shade cycles which occur in space. They designed an experimental program to assess the effects of severe thermal cycling on mechanical properties of various carbon fiber composites. Emphasis was placed on comparing the initial and residual material properties. The effects of thermal cycling were evaluated by nondestructive methods.

Table I contains a survey of the materials which were thermally cycled. Note that each material system was cured at a different temperature. The volume fraction of fibers is 0.60 and is equal in all materials. The specimens were preconditioned to minimize moisture. The laminate configuration is $[\pm45_2]s$ and is 1 mm (0.0393 in.) in total thickness. The specimens were cycled in a simulated space environment ranging from -155 °C (-247 °F) (shaded structure) to 95 °C (203 °F) (sunlit structure). Additional details on the experimental procedure itself can be found in reference 5.

The laminate mechanical properties are matrix-controlled due to the ±45° ply configuration. Therefore, Hartung and Bergmann expected to view damage such as matrix cracking and delamination as a result of the thermal cycling. They employed three nondestructive techniques to assess the damage: ultrasonic inspection to detect delamination, radiographs to detect matrix cracks, and electron beam micrographs to detect microcracks. Damage was detected by comparing specimen scans before and after cycling.

The epoxy-based composites did not delaminate; however, the polyimide laminates did exhibit delamination. Hartung and Bergmann expected to see matrix cracking since earlier calculations based on lamination theory had indicated severe matrix cracking. Radiographs did not reveal any matrix cracks in the epoxy-based laminates. Once again damage was observed in the polyimide laminate in the form of matrix cracks. The scanning electron micrographs of epoxy-based laminates did reveal microcracks; however, the researchers felt that the limited field of vision of the microscope made it difficult to establish reliable correlations.

Based on these results they concluded that, contrary to predictions, only minor cracking existed in the epoxy-based laminates as a result of the thermal cycling and that severe cracking and delaminations occurred in the polyimide-based laminates.

The detailed account on the specimens and procedures provided by Hartung and Bergmann allowed their experiments to be simulated analytically. From their data the following input parameters for ICAN are established: (1) The laminates consist of eight plies, each being 0.125 mm (0.005 in.) thick, in a $[\pm45_2]s$ configuration, (2) the fiber volume ratio is 0.60, (3) the moisture content is zero percent and (4) no external loads are applied. Many of the trade-mark materials used in the experimental program are not included, as such, in the resident data bank. Therefore, the material systems used for the comparable ICAN analysis (table II) were estimated using existing constituent materials in the data bank. Note that the resin of material No. 3 in table I is identified as an unmodified epoxy. As a result, two separate resins were selected to model this material in ICAN and are designated 3A and 3B in table II.

Two temperatures are required by ICAN for the analysis: (1) T_u which is a use or test temperature and (2) T_c which is the cure temperature. ICAN calculates the thermal differential and predicts the residual stresses. Since ICAN does not have cyclic capability each material is analyzed four times with the given thermal conditions: (1) $T_u = T_c$ = 21 °C (70 °F) which establishes a reference, (2) T_u = 21 °C (70 °F) and T_c = cure temperature (dependent upon the selected material) which predicts the residual stresses due to the curing process, (3) T_u = -155 °C (-247 °F) and T_c = variable, which simulates the shaded portion of the space cycle, and (4) T_u = 95 °C (203 °F) and T_c = variable, which simulates the sunlit portion of the cycle.

Tables III and IV list ICAN predictions of the ply transverse tensile strength and ply transverse residual stresses, respectively. In comparing the data from the two tables, the magnitudes of the residual stresses produced by the various thermal conditions are small with respect to the ply strengths. Therefore, little or no damage (in the form of matrix cracks) should occur in the laminate as a result of the thermal environment. Although not shown here, a review of the intraply delamination criterion used in ICAN indicates that the epoxy-based laminates did not delaminate. Also, a comparison between the predicted microstresses and the resin's tensile strength reveals that microcracking does not occur in the matrix. Therefore, according to ICAN predictions, the laminates should experience only minimal damage due to these thermal conditions. This is reflected in table V where the predicted failure stresses are shown with respect to the thermal environments. It can be seen from the data that there is no degradation in strength (compared to reference) as a result of the extreme thermal conditions. These conclusions, based upon ICAN predictions, apply only to the epoxy-based composites. The ICAN analysis of the polyimide-based composite required additional effort. To model the interfacial conditions which may be characteristic of polyimides, the input parameter "void percentage" was used. The polyimide was analyzed with 0, 2, and 5-percent voids at all temperatures. ICAN predicted that a polyimide without voids would experience some microcracking and transply cracking since the magnitudes of the ply residual stresses were approaching those of the ply transverse strengths (about 90 percent). For those polyimides with 2 and 5 percent voids, severe microcracking and transply cracking were predicted. In fact, at cryogenic temperatures, ICAN predicted that these two laminates failed due to transply cracking.

In summary, conclusions based upon ICAN predictions are in agreement with those from the experimental program. Based upon a "generalized" predictive equation for the durability/life of a graphite-fiber/epoxy-matrix composite (ref. 6), the number of fatigue cycles to fracture for the given material systems is found to be very high at both -155 °C (-247 °F) and 95 °C (203 °F). On the average 5.7×10^7 cycles and 6.6×10^8 cycles were calculated for the lower and higher temperatures, respectively. Since the majority of specimens in the study are nondestructively evaluated after only 1170 cycles, it is not surprising that damage (matrix cracks, delaminations, and microcracking) was not observed. In comparison, the polyimide-based composite is expected to have a short life due to the high residual stresses which were predicted. Therefore, after 1170 cycles, extensive damage should exist.

