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Composite Materials Testing for Remotely Piloted Vehicles

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Off-Board Countermeasures Branch
Tactical Electronic Warfare Division

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The purpose of this report is to test and evaluate the material properties of composites, built by Code 5712 of the Naval Research Laboratory, for use on Remotely Piloted Vehicles (RPV's). These composite materials are generally combinations of Balsa wood and Kevlar or Fiberglas, using Epoxy as a binder.

The specific requirement of these composites necessitate that the weight of the material be kept at a minimum. In accordance with this requirement a fabrication procedures has been adopted that deviates from that traditionally established in the composites field. The main difference is that in the construction of these composites no dam is used to surround the material while the Epoxy cures. Conventional composite fabrication procedures use a dam to prevent Epoxy (resin) from migrating away from the material. This fabrication process was examined in relation to it's affects on the material properties of these composites.

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19. ABSTRACT (Continued)

Laminate theory, as propounded by Tsai, allows one to break up a composite into constituent layers and define the properties of each layer separately. This study attempted to accomplish this by isolating the properties of Kevlar and Fiberglas within the constraints of the 'in house' fabrication process. In accordance with this, individual layers of Kevlar and Fiberglas were fabricated and tested independently. The material behavior of these independent layers was determined by testing for a specific set of key parameters. These parameters included Young's (Ex,Ey) Modulus, the Shear Modulus, Poisson's Ratio (vx), the volume fraction of fiber (vf), and the specific gravity of the materiai. Tables 3 and 4 at the end of the SUMMARY section list the theoretical and measured values of these key parameters for the two layers tested.

The results of the study show that the fabrication procedure saves weight at the cost of a minor reduction in the Young's Modulus, a 50% loss in Shear Modulus, a >200% increase in Poisson's ratio and a 10% increase in volume fiber. The Specific Gravity was lowered by more than 40%.

There was clearly a trade-off in strength associated with this fabrication process. This manifested itself in the material not demonstrating the full range of benefits that composites can provide. The Poisson's ratio and the Shear Modulus were impacted upon the most.

CONTENTS

COMPOSITE MATERIALS TESTING FOR REMOTELY PILOTED VEHICLES

INTRODUCTION

The Vehicle Research Section, of the Tactical Electronic Warfare Division of the Naval Research Laboratory, is currently interested in developing a body of knowledge in relation to the material properties of specific composite materials in use. The primary materials of concern are Kevlar/Balsa and Fiberglas/Balsa mixtures. These composites have been used in the construction of Remotely Piloted Vehicles (RPV's) built to facillitate Low Reynolds Number aerodynamic research projects. The Low Reynolds Number flight envelope translates into low speed/altitude, large (20') wingspan, large (7') fuselage RPV's. The key element in these applications is the importance of minimizing the weight of the composite, since the stresses may not be of the magnitudes often encountered in many composite applications.

PURPOSE

The purpose of this report is to apply a theoretical model to predict the material properties of these specific composite structures, to test and evaluate these materials, to determine their actual properties, and then to asses the impact of the fabrication process currently in use on these material properties.

The current fabrication process is of primary concern since it is still in the formative stage and has not been stand-

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ardized. It is hoped that the results of the material testing will yield some useful information in relation to this. It is also hoped that some further optimization of the fabrication process can be deduced from this study.

THE FABRICATION PROCEDURE

The current composite fabrication process is as described below. The fabrics used are.

Bi directional	Kevlar 49	cloth style 181
Bi directional	Fiberglas	cloth style 181

The core material is 3/8" Balsa wood with one layer of woven bi-directional cloth on both sides of the balsa. Initially the Balsa wood piece is covered with 45% hardener 55% Safe-t-poxy Epoxy mixture. The composite fiber is then overlaid on top of the Balsa wood, then the composite fiber is completely soaked in the same epoxy mixture. This procedure is repeated for both sides of the balsa wood piece. The piece is then wrapped in a perforated peel ply, surrounded by a layer of porous release fabric, which in turn is wrapped in a bleeder stack. This whole system is then vacuum bagged for 12 hours. The fabrication process currently implemented does not use a DAM structure to contain the epoxy during the cure stage.

These samples are then removed and cut into 1" by 2" strips for testing. This procedure is similar to the process developed and used by the section, and it is based on trail and error experiences. The process has not been looked at critically for optimization.

THE FABRICATION PROCEDURE

The following schematics show a cross-sectional view of the composite fabrication process used. Diagram 1 shows the standard method currently used with Kevlar/Balsa composites. This was the method used for all Kevlar and Kevlar/Balsa testing done for this report. Diagram 2 shows a method used with Fiberglas only (no core material), which gives a very smooth finish to the side of the Fiberglas facing the tool, while the other side stays relatively rough. This is the method used to fabricate the Fiberglas pieces tested for this report. This method, shown in diagram 2, has one less porous layer on one side of the piece during the cure stage. Both of these methods, by not using a dam, allow for only the vacuum pressure and inherent resistance to flow to act as a inhibitor to resin migration away from the cloth.

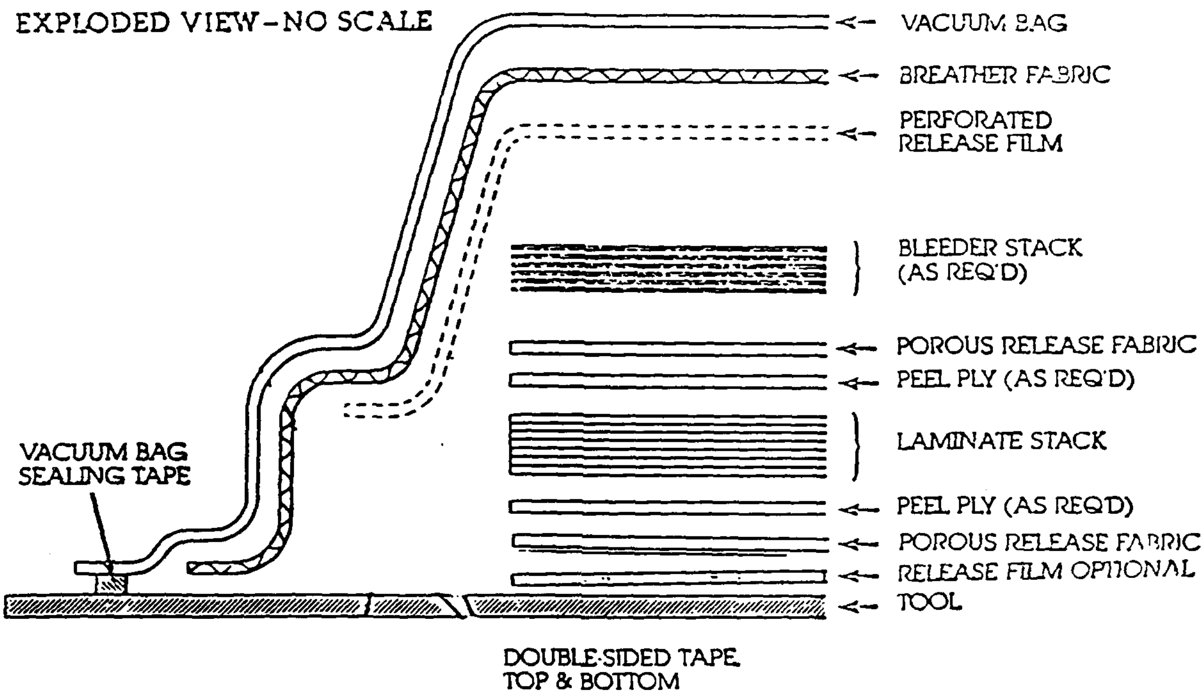
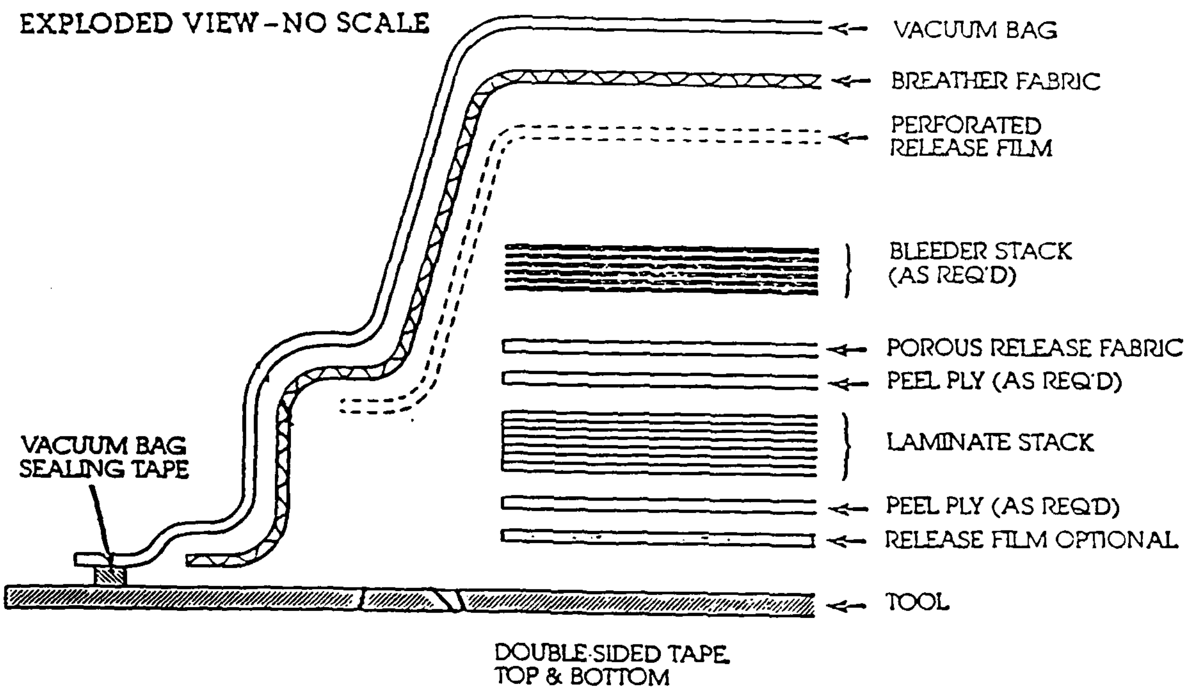

