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MECHANICAL PROPERTY CHARACTERIZATION OF INTRAPLY HYBRID COMPOSITES

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ABSTRACT

A investigation was conducted to characterize the mechanical properties of intraply hybrids made from graphite fiber/epoxy matrix (primary composites) hybridized with varying amounts of secondary composites made from S-glass or Kevlar 49 fibers. The tests were conducted using thin laminates having the same thickness. The specimens for these tests were instrumented with strain gages to determine stress-strain behavior. The results show that the mechanical properties of intraply hybrid composites can be measured using available test methods such as the ten-degree off-axis method for intralaminar shear, and conventional test methods for tensile, flexure, and Izod impact properties. Intraply hybrids have linear stress-strain curves to fracture for longitudinal tension and nonlinear stress-strain curves for intralaminar shear.

The results also showed that combinations of high modulus graphite/ S-glass/ epoxy matrix composites exist which yield intraply hybrid laminates with the "best" balanced properties, for example: 100-percent increase in impact resistance, 35-percent increase in tensile and flexural strengths, with no reduction in modulus compared to graphite fiber/ epoxy matrix composites. In addition, the results showed that the translation efficiency of mechanical properties from the consistituent composites to intraply hybrids may be assessed using a simple equation.

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INTRODUCTION

Intraply hybrid composites have two kinds of fibers embedded in the matrix in general within the same ply. They have evolved as a logical seque to conventional composites and to interply hybrids. Intraply hybrid composites have unique features that can be used to meet diverse and competing design requirements in a more costeffective way than either advanced or conventional composites. Some of the specific advantages of intraply hybrids over other composites are balanced strength and stiffness, balanced bending and membrane mechanical properties, balanced thermal distortion stability, reduced weight and/or cost, improved fatigue resistance, reduced notch sensitivity, improved fracture toughness and/or crack-arresting properties, and improved impact resistance. By using intraply hybrids, it is possible to obtain a viable compromise between mechanical properties and cost to meet specified design requirements.

The available methodology for analysis and design of intraply hybrids as well as areas that need further research, were covered in a recent review on hybrid composites in general (ref. 1). Two of the areas identified in that reference are: (1) the development of micromechanics equations for predicting the various mechanical and thermal properties of unidirectional intraply hybrids, and (2) the characterization of mechanical properties of intraply hybrid composites. Approximate equations based on the rule-of-mixtures" were presented in reference 2. Equations based on micromechanics concepts are described in reference 3. Comparisons of properties using these micromechanics equations, linear laminate theory and finite element analysis are also given in reference 3. Verification of all these predictive methods requires measured properties obtained from the same laminate in order to minimize any effects that may be induced by processing and fabrication variables. The objective of this investigation was to determine whether available test methods for measuring mechanical properties such as longitudinal and transverse tensile, shear, flexural and Izod impact strengths can be used for the mechanical property characterization of intraply hybrids using thin composite laminates. Another objective was to assess the load transfer efficiency from the constituent composites to the intraply hybrid using available equations.

CONSTITUENT COMPOSITES AND INTRAPLY HYBRIDES

The constituent composites used in this investigation were made from low and high modulus graphite fibers (AS and HMS), S-glass fibers and Kevlar 49 fibers and PR288 epoxy resin matrix. These constituent composites will be referred to, respectively, as AS/E, HMS/E, S-G/E and KEV/E throughout the paper.

The unidirectional properties of the constituent composites that were used in this investigation are summarized in table 1. The use of the properties in this table will be described later.

The intraply hybrids made from these constituent composites consisted of the following primary/secondary composite volume percentages: 90/10, 80/20, and 70/30 of AS/E with either S-G/E or KEV/E, and HMS/E with either S-G/E or KEV/E. These intraply hybrids will be identified using the following notation AS/E//S-G/E, AS/E//KEV/E, HMS/E//S-G/E and HMS/E//KEV/E.

SPECIMEN FABRICATION, PREPARATION, INSTRUMENTATION AND TESTING

Constituents and intraply hybrid composite laminates were made by press curing a total of eight unidirectional prepreg plies into laminates having a thickness of 0.10 cm (0.040 in.), a width of 15 cm (6 in.), and a length of 30 cm (12 in.). The constituent and intraply hybrid composite plies were made by combining continuous strands of fibers and a matrix resin, followed by staging to provide a prepreg material that could be cut and fitted into the laminate molds. The intraply hybrid composite plies were made by combining various percentages, by volume, of the primary composites with secondary, or hybridizing, composites in a "tow-by-tow" fashion (fig. 1) that grouped the fibers in discrete bundles within the ply to give the volume percentages mentioned previously. A PR288 epoxy resin system (3 M Company designation) was used as the resin matrix for all of the laminates. The supplier's recommended curing procedure was used for fabrication of the laminates (2 hours at 149°C (300°F)).

The laminates were cut into 1.27 cm (0.5 in.) wide specimens by using a precision wafer cutting machine equipped with a diamond wheel. A typical laminate cutting plan and specimen description is shown in figure 2.