CASE 2: MECHANICAL PROPERTIES OF A FIBERGLASS WOVEN FABRIC PREPREG SYSTEM AT CRYOGENIC AND OTHER TEMPERATURES

Klich and Cockrell (ref. 7) reported on the mechanical properties of a fiberglass woven fabric prepreg system at cryogenic and other temperatures. This was in support of a program to fabricate fan blades for a new cryogenic wind tunnel using an E-glass cloth preimpregnated with an epoxy resin. Because of the limited data available on E-glass at cryogenic temperatures, a comprehensive testing program was undertaken to develop a data base.

Tests were conducted on three material systems which completely characterized their strength and elastic properties. The material systems were: (1) 7781 E-glass cloth with EF-2 resin, (2) 7576 E-glass cloth with EF-2 resin, and (3) a representative laminate which was a combination of the two glass cloths and which represented the construction of the fan blade.

The 7781 E-glass cloth had a ratio of 60 fibers in the warp direction and 54 fibers in the fill direction. The laminate consisted of 14 plies and each ply was 0.216 mm (0.0085 in.) thick. The 7576 E-glass laminate consisted of 11 plies where each ply was 0.279 mm (0.011 in.) thick, with a ratio of 120 and 24 fibers in the warp and fill directions, respectively. The representative laminate consisted of 19 plies in the configuration [A/B/D/C/A/D/C/B_2/A/B_2/C/D/A/C/D/B/A] where A = 7576 at 0° ply, B = 7781 at 0° ply, C = 7781 at +30° ply and D = 7781 at -30° ply. Total thickness for the representative laminate was 4.6 mm (0.181 in.). The laminates were cured at 171 °C (340 °F) and the tensile specimens were tested at -185 °C (-300 °F), 21 °C (70 °F), and 93 °C (200 °F).

Trends in their experimental data (to be discussed later) indicate that as temperature decreases, both strength and modulus increase. Another observation is that the strength of the representative laminate is greater in magnitude than the 7781 E-glass cloth but less than the 7576 E-glass cloth.

Once again, based upon the information provided in reference 7, the ICAN input parameters are readily defined. Figure 2 shows the constituent materials selected for the analysis and their properties as they appear reproduced from the data bank in the output. The code name, EGLA, refers to an E-glass fiber and is used to simulate the 7781 and 7576 E-glass in the cloths. The code name, EPOC, refers to an epoxy resin and is selected to represent the EF-2 resin. Other parameters include: (1) Fiber volume ratio (FVR) = 0.60, (2) T_c = 171 °C (340 °F), and (3) T_u = -185 °C (-300 °F), 21 °C (70 °F), and 93 °C (200 °F).

ICAN was designed to analyze aligned continuous fiber ply composites; therefore, a technique was developed to simulate a woven fabric (cloth) using the existing parameters in the input data set. The technique involves manipulation of the plies and fiber volume ratios. Each cloth ply is modeled as two plies in ICAN. One ply is oriented in the 0° direction analogous to the warp direction and the second ply is oriented in the 90° direction corresponding to the fill direction. The thickness (t) of each ICAN ply is equal to a percentage of the total cloth ply thickness as shown in the following equations:

$$t_{0^\circ\ \text{ply}} = t_{\text{cloth ply}} \times \left(\frac{\text{fibers in warp direction}}{\text{total fibers in cloth ply}}\right) \tag{1a}$$

and

$$t_{90^\circ\ \text{ply}} = t_{\text{cloth ply}} \times \left(\frac{\text{fibers in fill direction}}{\text{total fibers in cloth ply}}\right) \tag{1b}$$

The thickness of these two ICAN plies equals the thickness of one cloth ply. The FVR is altered in a similar manner. Two material systems corresponding to the 0° and 90° plies are used in ICAN to model the cloth. Each ICAN material system has a different FVR which is a percentage of the given FVR, 0.60 and is determined by the following equations:

$$FVR_{0^\circ\ ply} = FVR_{cloth} \left(\frac{\text{fibers in warp direction}}{\text{largest amount of fibers in any direction}} \right) \tag{2a}$$

and

$$FVR_{90^\circ\ ply} = FVR_{cloth} \left(\frac{\text{fibers in fill direction}}{\text{largest amount of fibers in any direction}} \right) \tag{2b}$$

Although this procedure to model a woven fabric/cloth for ICAN appears a little complicated, it is, in fact, quite easy to implement.

Figure 3 displays the input data for an ICAN run which simulates the 7781 E-glass cloth. There are 28 ICAN plies to model the 14 cloth plies. The data are read in pairs of plies accordingly: ply 1 corresponds to the warp (0°) direction and is 0.114 mm (0.0045 in.) thick from equation (1a) (0.216 mm (0.0085 in.) x (60/(60 + 54))) with a FVR of 0.60 from equation (2a) (0.6 x (60/60)); ply 2 corresponds to the fill (90°) direction and is 0.102 mm (0.004 in.) thick from equation (1b) (0.216 mm (0.0085 in.) x (54/(60 + 54))) with a FVR of 0.54 from equation (2b) (0.6 x (54/60)). The data related to a pair of ICAN plies simulate one cloth ply. The data listed in 28 ICAN plies are the simulation of the 7781 E-glass cloth laminate. The 7576 E-glass cloth is modeled using the same technique and the input data for ICAN are shown in figure 4.