EXPLODED VIEW-NO SCALE
VACUUM BAG
BREATHER FABRIC
PERFORATED
RELEASE FILM
BLEEDER STACK
(AS REQ'D)
POROUS RELEASE FABRIC
PEEL PLY (AS REQ'D)
LAMINATE STACK
PEEL PLY (AS REQ'D)
POROUS RELEASE FABRIC
RELEASE FILM OPTIONAL
TOOL
VACUUM BAG
SEALING TAPE
DOUBLE-SIDED TAPE
TOP & BOTTOM

Diagram 1


EXPLODED VIEW - NO SCALE
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(AS REQ'D)
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PEEL PLY (AS REQ'D)
LAMINATE STACK
PEEL PLY (AS REQ'D)
RELEASE FILM OPTIONAL
TOOL
VACUUM BAG
SEALING TAPE
DOUBLE-SIDED TAPE
TOP & BOTTOM

Diagram 2

TESTING

To allow for a systematic analysis the first series of tests were on test samples with no core material, using only Fiberglas cloth or Kevlar 49 cloth and epoxy. Once the data was obtained, and the analysis for these preliminary cases was completed, the balsa core samples were then analyzed.

TEST PROCEDURES

The previously described test samples were fastened on to two one inch pieces of aluminum metal at each end to allow for a gripping surface in a Ingstrom tension machine. The testing of the materials consists of pulling these, four inch by one inch, test pieces in tension. Four strain gages were used for each test, two on each side of the sample piece back to back. One set of gages measured lateral strain the other measured longitudinal strain. The purpose of using two gages for each axis of concern was to minimize erroneous readings due to any warping of the material that may have occurred in testing.

STRAIN GAGES

In the early stages the only gages available to test with were EA-13-250BB-120 ohm - Micro-Measurements strain gages. The initial testing was done using these. It was soon learned, in the course of testing with these gages, that enough heat was generated to affect the properties of the material, and thus limit the useful testing time. A more appropriate selection of gages were obtained, and this testing was repeated using these CEA-13-125UW-350 Ohm Gages. The results of testing in this report include the results of using both these gages, these tended to be generally consistent.

STRAIN GAGE APPLICATION

Prior to the strain gage application the material surface was prepared in the following manner. Initially, the immediate area was gently sanded and then cleaned using a tissue lightly moistened with acetone. The strain gage was coated on the back side using a cyanoacrylic catalyst while a cyanoacrylic bonding agent was placed on the material surface. Pressure was applied to the gage by pressing ones finger tip and rolling gently for one minute. The piece was allowed to dry overnight, and examined the next day (under a microscope) to insure that the corners and edges of the strain gage were securely attached.

THEORETICAL ESTIMATION OF MATERIAL PROPERTIES

KEVLAR CLOTH WITH NO CORE MATERIAL

THE CASH REGISTER METHOD

Before using this method (described in Tsai's textbook Composites Design 1986, in chapt.7) to calculate in-plane stiffness of these materials, some assumptions must be clarified. The materials used for this report were woven fibers at 0/90 degree angles overlaid on top of each other with a thickness h(o)'=.343* mm for each woven layer. Tsai's method assumes unidirectional fibers, only, associated with each layer. Thus the 0/90 woven layer would be approximated with one unidirectional layer, with a 0 degrees orientation, overlaid on top of a second 90 degree layer. Tsaï defines his h(o) as the thickness of each unidirectional layer, in our woven case this would then be h(o)'/2 or .1715 mm for the Kevlar case. The implication here is that the woven case is analytically similar to the layered unidirectional case. Additionally due to the space taken up due to the weave the number of fibers in each unidirectional 'layer' for the woven case is significantly less than that of the layered unidirectional case. This should make the theoretical predictions stiffer than the actual woven case.

The theoretical values calculated using the cash register method for the 0/90/90/0 cases are shown on the following few pages. The theoretical values for the -45/45/45/-45 cases are shown on the pages immediately following the similar composite material's 0/90/90/0 case.

* refers to Kevlar ply thickness

Due to the absence of a standardized set of subscripts for the stress and strain components, the tables below are included as a cross reference to the reader. This is presented as a precaution to avoid confusing a reader who may be used to a different nomenclature. All the subscripts in any one column on any one table have identical meanings.

TABLE 1

STRESS COMPONENTS

STANDARD SUBSCRIPTS	σ_{xx}	σ_{yy}	σ_{zz}	σ_{yz}	σ_{zx}	σ_{xy}
NUMERIC SUBSCRIPTS	σ_{11}	σ_{22}	σ_{33}	σ_{23}	σ_{31}	σ_{12}
CONTRACTED NUMERIC	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6
CONTRACTED LETTER	σ_x	σ_y	σ_z	σ_t	σ_u	σ_s

TABLE 2

STRAIN COMPONENTS

REGULAR SUBSCRIPTS	e_{xx}	e_{yy}	e_{zz}	e_{yz}	e_{zx}	e_{xy}
NUMERIC SUBSCRIPTS (Used by Jones)	e_{11}	e_{22}	e_{33}	e_{23}	e_{31}	e_{12}
CONTRACTED NUMERIC (Used by Tsai)	e_1	e_2	e_3	$e_4/2$	$e_5/2$	$e_6/2$
CONTRACTED LETTER	e_x	e_y	e_z	$e_t/2$	$e_u/2$	$e_s/2$

THEORETICAL VALUES FOR [0/90/90/0] TOTAL KEVLAR 49

Using Tsai's values for modulus and adjusting for a laminate thickness of .000686 m (made of two ply groups) the following values are arrived at:

h = laminate thickness = .000686 m

hi = each ply group thickness = .000343 m

ho = unit ply thickness = .0001715 m

Using these measured values for ply thickness the adjusted values for the in plane stiffness are:

[A]/0			[A]/90		
11	13.144	MN/M	11	.9518	MN/M
22	.9518	MN/M	22	13.144	MN/M
12=21	.324	MN/M	12=21	.324	MN/M
66	.394	MN/M	66	.394	MN/M

The formula for the Cash Register Method of summation is;

$[A]$ = the summation of $[A^{o}](i)\,n(i)$ for $i=1$ to m

where;

m = number of ply groups

n = number of layers in that ply group

$[A^{o}]$ is the in plane stiffness sub-matrix of a sub-laminate.

and $A^{o}ij = Qij(m)*h(o)$

Substituting the above values into the cash register formula one obtains.

A11 = 2(13.144 + .9518) = 28.1916 MN/M = A22

A12 = 2(.324 + .324) = 1.296 MN/M = A21

A66 = 2(.394 + .394) = 1.576 MN/M

A16 = 0 = A26

From Tsai:

|A| = {A11*A22 - A12*A12}A66 + 2*A12*A26*A16 - A11*A26*A26 - A22*A16*A16

a11 = {A22*A66 - A26*A26}/|A|

a22 = {A11*A66 - A16*A16}/|A|

a12 = {A16*A26 - A12*A66}/|A|

a66 = {A11*A22 - A12*A12}/|A|

a16 = {A12*A26 - A22*A16}/|A|

a26 = {A12*A16 - A11*A26}/|A|

and

$\underline{E1^{o} = 1/a11^{*} = E2^{o}}$ $\underline{E6^{o} = 1/a66^{*}}$ $\underline{v21^{o} = -a21/a11 = v12^{o}}$

[0/90/90/0]T KEVLAR CLOTH

|A| = (28.1916**2 - 1.296**2)1.576 = 1,249.9 (MN/m)**3

a11 = (28.18*1.576)/1,249.9 = .033554 m/MN

a21 = -1.296(1.576)/1,249.9 = -0.001634 m/MN

a66 = (28.19**2 - 1.296**2)/1,249.9 = .6344 m/MN

$a^{*}/h = a \quad h = .000686$ m

E1 = 1/a11 * (1/h) = 1/.03554 * (1/.000686) = 41.016 GPa.

E6 = 1/a66 * (1/h) = 1/.6344 * (1/.000686) = 2.297 GPa. = G12

v21 = v12 = -a21/a11 = .04598

THEORETICAL VALUES FOR [45/-45/-45/45] TOTAL KEVLAR 49

Again, using Tsai's values for modulus and adjusting for a laminate thickness of .000686 m (made of two ply groups) the following values are arrived at:

h = laminate thickness = .000686 m

hi = each ply group thickness = .000343 m

ho = unit ply thickness = .0001715 m

Using these measured values for ply thickness the adjusted values for the in plane stiffness are:

[A]/45			[A]/-45		
11	4.080	MN/M	11	4.080	MN/M
22	3.291	MN/M	22	3.291	MN/M
12=21	3.361	MN/M	12=21	3.361	MN/M
66	3.047	MN/M	66	-3.047	MN/M

The formula for the Cash Register Method of summation is;

$[A]$ = the summation of $[A^{o}](i)\ n(i)$ for i=1 to m

where;

m = number of ply groups

n = number of layers in that ply group

$[A^o]$ is the in plane stiffness sub-matrix of a sub-laminate.

and $A^o_{ij} = Q_{ij}(m)*h(o)$

Substituting the previous values into the cash register formula one obtains.

$$A_{11} = 2(4.08 + 4.08) = 16.32 \text{ MN/M} = A_{22}$$

$$A_{12} = 2(3.291 + 3.291) = 13.164 \text{ MN/M} = A_{21}$$

$$A_{66} = 2(3.361 + 3.361) = 13.44 \text{ MN/M}$$

$$A_{16} = 0 = A_{26}$$

From Tsai:

$$|A| = \{A_{11}*A_{22} - A_{12}*A_{12}\}A_{66} + 2*A_{12}*A_{26}*A_{16} - A_{11}*A_{26}*A_{26} - A_{22}*A_{16}*A_{16}$$

$$a_{11} = \{A_{22}*A_{66} - A_{26}*A_{26}\}/|A|$$

$$a_{22} = \{A_{11}*A_{66} - A_{16}*A_{16}\}/|A|$$

$$a_{12} = \{A_{16}*A_{26} - A_{12}*A_{66}\}/|A|$$

$$a_{66} = \{A_{11}*A_{22} - A_{12}*A_{12}\}/|A|$$

$$a_{16} = \{A_{12}*A_{26} - A_{22}*A_{16}\}/|A|$$

$$a_{26} = \{A_{12}*A_{16} - A_{11}*A_{26}\}/|A|$$

and

$$E_1^o = 1/a_{11}^* = E_2^o \qquad E_6^o = 1/a_{66}^* \qquad v_{21}^o = -a_{21}/a_{11} = v_{12}^o$$

[45/-45/-45/45]T KEVLAR CLOTH

$$|A| = (16.32^{2} - 13.164^{2})13.44 = 1250.6\ (MN/m)^{3}$$

$$a11 = (16.34 \cdot 13.44)/1{,}250.6 = .1754\ m/MN$$

$$a21 = -13.164(13.44)/1{,}250.5 = -.14148\ m/MN$$

$$a66 = (16.32^{2} - 13.164^{2})/1{,}250.5 = .0744\ m/MN$$

$$a^{*}/h = a \quad h = .000686\ m$$

$$E1 = 1/a11 \cdot (1/h) = 1/.1754 \cdot (1/.000686) = \underline{8.311\ GPa.}$$

$$E6 = 1/a66 \cdot (1/h) = 1/.0744 \cdot (1/.000686) = 19.592\ GPa.$$

$$v21 = v12 = -a21/a11 = \underline{.8066}$$

THEORETICAL VALUES FOR [0/90] TOTAL FIBERGLAS

Using Tsai's values for modulus and adjusting for a laminate thickness of .0004623 m (made of two ply groups) the following values are arrived at:

h = laminate thickness = .0004623 m

hi = each ply group thickness = .00023115 m

ho = unit ply thickness = .00023115 m

Using these measured values for ply thickness the adjusted values for the in plane stiffness are:

[A]/0			[A]/90		
11	9.0611	MN/M	11	1.942	MN/M
22	1.942	MN/M	22	9.0611	MN/M
12=21	.499	MN/M	12=21	.499	MN/M
66	.9616	MN/M	66	.9616	MN/M

The formula for the Cash Register Method of summation is;

[A] = the summation of $[A^o](i)\ n(i)$ for i=1 to m

where;

m = number of ply groups

n = number of layers in that ply group

where;

$[A^o]$ is the in plane stiffness sub-matrix of a sub-laminate.

and $A^o_{ij} = Q_{ij}(m)*h(o)$

Substituting the above values into the cash register formula one obtains.