The representative laminate is modeled in the same manner. Recall from the initial data provided that plies designated C and D in the laminate configuration are oriented +30° and -30°, respectively. This ply orientation is accounted for in the input data in figure 5. An ICAN ply which originally is oriented in the warp direction (0°) will reflect the new laminate configuration in either +30° or -30° directions. Likewise, an ICAN ply which originally is oriented in the fill direction (90°) will reflect the ±30 configuration with a 120° or 60° orientation, respectively.

Results from the experimental program and ICAN analysis are compared in tables VI and VII. The elastic modulus for all three material systems is shown in table VI. Similar to previous observations made from the experimental data, the modulus predicted by ICAN does increase with decreasing temperature. The predicted values for the 7781 E-glass cloth and the representative laminate are in good agreement with the experimental data in all temperature ranges. In comparison, the correlations of the moduli of the 7576 E-glass cloth are fair. This suggests that the constituent properties of the EGLA fiber used in ICAN do not adequately reflect the properties of the 7576 E-glass used in the cloth. Nonetheless, for preliminary design purposes, the results are acceptable.

Table VII shows the longitudinal tensile strengths of the glass cloth materials, both experimentally determined and analytically predicted. ICAN strength predictions based upon first ply failure and fiber failure establish a lower and upper bound, respectively, between which the experimental data fall. ICAN analyses show that the lower bound corresponds to the strength at which all plies in the fill (90°) direction fail. Likewise, the upper bound corresponds to the strength at which all fibers fail in the 0°-ply or warp direction. The out-of-plane angles of the woven fabric which exist in the warp (0°) direction are not accounted for in the ICAN model since the program bases its analysis upon continuous straight fibers. As a result, the strengths predicted by ICAN based upon fiber failure are optimistic.

In the cryogenic environment, the experimental data tend toward the upper bounds. At this low temperature, matrix damage is inhibited and laminate failure is most likely to occur as a result of fiber failure in the warp (0°) direction. At room and high temperatures, the experimental data tend toward the lower bounds. Given these thermal conditions, the resulting residual stresses induce matrix damage which causes ply failure in the fill (90°) direction.

In summary, very little effort and time was required to model the three E-glass cloth material systems. The versatility of ICAN is demonstrated in its ability to model woven fabrics using continuous straight fiber plies with relative ease. The comparison of data demonstrates ICAN as an effective means for estimating properties of woven fabrics.

CASE 3: MECHANICAL PROPERTIES OF NEW MATERIALS FOR SPACE APPLICATIONS

Lewis is currently conducting studies associated with several existing space programs. One of these programs is the Advanced Communications Technology Satellite (ACTS) scheduled for launch in 1989. The current ACTS design incorporates five antennae in the form of two main reflectors and three subreflectors. The design criteria for the antennae include near-zero thermal expansion coefficients, since relatively small thermal expansions can produce significant distortion in the transmitted beam. As a result, sandwich structures consisting of composite face sheets and a honeycomb core are chosen for antenna reflectors since the face sheets can be selected to have nearly zero thermal expansion coefficients.

Even though the ACTS is being developed under contract, NASA Lewis is conducting in-house research both experimentally and analytically in support of the project. Bowles and Vannucci (ref. 8) of the Materials Division are conducting an experimental program to assess the properties of new high modulus fibers which will be used as candidate materials for the antenna face sheets. They are conducting material characterization studies of two high-modulus-fiber prepreg systems at room temperature and at -157 °C (-250 °F) and 121°C (250°F) which correspond, respectively, to the shaded and sunlit regions of the orbit.

Simultaneously, the authors of this paper are conducting an analytical program to generate these composite properties using ICAN. The high modulus fibers and the resin system being used were not in the data bank. Therefore, a search was conducted for existing constituent properties. Table VIII lists typical properties provided by the material supplier for the Thornel carbon giber P-75S 2K and Thornel graphite fiber P-100 2K. Data were also available on some neat resin properties for a 934 resin system.

The coded names P-75 and P 100 were created for the Thornel carbon fiber and Thornel graphite fiber, respectively. The constituent properties provided by the material supplier are listed in the data bank (fig. 6) and all other data were supplemented by an existing high modulus fiber. Likewise a matrix, R934, was created with the available neat resin properties supplemented with others from an existing intermediate-modulus, high strength resin (fig. 7).

With the new materials incorporated into the ICAN data bank, analyses were performed on P-75/R934 and P 100/R934 laminates in various configurations ($[0]_{20}$, [0/90]s and [0/±60]s) with room temperature dry conditions and FVR = 0.60. In addition a P-75/R934 $[0]_8$ laminate was analyzed with ICAN using the specified temperatures and a cure temperature of 177 °C (350 °F). These ICAN input data sets were specifically tailored so that a direct comparison could be made to the limited experimental data which were available.

Table IX lists select properties for the P-75/R934 laminate at room temperature. The ICAN predictions are in very good agreement with the experimental data for all three laminate configurations. In table X, results of the 3-point bend and short beam shear tests conducted at various temperatures are shown with a deviation for the experimental data. ICAN predictions compare well and are acceptable for preliminary design purposes.