$$A11 = (9.0611 + 1.942) = 11.003 \text{ MN/M} = A22$$

$$A12 = (.499 + .499) = .998 \text{ MN/M} = A21$$

$$A66 = (.9616 + .9616) = 1.9232 \text{ MN/M}$$

$$A16 = 0 = A26$$

Again from Tsai:

$$|A| = \{A11*A22 - A12*A12\}A66 + 2*A12*A26*A16 - A11*A26*A26 - A22*A16*A16$$

$$a11 = \{A22*A66 - A26*A26\}/|A|$$

$$a22 = \{A11*A66 - A16*A16\}/|A|$$

$$a12 = \{A16*A26 - A12*A66\}/|A|$$

$$a66 = \{A11*A22 - A12*A12\}/|A|$$

$$a16 = \{A12*A26 - A22*A16\}/|A|$$

$$a26 = \{A12*A16 - A11*A26\}/|A|$$

and

$$E1^o = 1/a11^* = E2^o \qquad E6^o = 1/a66^* \qquad v21^o = -a21/a11 = v12^o$$

[0/90] TOTAL FIBERGLAS

|A| = (11.003**2 - .998**2)1.9232 = 230.915 (MN/m)**3

a11 = (11.003*1.9232)/230.915 = .0916395 m/MN

a21 = -.998(1.9232)/230.915 = -.0083118 m/MN

a66 = (11.003**2 - .998**2)/230.915 = .5199 m/MN

$a^*/h = a \quad h = .0004623$ m

E1 = 1/a11 * (1/h) = 1/.09164 * (1/.0004623) = <u>23.604 GPa.</u>

E6 = 1/a66 * (1/h) = 1/.5199 * (1/.0004623) = <u>4.160 GPa.</u> = G12

v21 = v12 = -a21/a11 = <u>.0907</u>

THEORETICAL VALUES FOR [45/-45] TOTAL FIBERGLAS

Using Tsai's values, as previously, for modulus and adjusting for a laminate thickness of .0006223 m (made of two ply groups) the following values are arrived at:

h = laminate thickness = .0006223 m

hi = each ply group thickness = .00031115 m

ho = unit ply thickness = .00031115 m

Using these measured values for ply thickness the adjusted values for the in plane stiffness are:

[A]/45			[A]/-45		
11	5.327	MN/M	11	5.327	MN/M
22	2.763	MN/M	22	2.763	MN/M
12=21	3.36	MN/M	12=21	3.36	MN/M
66	.2389	MN/M	66	-.2389	MN/M

The formula for the Cash Register Method of summation is;

$[A]$ = the summation of $[A^{o}](i)\ n(i)$ for i=1 to m

where;

m = number of ply groups

n = number of layers in that ply group

where;

$[A^{o}]$ is the in plane stiffness sub-matrix of a sub-laminate.

and $A_{ij}^{o} = Q_{ij}(m)*h(o)$

Substituting the above values into the cash register formula one obtains.

$$A11 = (5.327 + 5.327) = 10.654 \text{ MN/M} = A22$$

$$A12 = (2.763 + 2.763) = 5.526 \text{ MN/M} = A21$$

$$A66 = (3.36 + 3.36) = 6.72 \text{ MN/M}$$

$$A16 = 0 = A26$$

From Tsai:

$$|A| = \{A11*A22 - A12*A12\}A66 + 2*A12*A26*A16 - A11*A26*A26 - A22*A16*A16$$

$$a11 = \{A22*A66 - A26*A26\}/|A|$$
$$a22 = \{A11*A66 - A16*A16\}/|A|$$
$$a12 = \{A16*A26 - A12*A66\}/|A|$$
$$a66 = \{A11*A22 - A12*A12\}/|A|$$
$$a16 = \{A12*A26 - A22*A16\}/|A|$$
$$a26 = \{A12*A16 - A11*A26\}/|A|$$

and

$$E1^{o} = 1/a11^{*} = E2^{o} \qquad E6^{o} = 1/a66^{*} \qquad v21^{o} = -a21/a11 = v12^{o}$$

[45/-45] TOTAL FIBERGLAS

|A| = (10.654**2 - 5.526**2)6.72 = 557.565 (MN/m)**3

a11 = (10.654*6.72)/557.56 = .128406 m/MN

a21 = -5.526(6.72)/557.565 = -.0666 m/MN

a66 = (10.654**2 - 5.526**2)/557.565 = .1488 m/MN

$a^{*}/h = a \quad h = .0006223$ m

E1 = 1/a11 * (1/h) = 1/.1284 * (1/.0006223) = 12.514 GPa.

E6 = 1/a66 * (1/h) = 1/.1488 * (1/.0006223) = 10.798 GPa.

v21 = v12 = -a21/a11 = .5186

RESULTS OF TENSION TESTING $[0/90/90/0]_T$ KEVLAR WITH NO CORE

The actual results of the testing for the 0/90/90/0 case are shown on the next page. The results for the [-45/45]s case are shown on the following subsection. The relevant parameters for the [0/90]s Kevlar 49 are listed below. The Kevlar had a Longitudinal (Ex)/Transverse (Ey) Young's modulus of 32.686 GPa.. Looking at the longitudinal plot on Figure # 1 one can see that the material's stress strain curve was slightly nonlinear throughout the test. As stress levels were increased during the test the curve tended to show slightly greater elasticity causing this nonlinear behavior. Looking at the transverse axis plot (in pyramids), on Figure 1, one can see a that the slope of this plot is about ten times as steep as the stress strain curve of the longitudinal axis. The exact Poisson's ratio was $-e(y)/e(x) = 0.0969$.

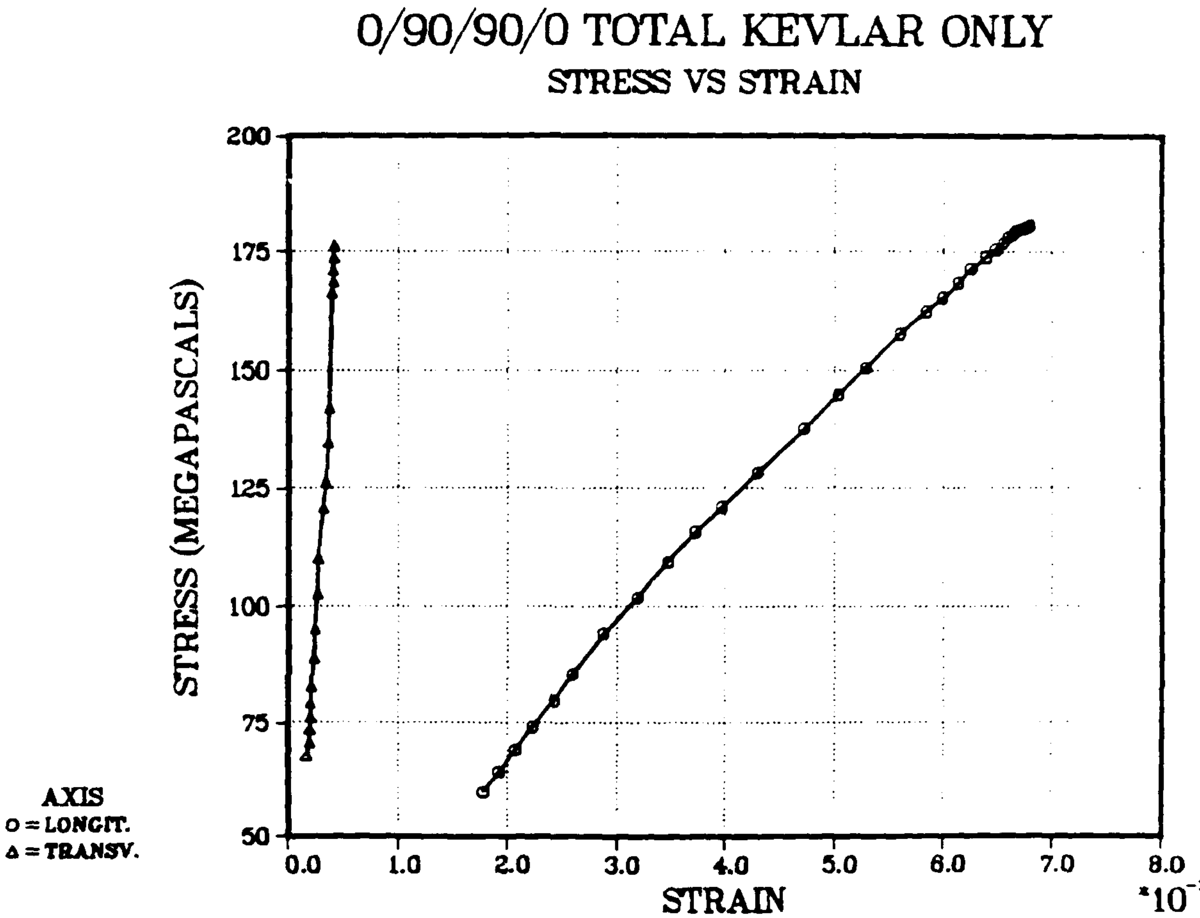

0/90/90/0 TOTAL KEVLAR ONLY
STRESS VS STRAIN
STRESS (MEGAPASCALS)
200
175
150
125
100
75
50
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
STRAIN
*10⁻³
AXIS
o = LONGIT.
Δ = TRANSV.