SUMMARY AND CONCLUSIONS

ICAN, a stand-alone computer code, was developed to analyze/design multilayered fiber composite structures using micromechanics equations and laminate theory. To establish confidence in the predictive capabilities of ICAN, three sets of experimental data were selected for comparison and verification. ICAN predictions and measured data were summarized for each case: (1) composite systems subject to severe thermal environments, (2) woven fabric/cloth composites at cryogenic and other temperatures, and (3) new materials for space applications. The comparison studies revealed several unique features of ICAN: (1) input parameters are readily established provided sufficient information is available on the experimental procedure and specimen preparation, (2) properties of new fibers and resins can be created for the data bank as they appear on the market, and (3) user and computational time required to generate ICAN predictions is trivial in comparison to the effort required for the experimental programs discussed.

The versatility of ICAN is demonstrated by its ability to analyze woven fabric/cloth composites and new material systems in hostile environments. The effectiveness of ICAN is established by the correlation which exists between the predicted properties and the measured data. Thus ICAN is verified as an effective tool for the preliminary design of composite structures.

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TABLE I. - SURVEY OF MATERIALS

Material designation[a]	ICAN designation	Type of fiber	Type of resin	Cure temperature	
				°C	°F
914C-TS-5	1	High-tenacity Toray T300	CIBA 914	190	374
HY-E-1548A1B	2	High-modulus Celion GY-70	Fiberite 948 A1	120	248
LY556/HY917/ XB2692/T300	3	High-tenacity Toray T300-6000	Unmodified epoxy	140	284
HY-E 2034D	4	High-modulus Thornel pitch	Fiberite 934	180	356
T6T F178	5	High-tenacity Union Carbide T300-3000	Hexcel F178 (polyimide)	210	410
T6T 262-12F 550	6	High-tenacity Union Carbide T300-6000	Hexcel F550	120	248

[a]From Ref. 5; volume fractions of fibers and resins are equal in all materials.

TABLE II. - ICAN MATERIAL DESCRIPTIONS

Material designation	Fiber/matrix	Cure temperature	
		°C	°F
1	T300/HMHS[a]	190	374
2	P-70[b]/HMHS[a]	120	248
3A	T300/HMHS	140	284
3B	T300/IMHS[c]	140	284
4	P-75[d]/R934	180	356
5	T300/POLY[e]	210	410
6[f]	T300/HMHS[a]	120	248

[a]High modulus/high strength.
[b]High modulus graphite fibers possessing a modulus of 70 mpsi.
[c]Intermediate modulus/high strength.
[d]High modulus graphite fibers possessing a modulus of 75 mpsi.
[e]Polyimide resin.
[f]4-ply configuration.

TABLE III. - PLY TRANSVERSE TENSILE STRENGTH PREDICTED BY ICAN

Laminate designation	Thermal environment; T_u/T_c[a]					
	21 °C (70 °F)/variable		-155 °C (-247 °F)/variable		95 °C (203 °F)/variable	
	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi
1	97	14	193	28	110	16
2	131	19	193	28	110	16
3A	97	14	193	28	110	16
3B	69	10	145	21	83	12
4	41	6	69	10	34	5
6	97	14	186	27	110	16

[a]T_u = use temperature; T_c = cure temperature (material dependent).

TABLE IV. - PLY TRANSVERSE RESIDUAL STRESSES PREDICTED BY ICAN

Laminate designation	Thermal environment; T_u/T_c[a]					
	21 °C (70 °F)/variable		-155 °C (-247 °F)/variable		95 °C (203 °F)/variable	
	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi
1	45	6.5	82	11.9	26	4.0
2	17	2.5	41	6.0	5	0.71
3A	32	4.6	70	10.1	13	1.9
3B	25	3.6	57	8.3	10	1.4
4	24	3.5	44	6.4	14	2.1
6	26	3.8	66	9.5	7	1.0

[a]T_u = use temperature; T_c = cure temperature (material dependent).

TABLE V. - TRANSVERSE FAILURE STRESS FOR VARIOUS THERMAL CONDITIONS PREDICTED BY ICAN

[Epoxy-based laminates.]

Laminate Designation	Thermal environment; T_u/T_c[a]							
	Base 21 °C (70 °F)/21 °C (70 °F)		Residual 21 °C (70 °F)/variable		Low-shade -155 °C (-247 °F)/variable		High-sun 95 °C (203 °F)/variable	
	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi
1	165	24	165	24	283	41	165	24
2	172	25	172	25	283	41	165	24
3A	165	24	165	24	283	41	165	24
3B	131	19	131	19	248	36	138	20
4	55	8	55	8	97	14	55	8
6	165	24	165	24	283	41	165	24

[a]T_u = use temperature; T_c = cure temperature (material dependent).

TABLE VI. - LONGITUDINAL ELASTIC MODULUS OF E-GLASS CLOTHS AT DIFFERENT TEMPERATURES LANGLEY EXPERIMENTAL VERSUS ICAN PREDICTIONS

Laminate material	Experimental						ICAN predictions					
	-184 °C/-300 °F		21 °C/70 °F		93 °C/200 °F		-184 °C/-300 °F		21 °C/70 °F		93 °C/200 °F	
	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi
7781 E-glass cloth	31717	4600	30131	4370	27373	3970	31641	4589	29311	4251	28104	4076
7576 E-glass cloth	45093	6540	41508	6020	41715	6050	38522	5587	37199	5395	37626	5457
Representative	36681	5320	30131	4370	28614	4150	30614	4440	28366	4114	27221	3948

TABLE VII. - LONGITUDINAL TENSILE STRENGTH OF E-GLASS CLOTHS AT DIFFERENT TEMPERATURES
LANGLEY EXPERIMENTAL VERSUS ICAN PREDICTIONS

Laminate material	Experimental						ICAN predictions[a]		
	-184 °C/-300 °F		21 °C/70 °F		93 °C/200 °F		-184 °C/-300 °F	21 °C/70 °F	93 °C/200 °F
	N/mm^2	ksi	N/mm^2	ksi	N/mm^2	ksi	N/mm^2 / ksi	N/mm^2 / ksi	N/mm^2 / ksi
7781 E-glass cloth	717	104	393	57	338	49	290/1027 / 42/149	159/938 / 23/136	234/896 / 34/130
7576 E-glass cloth	1110	161	731	106	738	107	772/1276 / 112/185	772/1241 / 112/180	738/1227 / 107/178
Representative	876	127	455	66	414	60	296/1096 / 43/159	165/945 / 24/137	241/903 / 35/131

[a]First ply failure/fiber failure.