Figure 1

RESULTS OF TESTING $[45/-45/-45/45]_T$ KEVLAR WITH NO CORE

The actual results of the testing for the Kevlar 49 [45/-45/]s case are shown on the next page. The results for the FIBERGLAS cases are shown on the pages following this section. The relevant parameters were calculated using EQ 2.92 from JONES R.M., MECHANICS OF COMPOSITE MATERIALS (1975), McGRAW HILL. These calculations are shown below.

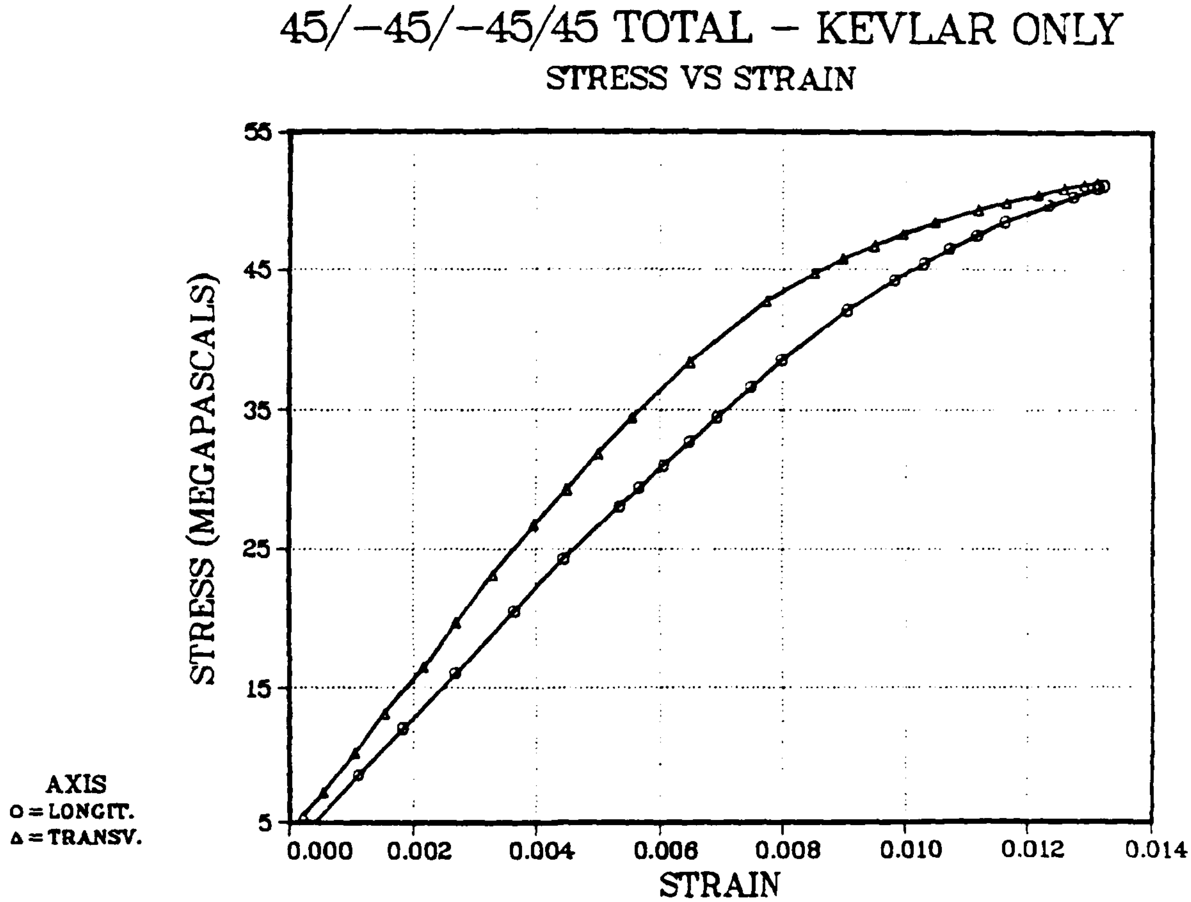
The basic equation, taken from JONES, is;

$$1/Ey = 1/E1 * \sin^4 X + (1/G12 - 2*v12/E1)\sin^2 X \cos^2 X + 1/E2 * \cos^4 X$$

This was manipulated to solve for G12 (E6 in Tsai's nomenclature)

$$G12 = \frac{-\sin^2 X \cos^2 X}{(1/E1)\cos^4 X - 2(v12/E1)\sin^2 X \cos^2 X + (1/E2)\sin^4 X - 1/Ex}$$

This equation was then solved for G12 using the longitudinal and transverse Young's modulus and Poisson's ratio from the [0/90]s test for E1, E2, and v12 respectively. The value of Ex in this equation was that of the longitudinal Young's Modulus (5.227 GPa.) for the [45/-45] test, taken from Figure 2 on a following page.



45/−45/−45/45 TOTAL − KEVLAR ONLY
STRESS VS STRAIN
STRESS (MEGAPASCALS)
55
45
35
25
15
5
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
STRAIN
AXIS
O = LONGIT.
Δ = TRANSV.

Figure 2

Longitudinal/lateral Young's Modulus and Poisson's ratio for this [45/-45]s case are 5.227 GPa. and .8 respectively. The values to be plugged into the above, previously described, equation to be solved for G12 are;

X = 45 DEG.	Ex = 5.227 GPa
E1 = 32.7 GPa = E2	v12 = .0969

Giving a value for G12 = 1.409 GPa.

RESULTS OF TENSION TESTING $[0/90]_T$ FIBERGLAS WITH NO CORE

The actual results of the testing for the [0/90]t case are shown on the next page. The results for the [-45/45]t case are shown on the following subsection. The relevant par- for the [0/90]t Fiberglas are listed below. The Fiberglas had a Longitudinal (Ex)/Transverse (Ey) Young's modulus of 20.29 GPa.. Looking at the longitudinal plot on Figure # 3 one can see that the material's stress strain curve was linear throughout the test. As stress levels were increased during the test the material tended to show constant elasticity.

Upon observing the transverse axis plot (in pyramids), on Figure 1, one can see that the slope of this plot is about four times as steep as the stress strain curve of the longitudinal axis. The exact Poisson's ratio was -e(y)/e(x) = 0.2564.