TABLE VIII. - SELECT CONSTITUENT PROPERTIES FROM MATERIAL
SUPPLIER DATA SHEETS

Property	Carbon fiber, P-75S 2K	Graphite fiber, P-100 2K
Tensile strength, GPa (ksi)	2.1 (300)	2.2 (325)
Tensile modulus, GPa (mpsi)	520 (75)	724 (105)
Density, mg/m^3 (lb/in.^{3})	2.0 (0.072)	2.15 (0.078)
Filament diameter, μm (μ)	10 (10)	10 (10)
Longitudinal thermal conductivity, W/m-K (Btu-ft/(hr-ft^2-°F))	155 (90)	520 (300)
Longitudinal CTE at 21 °C (70 °F), ppm/K (ppm/°F)	-1.3 (-0.7)	-1.6 (-0.9)

TABLE IX. - SELECT ROOM TEMPERATURE MATERIAL PROPERTIES FOR P-75/R934 LAMINATES LEWIS EXPERIMENTAL VERSUS ICAN PREDICTIONS

Material properties	Laminate configuration					
	$[0]_8$		$[0/90]_s$		$[0/\pm 60]_s$	
	Experimental	ICAN	Experimental	ICAN	Experimental	ICAN
Failure stress N/mm^2, (ksi)	862(125)	938(136)	414(60)	476(69)	331(48)	324(47)
Failure strain mm/mm (in./in.)	0.0031	0.0030	0.0028	0.0030	0.0031	0.0030
Elastic modulus, GPa (mpsi)	284(41.2)	311(45.2)	152(22.0)	158(23.0)	109(15.8)	109(15.8)
Poisson's ratio	0.300	0.260	0.040	0.009	0.309	0.320

TABLE X. - UNIDIRECTIONAL P-75/R934 LAMINATE STRENGTHS LEWIS EXPERIMENTAL VERSUS ICAN PREDICTED

Test method temperature	Experimental		ICAN	
	N/mm^2	ksi	N/mm^2	ksi
3-point bend				
-157 °C (-250 °F)	689$\pm$9.9	100$\pm$1.4	721	104.6
21 °C (70 °F)	779$\pm$35	113$\pm$5.1	719	104.4
121 °C (250 °F)	633$\pm$24	92$\pm$3.5	718	104.2
Short beam shear				
-157 °C (-250 °F)	50$\pm$7.3	7.3$\pm$1.1	73	10.6
21 °C (70 °F)	52$\pm$7.0	7.5$\pm$1.0	40	5.9
121 °C (250 °F)	53$\pm$2.8	7.7$\pm$0.4	34	4.9

```
FOUR PLY SYMMETRIC LAMINATE. ICAN SAMPLE INPUT DATA.
  STDATA        4         1         2
     T                                              COMSAT
     F                                              CSANB
     F                                              BIDE
     F                                              RINDV
     T                                              NONUDF
     PLY        1         1  70.00   350.0     1.8         0.0   .010
     PLY        2         2  70.00   350.0     1.8        90.0   .005
     PLY        3         2  70.00   350.0     1.8        90.0   .005
     PLY        4         1  70.00   350.0     1.8         0.0   .010
  MATCRDAS--IMLS   .55      .02   AS--IMLS   0.0      .57       .03
  MATCRDSGLAHMHS   .55      .01   AS--IMHS   0.4      .57       .01
   PLOAD 1000.     0.0      0.0      0.0             NX,NY,NXY,THCS
   PLOAD  0.0      0.0      0.0                      MX,MY,MXY
   PLOAD  0.0      0.0                               DMX/QX,DMY/QY,PRSS
  OPTION        0
```

INPUT DATA SET

```
      AS--   GRAPHITE FIBER.
      FP   10000 0.300E-03 0.630E-01
      FE   0.310E 08 0.200E 07 0.200E 00 0.250E 00 0.200E 07 0.100E 07
      FT  -0.550E-06 0.560E-05 0.580E 03 0.580E 02 0.170E 00
      FS   0.400E 06 0.400E 06     0.000     0.000     0.000     0.000

      SGLA    S- GLASS FIBER.
      FP     204 0.360E-03 0.900E-01
      FE   0.124E 08 0.124E 08 0.200E 00 0.200E 00 0.517E 07 0.517E 07
      FT   0.280E-05 0.280E-05 0.750E 01 0.750E 01 0.170E 00
      FS   0.360E 06 0.300E 06 0.360E 06 0.300E 06 0.180E 06 0.180E 06

IMLS  INTERMEDIATE MODULUS LOW STRENGTH MATRIX.
MP   0.460E-01
ME   0.500E 06 0.410E 00 0.570E-04
MT   0.125E 01 0.250E 00
MS   0.700E 04 0.210E 05 0.700E 04 0.140E-01 0.420E-01 0.320E-01 0.320E-01
MV   0.225E 00 0.420E 03

HMHS  HIGH MODULUS HIGH STRENGTH MATRIX.
MP   0.450E-01
ME   0.750E 06 0.350E 00 0.400E-04
MT   0.125E 01 0.250E 00
MS   0.200E 05 0.500E 05 0.150E 05 0.200E-01 0.500E-01 0.400E-01 0.400E-01
MV   0.225E 00 0.420E 03

IMHS  INTERMEDIATE MODULUS HIGH STRENGTH MATRIX.
MP   0.440E-01
ME   0.500E 06 0.350E 00 0.360E-04
MT   0.125E 01 0.250E 00
MS   0.150E 05 0.350E 05 0.130E 05 0.200E-01 0.500E-01 0.350E-01 0.350E-01
MV   0.225E 00 0.420E 03
```