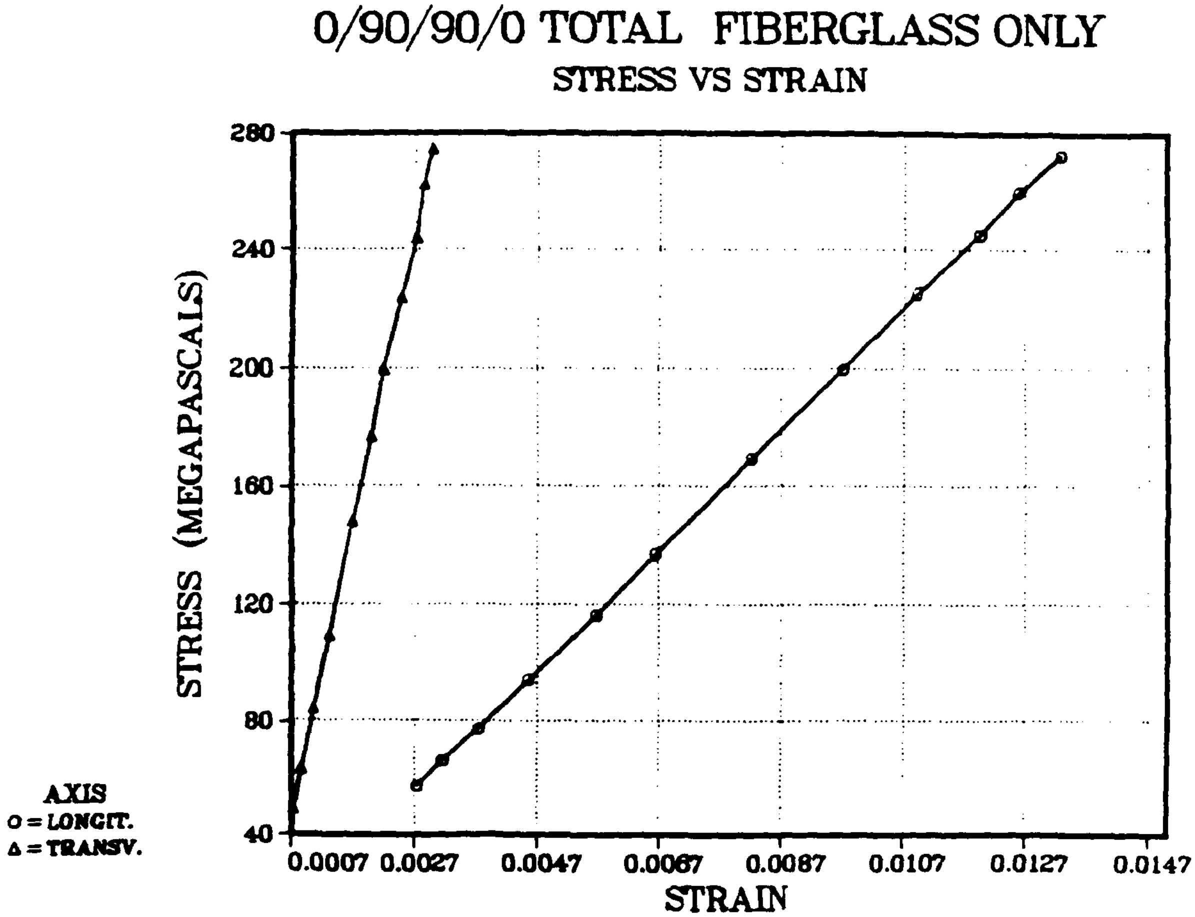

0/90/90/0 TOTAL FIBERGLASS ONLY
STRESS VS STRAIN
STRESS (MEGAPASCALS)
280
240
200
160
120
80
40
0.0007 0.0027 0.0047 0.0067 0.0087 0.0107 0.0127 0.0147
STRAIN
AXIS
O = LONGIT.
Δ = TRANSV.

Figure 3

RESULTS OF TESTING $[45/-45/]_T$ FIBERGLAS WITH NO CORE

The actual results of the testing for the [45/-45/]t Fiberglas case are shown on the next page. The results for the Kevlar/Balsa cases are shown on the pages following this section. The relevant parameters were calculated using EQ 2.92 from JONES R.M., MECHANICS OF COMPOSITE MATERIALS (1975), McGRAW HILL. These calculations are shown below.

The same equation, taken from JONES, is;

$$1/Ey = 1/E1*\sin^4 X + (1/G12 - 2*v12/E1)\sin^2 X\cos^2 X + 1/E2*\cos^4 X$$

This was manipulated to solve for G12;

$$G12 = \frac{-\sin^2 X \cos^2 X}{(1/E1)\cos^4 X - 2(v12/E1)\sin^2 X\cos^2 X + (1/E2)\sin^4 X - 1/Ex}$$

This equation was then solved for G12 using the longitudinal and transverse Young's modulus and Poisson's ratio from the [0/90]t test for E1, E2, and v12 respectively. The value of Ex in this equation was that of the longitudinal Young's Modulus (6.0 GPa.) for the [45/-45] test, taken from Figure 4 on the next page.

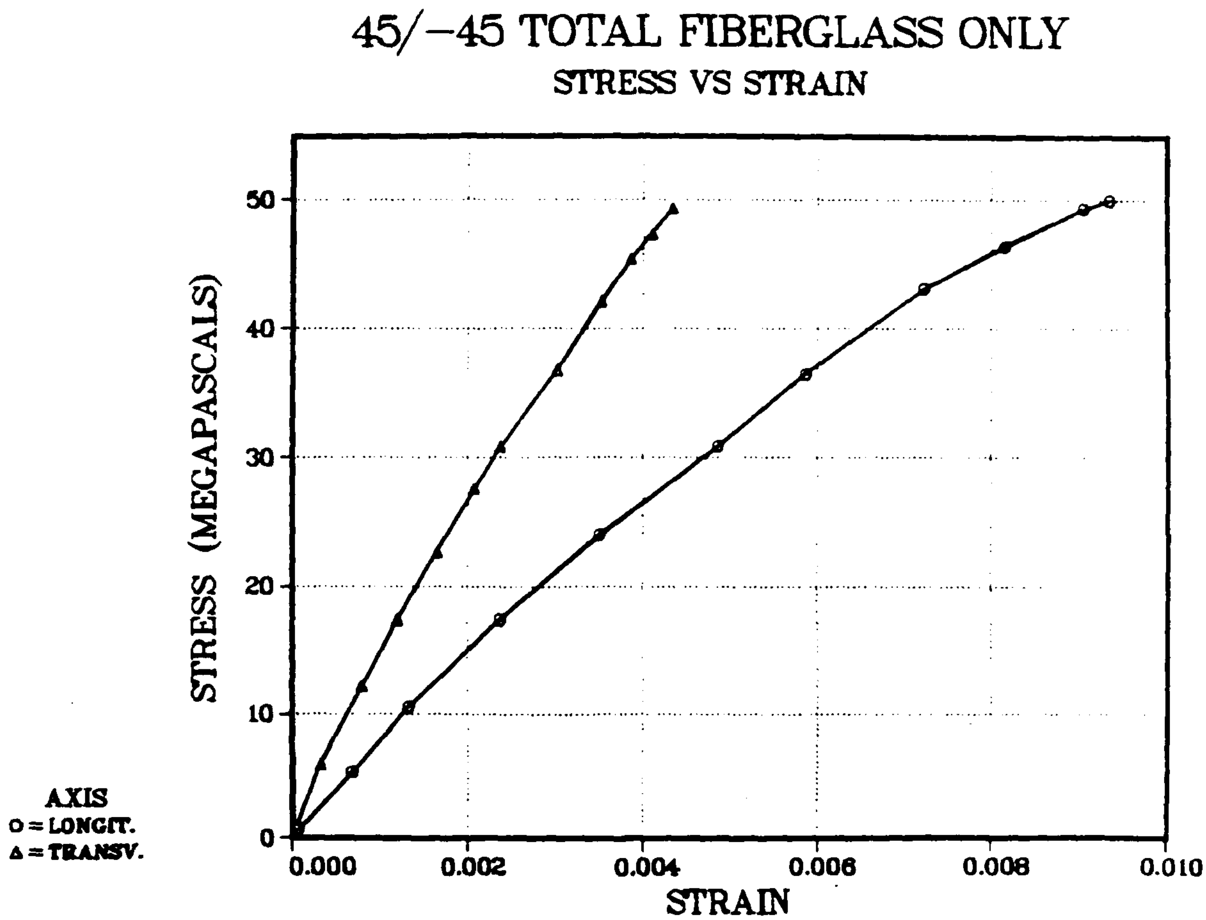

45/−45 TOTAL FIBERGLASS ONLY
STRESS VS STRAIN
STRESS (MEGAPASCALS)
50
40
30
20
10
0
0.000
0.002
0.004
0.006
0.008
0.010
STRAIN
AXIS
O = LONGIT.
Δ = TRANSV.

Figure 4

The Poisson's ratio for the [45/-45]s Fiberglas case is .5. The values to be plugged into the above equation to be solved for G12 are;

X = 45 DEG.	Ex = 6.0 GPa
E1 = 20.285 GPa = E2	v12 = .2564

Giving a value for G12 = 1.685 GPa.