RESIDENT DATA BANK ECHO

Figure 1. - Samples of the input data set and the constituent properties in the data bank.

```
--> CONSTITUENT PROPERTIES: ECHO FROM DATA BANK. <--

 PRIMARY FIBER PROPERTIES;     EGLA   FIBER

        1      ELASTIC MODULI           EFP1       0.1050E 08
        2                               EFP2       0.1050E 08
        3      SHEAR MODULI             GFP12      0.4370E 07
        4                               GFP23      0.4370E 07
        5      POISSON'S RATIO          NUFP12     0.2000E 00
        6                               NUFP23     0.2000E 00
        7      THERM. EXP. COEF.        CTEFP1     0.2800E-05
        8                               CTEFP2     0.2800E-05
        9      DENSITY                  RHOFP      0.9000E-01
       10      NO. OF FIBERS/END        NFP        0.2040E 03
       11      FIBER DIAMETER           DIFP       0.3600E-03
       12      HEAT CAPACITY            CFPC       0.1700E 00
       13      HEAT CONDUCTIVITY        KFP1       0.7500E 01
       14                               KFP2       0.7500E 01
       15                               KFP3       0.7500E 01
       16      STRENGTHS                SFPT       0.3600E 06
       17                               SFPC       0.3600E 06

 PRIMARY MATRIX PROPERTIES;      EPOC  MATRIX.  DRY RT. PROPERTIES.

        1      ELASTIC MODULUS          EMP        0.5000E 06
        2      SHEAR MODULUS            GMP        0.1852E 06
        3      POISSON'S RATIO          NUMP       0.3500E 00
        4      THERM. EXP. COEF.        CTEMP      0.3600E-05
        5      DENSITY                  RHOMP      0.4400E-01
        6      HEAT CAPACITY            CMPC       0.2500E 00
        7      HEAT CONDUCTIVITY        KMP        0.1700E 01
        8      STRENGTHS                SMPT       0.1500E 05
        9                               SMPC       0.2500E 05
       10                               SMPS       0.1300E 05
       11      MOISTURE COEF            BTAMP      0.4000E-02
       12      DIFFUSIVITY              DIFMP      0.2000E-03
```

Figure 2. - Constituent materials and properties used in ICAN to simulate woven fabric fiberglass composites.

```
                 I C A N
        I N P U T  D A T A  E C H O

THIS IS A 7781/EPOC SPECIMEN.
 STDATA      28         1         2
    T
    F
    F
    F
    T
    PLY       1         1     70.0     340.0     0.0      0.0  0.00450
    PLY       2         2     70.0     340.0     0.0     90.0  0.00400
    PLY       3         1     70.0     340.0     0.0      0.0  0.00450
    PLY       4         2     70.0     340.0     0.0     90.0  0.00400
    PLY       5         1     70.0     340.0     0.0      0.0  0.00450
    PLY       6         2     70.0     340.0     0.0     90.0  0.00400
    PLY       7         1     70.0     340.0     0.0      0.0  0.00450
    PLY       8         2     70.0     340.0     0.0     90.0  0.00400
    PLY       9         1     70.0     340.0     0.0      0.0  0.00450
    PLY      10         2     70.0     340.0     0.0     90.0  0.00400
    PLY      11         1     70.0     340.0     0.0      0.0  0.00450
    PLY      12         2     70.0     340.0     0.0     90.0  0.00400
    PLY      13         1     70.0     340.0     0.0      0.0  0.00450
    PLY      14         2     70.0     340.0     0.0     90.0  0.00400
    PLY      15         1     70.0     340.0     0.0      0.0  0.00450
    PLY      16         2     70.0     340.0     0.0     90.0  0.00400
    PLY      17         1     70.0     340.0     0.0      0.0  0.00450
    PLY      18         2     70.0     340.0     0.0     90.0  0.00400
    PLY      19         1     70.0     340.0     0.0      0.0  0.00450
    PLY      20         2     70.0     340.0     0.0     90.0  0.00400
    PLY      21         1     70.0     340.0     0.0      0.0  0.00450
    PLY      22         2     70.0     340.0     0.0     90.0  0.00400
    PLY      23         1     70.0     340.0     0.0      0.0  0.00450
    PLY      24         2     70.0     340.0     0.0     90.0  0.00400
    PLY      25         1     70.0     340.0     0.0      0.0  0.00450
    PLY      26         2     70.0     340.0     0.0     90.0  0.00400
    PLY      27         1     70.0     340.0     0.0      0.0  0.00450
    PLY      28         2     70.0     340.0     0.0     90.0  0.00400
 MATCRDEGLAEPOC       0.6      0.0EGLAEPOC  0.0
 MATCRDEGLAEPUC      0.54      0.0EGLAEPUC  0.0
  PLOAD      0.0      0.0      0.0      0.0
  PLOAD      0.0      0.0      0.0
  PLOAD      0.0      0.0
```

Figure 3. - Sample input data set simulating the 7781 E-Glass cloth laminate.

```
                 I C A N
        I N P U T  D A T A  E C H O

THIS IS A EGLA/EPOC SPECIMEN.
 STDATA      22         1         2
    T
    F
    F
    F
    T
    PLY       1         1     70.0     340.0     0.0      0.0  0.0090
    PLY       2         2     70.0     340.0     0.0     90.0  0.0020
    PLY       3         1     70.0     340.0     0.0      0.0  0.0090
    PLY       4         2     70.0     340.0     0.0     90.0  0.0020
    PLY       5         1     70.0     340.0     0.0      0.0  0.0090
    PLY       6         2     70.0     340.0     0.0     90.0  0.0020
    PLY       7         1     70.0     340.0     0.0      0.0  0.0090
    PLY       8         2     70.0     340.0     0.0     90.0  0.0020
    PLY       9         1     70.0     340.0     0.0      0.0  0.0090
    PLY      10         2     70.0     340.0     0.0     90.0  0.0020
    PLY      11         1     70.0     340.0     0.0      0.0  0.0090
    PLY      12         2     70.0     340.0     0.0     90.0  0.0020
    PLY      13         1     70.0     340.0     0.0      0.0  0.0090
    PLY      14         2     70.0     340.0     0.0     90.0  0.0020
    PLY      15         1     70.0     340.0     0.0      0.0  0.0090
    PLY      16         2     70.0     340.0     0.0     90.0  0.0020
    PLY      17         1     70.0     340.0     0.0      0.0  0.0090
    PLY      18         2     70.0     340.0     0.0     90.0  0.0020
    PLY      19         1     70.0     340.0     0.0      0.0  0.0090
    PLY      20         2     70.0     340.0     0.0     90.0  0.0020
    PLY      21         1     70.0     340.0     0.0      0.0  0.0090
    PLY      22         2     70.0     340.0     0.0     90.0  0.0020
 MATCRDEGLAEPOC       .60      0.0EGLAEPOC  0.0
 MATCRDEGLAEPOC       .12      0.0EGLAEPOC  0.0
  PLOAD      0.0      0.0      0.0      0.0
  PLOAD      0.0      0.0      0.0
  PLOAD      0.0      0.0
```

Figure 4. - Sample input data set simulating the 7576 E-Glass cloth laminate.

```
            I C A N
      I N P U T  D A T A  E C H O

THIS IS A EGLA/EPOC SPECIMEN.
 STDATA      38        1        4
    T
    F
    F
    F
    T
    PLY       1        1     70.0     340.0       0.0       0.0   0.009
    PLY       2        2     70.0     340.0       0.0      90.0   0.002
    PLY       3        3     70.0     340.0       0.0       0.0   0.0045
    PLY       4        4     70.0     340.0       0.0      90.0   0.004
    PLY       5        3     70.0     340.0       0.0     -30.0   0.0045
    PLY       6        4     70.0     340.0       0.0      60.0   0.004
    PLY       7        3     70.0     340.0       0.0      30.0   0.0045
    PLY       8        4     70.0     340.0       0.0     120.0   0.004
    PLY       9        1     70.0     340.0       0.0       0.0   0.009
    PLY      10        2     70.0     340.0       0.0      90.0   0.002
    PLY      11        3     70.0     340.0       0.0     -30.0   0.0045
    PLY      12        4     70.0     340.0       0.0      60.0   0.004
    PLY      13        3     70.0     340.0       0.0      30.0   0.0045
    PLY      14        4     70.0     340.0       0.0     120.0   0.004
    PLY      15        3     70.0     340.0       0.0       0.0   0.0045
    PLY      16        4     70.0     340.0       0.0      90.0   0.004
    PLY      17        3     70.0     340.0       0.0       0.0   0.0045
    PLY      18        4     70.0     340.0       0.0      90.0   0.004
    PLY      19        1     70.0     340.0       0.0       0.0   0.009
    PLY      20        2     70.0     340.0       0.0      90.0   0.002
    PLY      21        3     70.0     340.0       0.0       0.0   0.0045
    PLY      22        4     70.0     340.0       0.0      90.0   0.004
    PLY      23        3     70.0     340.0       0.0       0.0   0.0045
    PLY      24        4     70.0     340.0       0.0      90.0   0.004
    PLY      25        3     70.0     340.0       0.0      30.0   0.0045
    PLY      26        4     70.0     340.0       0.0     120.0   0.004
    PLY      27        3     70.0     340.0       0.0     -30.0   0.0045
    PLY      28        4     70.0     340.0       0.0      60.0   0.004
    PLY      29        1     70.0     340.0       0.0       0.0   0.009
    PLY      30        2     70.0     340.0       0.0      90.0   0.002
    PLY      31        3     70.0     340.0       0.0      30.0   0.0045
    PLY      32        4     70.0     340.0       0.0     120.0   0.004
    PLY      33        3     70.0     340.0       0.0     -30.0   0.0045
    PLY      34        4     70.0     340.0       0.0      60.0   0.004
    PLY      35        3     70.0     340.0       0.0       0.0   0.0045
    PLY      36        4     70.0     340.0       0.0      90.0   0.004
    PLY      37        1     70.0     340.0       0.0       0.0   0.009
    PLY      38        2     70.0     340.0       0.0      90.0   0.002
 MATCRDEGLAEPOC      0.6       0.0EGLAEPOC    0.0
 MATCRDEGLAEPOC     0.12       0.0EGLAEPOC    0.0
 MATCRDEGLAEPOC      0.6       0.0EGLAEPOC    0.0
 MATCRDEGLAEPOC     0.54       0.0EGLAEPOC    0.0
   PLOAD     0.0       0.0     0.0       0.0
   PLOAD     0.0       0.0     0.0
   PLOAD     0.0       0.0
```