RESULTS OF TENSION TESTING $[0/90/BALSA/90/0]_T$ KEVLAR BALSA KEVLAR

The actual results of the testing for this Balsa Kevlar case are shown on the next page. The results for the [45/-45/Balsa/-45/45]t case are shown on the following subsection. The relevant parameters for this case are listed below. This composite had a Longitudinal (Ex)/Transverse (Ey) Young's modulus of 2.44 GPa.. Looking at the longitudinal plot on Figure # 5 one can see that the material's stress strain curve was linear throughout the test.

Upon observing the transverse axis plot (in pyramids), on Figure 1, one can see a that the slope of this plot is about four times as steep as the stress strain curve of the longitudinal axis. The exact Poisson's ratio was -e(y)/e(x) = 0.2322

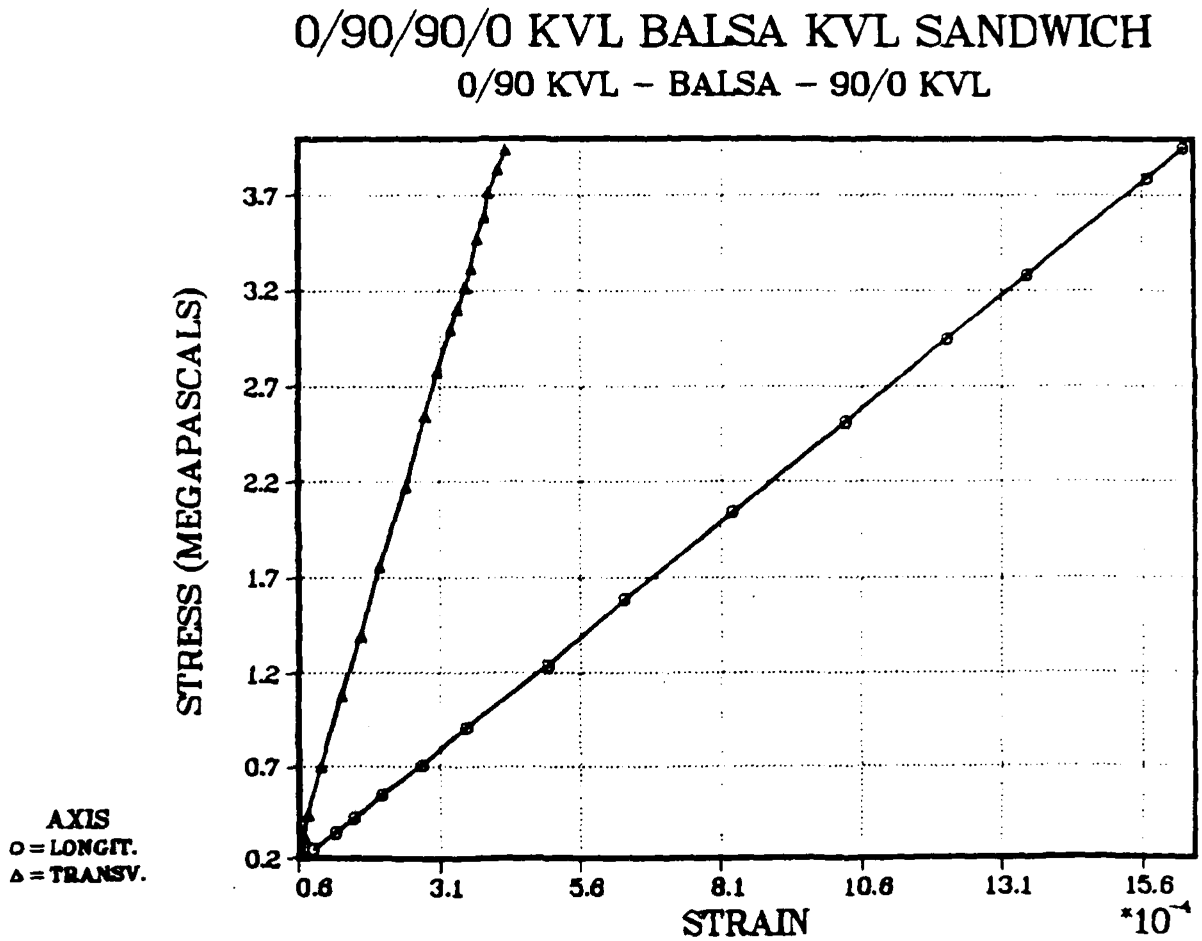

0/90/90/0 KVL BALSA KVL SANDWICH
0/90 KVL - BALSA - 90/0 KVL
STRESS (MEGAPASCALS)
3.7
3.2
2.7
2.2
1.7
1.2
0.7
0.2
0.6
3.1
5.6
8.1
10.6
13.1
15.6
STRAIN
*10⁻⁴
AXIS
o = LONGIT.
Δ = TRANSV.

Figure 5

RESULTS OF TESTING $[45/-45/BALSA/-45/45]_T$ KEVLAR/BALSA/KEVLAR

The actual results of the testing for the [45/-45/Balsa/-45/45]t composite are shown on the next page. The relevant parameters were calculated in the usual way using EQ 2.92 from JONES. For the sake of completeness, these calculations are again repeated below.

The equation is;

$$1/Ey = 1/E1*\sin^4 X + (1/G12 - 2*v12/E1)\sin^2 X\cos^2 X + 1/E2*\cos^4 X$$

This again is manipulated to solve for G12;

$$G12 = \frac{-\sin^2 X \cos^2 X}{(1/E1)\cos^4 X - 2(v12/E1)\sin^2 X\cos^2 X + (1/E2)\sin^4 X - 1/Ex}$$

This equation was then solved for G12 in the manner previously described. The value for Ex was taken from Figure 6 on the next page. On the whole the stress strain curve was linear. The values to be plugged into the above equation, for G12, are;

X = 45 DEG.	Ex = 1.506 GPa
E1 = 2.44 GPa = E2	v12 = .2322

Giving a value for G12 = .4935 GPa.

Poisson's ratio for this test was ~1.2.