Figure 5. - Sample input data set for the glass cloth representative laminate.

--> CONSTITUENT PROPERTIES: ECHO FROM DATA BANK. <--

PRIMARY FIBER PROPERTIES; P-75 FIBER

1	ELASTIC MODULI	EFP1	0.7500E 08
2		EFP2	0.9000E 06
3	SHEAR MODULI	GFP12	0.1100E 07
4		GFP23	0.7000E 06
5	POISSON"S RATIO	NUFP12	0.2000E 00
6		NUFP23	0.2500E 00
7	THERM. EXP. COEF.	CTEFP1	-0.7000E-06
8		CTEFP2	0.5600E-05
9	DENSITY	RHOFP	0.7200E-01
10	NO. OF FIBERS/END	NFP	0.1000E 05
11	FIBER DIAMETER	DIFP	0.3900E-03
12	HEAT CAPACITY	CFPC	0.1700E 00
13	HEAT CONDUCTIVITY	KFP1	0.9000E 02
14		KFP2	0.5800E 02
15		KFP3	0.5800E 02
16	STRENGTHS	SFPT	0.2250E 06
17		SFPC	0.1000E 06

--> CONSTITUENT PROPERTIES: ECHO FROM DATA BANK. <--

PRIMARY FIBER PROPERTIES; P100 FIBER

1	ELASTIC MODULI	EFP1	0.1050E 09
2		EFP2	0.9000E 06
3	SHEAR MODULI	GFP12	0.1100E 07
4		GFP23	0.7000E 06
5	POISSON"S RATIO	NUFP12	0.2000E 00
6		NUFP23	0.2500E 00
7	THERM. EXP. COEF.	CTEFP1	-0.9000E-06
8		CTEFP2	0.5600E-05
9	DENSITY	RHOFP	0.7800E-01
10	NO. OF FIBERS/END	NFP	0.1000E 05
11	FIBER DIAMETER	DIFP	0.3900E-03
12	HEAT CAPACITY	CFPC	0.1700E 00
13	HEAT CONDUCTIVITY	KFP1	0.3000E 03
14		KFP2	0.5800E 02
15		KFP3	0.5800E 02
16	STRENGTHS	SFPT	0.3250E 06
17		SFPC	0.2000E 06

Figure 6. - Constituent properties developed for the new high modulus fibers.

PRIMARY MATRIX PROPERTIES; R934 MATRIX. DRY RT. PROPERTIES.

1	ELASTIC MODULUS	EMP	0.5600E 06
2	SHEAR MODULUS	GMP	0.2074E 06
3	POISSON"S RATIO	NUMP	0.3500E 00
4	THERM. EXP. COEF.	CTEMP	0.3600E-04
5	DENSITY	RHOMP	0.4700E-01
6	HEAT CAPACITY	CMPC	0.2500E 00
7	HEAT CONDUCTIVITY	KMP	0.1250E 01
8	STRENGTHS	SMPT	0.7100E 04
9		SMPC	0.3500E 05
10		SMPS	0.5000E 04
11	MOISTURE COEF	BTAMP	0.4000E-02
12	DIFFUSIVITY	DIFMP	0.2000E-03

PRIMARY MATRIX PROPERTIES; IMHS MATRIX. DRY RT. PROPERTIES.

1	ELASTIC MODULUS	EMP	0.5000E 06
2	SHEAR MODULUS	GMP	0.1852E 06
3	POISSON"S RATIO	NUMP	0.3500E 00
4	THERM. EXP. COEF.	CTEMP	0.3600E-04
5	DENSITY	RHOMP	0.4400E-01
6	HEAT CAPACITY	CMPC	0.2500E 00
7	HEAT CONDUCTIVITY	KMP	0.1250E 01
8	STRENGTHS	SMPT	0.1500E 05
9		SMPC	0.3500E 05
10		SMPS	0.1300E 05
11	MOISTURE COEF	BTAMP	0.4000E-02
12	DIFFUSIVITY	DIFMP	0.2000E-03

Figure 7. - Constituent properties developed for a new resin system (R934) using an existing one (IMHS) from the data bank.

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15. Supplementary Notes

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16. Abstract

ICAN (Integrated Composites ANalyzer), a stand-alone computer code, incorporates micromechanics equations and laminate theory to analyze/design multilayered fiber composite structures. Procedures for both the implementation of new data in ICAN and the selection of appropriate measured data for comparison are described in detail. ICAN predictions and experimental data are summarized for: (1) composite systems subject to severe thermal environments, (2) woven fabric/cloth composites, and (3) select new composite systems including those made from high strain-to-fracture fibers. The comparisons demonstrate the versatility of ICAN as a reliable method for determining composite properties suitable for preliminary design.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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