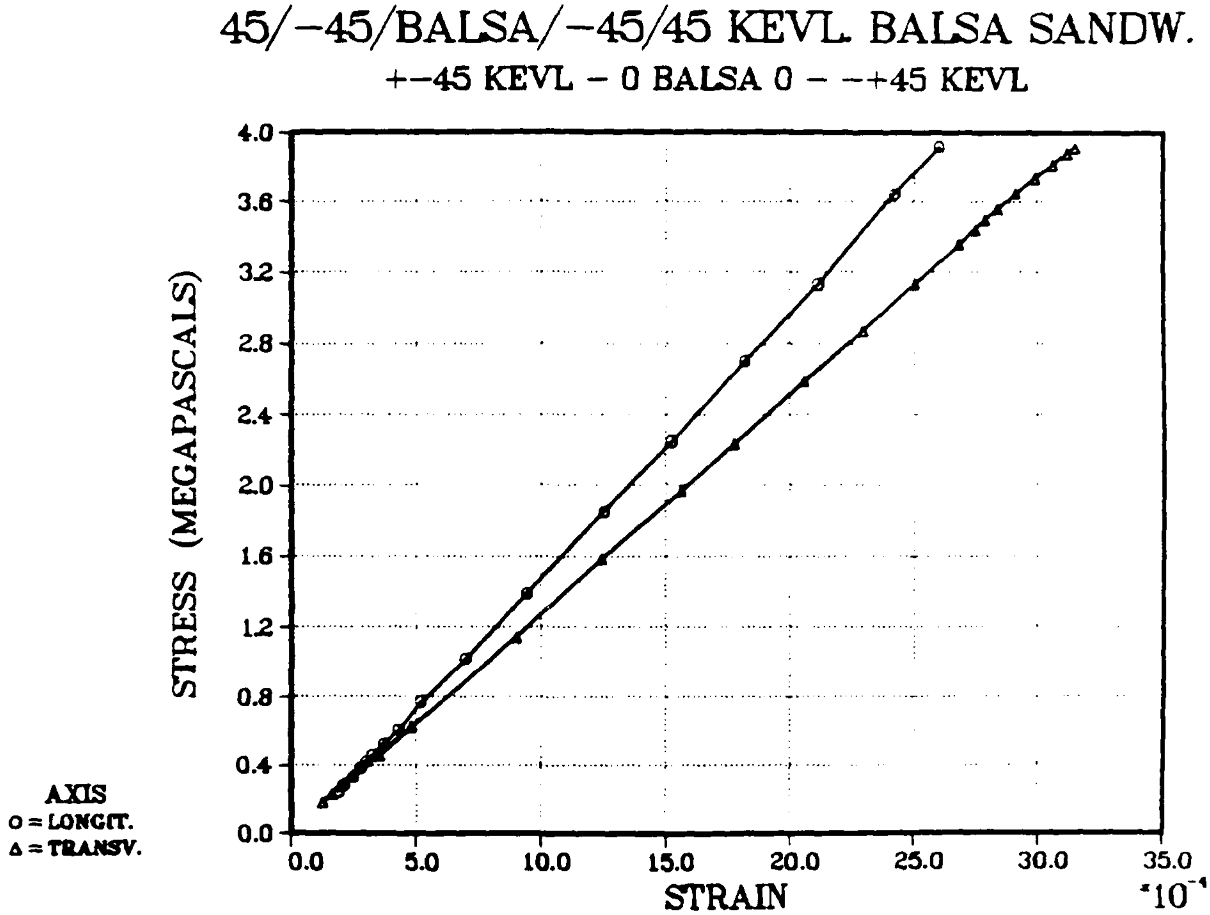

45/-45/BALSA/-45/45 KEVL. BALSA SANDW.
+-45 KEVL - 0 BALSA 0 - -+45 KEVL
STRESS (MEGAPASCALS)
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
STRAIN
*10⁻⁴
AXIS
O = LONGIT.
Δ = TRANSV.

Figure 6

SUMMARY OF TEST RESULTS FOR $[0/90/90/0]_T$ KEVLAR

For this composite the theoretical value for Young's Modulus was 41.0 GPa., but this was based on four unidirectional plies. In this case there are in reality two sets of two interwoven layers. This discrepancy implies that the theoretical value should be fractionally larger than the tested value by a indeterminant amount. Additionally, the theory assumes a standard composite fabrication procedure, not like the one used by code 5712. The actual test value of 32.7 GPa. agrees favorably with the theory, taking into account the above variations.

The theoretical Poisson's ratio was 0.04598, also based on four unidirectional layers. The actual test results indicate a Poisson's ration of twice this amount or .097. This again can be partially attributed to the fact that the interwoven 0/90 layers, in tension, have a greater impact (as is intuitively obvious) on the orthogonal axis than would two overlapping layers. This appears to have been compounded by the fact that by not using a dam during fabrication, the resin would not have adhered to the composite as completely as would otherwise be the case. This could allow for more give in the orthogonal axis, hence the higher Poisson's ratio.

SUMMARY OF $[45/-45/-45/45]_T$ KEVLAR TEST RESULTS

The Young's modulus in the longitudinal/lateral axis was predicted to be 8.3 GPa. based on four unidirectional layers. The actual value during the test changed from ~7 GPa. to ~3 GPa. due to the non linear response of the material. This non linearity was attributed to the fabrication process and the scissoring effect of the interwoven fibers upon application of increasing stresses. The typical value for this Young's Modulus was taken as 5.227 GPa. Poisson's ratio for the Longitudinal VS Transverse axis was ~.8 which agrees with the theoretical value of .81. The results of this test compare favorably with the theoretical estimates if the variations in the fabrication process are taken into account.

SUMMARY OF $[0/90]_T$ FIBERGLAS TEST RESULTS

The results of [0/90]t Fiberglas compared favorably with the theoretical predictions. To the extent that they wavered from the theory, they showed the same general patterns as the 0/90 Kevlar case. These were expected variations because of the difference in material properties due to the presence of woven layers and the absence of a dam during fabrication. The theoretical Ex/Ey values were 23.6 GPa. compared with 20.3 GPa. for actual test results. The theoretical Poisson's ration was .0907 while the actual test value was .2564 approximately 2 1/2 times that expected for unidirectional layers. Again, this can be attributed somewhat to the increased impact/sensitivity of a woven fiber to the orthogonal axis (hence Poisson's ratio), and to the fabrication process.

SUMMARY OF $[45/-45]_T$ FIBERGLAS TEST RESULTS

The results of the [45/-45]t Fiberglas test were less predictable than the previous materials, but they did tend to show the same general trends as the Kevlar samples. The theoretical value for Ex/Ey [45/-45]t case was 12.514 GPa. the actual test result showed a Young's modulus of 6.0 GPa., or one half the predicted unidirectional value. This is a more dramatic difference than previously encountered but is in a direction consistent with expectations. The Poisson's ratio showed a almost identical match with the predicted estimate. The test result showed a Poisson's ratio of .5 the theoretical prediction was for .52.

SUMMARY OF [0/90/BALSA/90/0] AND THE [45/-45/BALSA/45/-45]

KEVLAR BALSA CORE KEVLAR

TEST RESULTS

Since there were no theoretical values calculated for the Balsa core cases, there are no direct comparisons to be made. However, since the Balsa core greatly increases the effective cross sectional area, but is significantly weaker across this area (than Kevlar alone), one should expect a steep decline in the Young's Modulus of the material. This was clearly the case with the 0/90 case having a Ex = 2.44 GPa., while the 45/-45 case had a Ex= 1.506 GPa., compared to the respective Kevlar alone Ex values (with no Balsa) of 32.7 GPa. (0/90 case) and 5.23 GPa. (45/-45 case). The Poisson's ratio for the 0/90 case was .2322 about 2 1/2 times the Kevlar alone value. The Poisson's ratio for the 45/-45 case was ~1.2 or 1 1/2 times the Kevlar alone value. The E6 (G12 IN JONES) value for this material was .4935 GPa., not surprisingly the lowest yet.

CONCLUSION

The tables below gives a synopsis of the key parameters for the comparison of predicted values (for conventional composite materials) against the actual values for the materials tested.

THEORETICAL VALUES

MATERIAL	Ex	Ey	vx	Es	vf	Spec. Grav.
Fiberglas	23.6	23.6	.091	4.16	.45	1.8
Kevlar	41.0	41.0	.046	2.3	.60	1.46

ACTUAL VALUES

MATERIAL	Ex	Ey	vx	Es	vf	Spec. Grav.
Fiberglas	20.3	20.3	.256	1.685	.50	1.025
Kevlar	32.7	32.7	.0969	1.41	.66	0.805
KVL/Balsa Core	2.4	2.4	.2322	.4935	--	--

CONCLUSION

This study was conducted to determine the key material properties needed to fully describe the behavior of certain composite materials. In accordance with established practice, the materials of concern were broken up into their constituent layers and tested. The atypical fabrication process used in the manufacturing of these composites had a direct impact on the parameters of concern. The table on the last page lists the key parameters measured, along with their theoretical values, had a conventional fabrication process been used.

For the Kevlar composite tested the Shear Modulus was decreased by 39%, the Poisson's ratio doubled, the specific gravity decreased by 45% while the percentage of volume fiber went up 10%. For the Fiberglas composite the Shear Modulus decreased by 60%, the Poisson's ratio more than doubled, the specific density decreased by 43%, the volume fiber went up by 12%. These numbers are comparisons done against theoretical values predicted for the same composite, fabricated with a dam structure in place.

The testing showed that the cost of using the existing fabrication process is a reduction in the material properties associated with a conventional fabrication procedure. Apparently, the presence of a dam increases the Longitudinal Shear Modulus, as well as other material properties by holding more of the resin more evenly over the entire composite. This cost, associated with the existing fabrication process, should be closely weighed against the benefits of the weight reductions for each specific application.

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