The ends of the specimens subjected to tensile loading were reinforced with fiberglass/epoxy tabs adhesively-bonded to the specimen surfaces. The longitudinal and transverse tensile and the 10° off-axis shear specimens were equipped with back-to-back strain gages. Details of the types and locations of the strain gages along with specimen dimensions are shown in figure 3.

Three replicates of tensile specimens for longitudinal, transverse and 10° off-axis properties were loaded to fracture using a mechanically actuated universal testing machine. The loading rate was 0.13 cm/min (0.05 in/min). Loading of all specimens was halted at periodic intervals so that strain gage data could be obtained using a digital strain recorder. The digital data was processed using a strain-gage data reduction computer program (ref. 4) for stress-strain curves, moduli and Poisson's ratios. This computer program also generates the intralaminar shear stress-strain curves and moduli from the 10° off-axis tensile data as described in reference 5.

The flexural specimens were tested for flexural strength in a mechanically actuated universal testing machine using a three point loading system. The length of the specimens was 7.62 cm (3 in). The span between supports was 5.08 cm (2 in) or a span-to-depthratio of about 51 which is considered more than adequate for measuring flexural properties with negligible contribution from interlaminar shear. The flexural strength was calculated from the bending load at fracture using the simple beam equation.

The Izod impact specimens had a cantilever length of 3.2 cm (1.25 in) and were tested using an Izod impact tester (TMI) equipped with a 0.9 kilogram (2-lb) hammer. The velocity of the hammer was approximately 3 meter/sec (10 ft/sec). The data obtained were normalized with respect to the cross sectional area of the specimens for convenience of comparison.

RESULTS, COMPARISON AND DISCUSSION

Typical stress-strain curves obtained from the reduction of the strain gage data are shown in figures 4, 5 and 6. The curves in figures 4 and 5 show linear and approximately linear behavior to fracture for longitudinal and transverse tension. One conclusion from the curves in figures 4 and 5 is that the intraply hybrids exhibit "hybrid action". If this were not the case, the stress-strain curves would exhibit at least a bilinear behavior to fracture. The deviation from the first linear portion would occur after extensive fractures in the primary composite (AS/E or HMS/E). The intralaminar shear stress-strain curve in figure 6 is nonlinear which should be expected since the corresponding curves of the constituents are also nonlinear. Photographs of typical fractured specimens are shown in figure 7. As can be seen, the specimens failed within the test gage section.

The measured results, averages of three replicates, for the mechanical properties of the various intraply hybrids are summarized in tables 2 to 5.

The mechanical properties for AS/E//S-G/E hybrid are shown in table 2. Those for the HMS/E//S-G/E hybrid are shown in table 3; for AS/E//KEV/E, in table 4 and those for HMS/E//KEV/E are shown in table 5.

To facilitate comparisons and discussion, significant properties of the intraply hybrids and the constituent properties are summarized in bar charts in figures 8 to 11. The bar chart summary for the tensile strength is shown in figure 8. It can be seen in this figure that the intraply hybrids from AS/E//S-G/E and AS/E//KEV/E utilize the tensile strength of the consitituent composites effectively. That is, the tensile strength of these intraply hybrids is about equal to or greater than the lower property of the constituent composites (AS/E, S-G/E or KEV/E). The tensile strength of the 90/10 AS/E//S-G/E is about 24 percent greater than the tensile strength of the AS/E constituent composite indicating some synergistic effect.

The bar chart summary for tensile modulus is shown in figure 9. It can be seen in this figure that all intraply hybrids utilize the tensile modulus of the constituent composites effectively. The bar chart summary for flexural strength is shown in figure 10. Again, all the intraply hybrids utilize the flexural strength of the constituent composites effectively. The AS/E//KEV/E intraply hybrids show some 8 to 20 percent synergistic effect while the 90/10 HMS/E//KEV/E intraply hybrid shows considerable (about 69 percent) synergistic effect.

The bar chart summary for thin specimen Izod longitudinal impact is shown in figure 11. The results in this figure show improvement in the longitudinal impact resistance of the intraply hybrids, relative to the primary composite (AS/E or HMS/E), as follows: (1) from 61 to 117 percent for the AS/E//S-G/E, (2) from 286 to 449 percent for the HMS/E//S-G/E, (3) from 25 to 169 percent for the AS/E//KEV/E and (4) from 111 to 133 percent for the HMS/E//KEV/E. Note the test data shows a decrease for the 70/30 HMS/E//KEV/E intraply hybrid which may indicate that an optimum hybridizing ratio exists for this class of intraply hybrids. The conclusion from these data is that hybridizing via the intraply hybrid is a very effective way for greatly improving the impact resistance of graphite fiber composites.

Taking the data for all the properties collectively, the AS/E//S-G/E intraply hybrids utilize the constituents most effectively. These intraply hybrids provide significant improvement in impact resistance, some improvement in tensile and flexural strengths, and negligible or no degradation in tensile modulus. Also large improvements in impact resistance can be realized by hybridizing HMS/E with S-G/E.

The discussion thus far was relative to comparisons of intraply hybrid properties with the properties of either one or both constituent composites. The anticipated properties for intraply hybrids may be predicted from the constituent composite properties by using the following "rule-of-mixtures" equation

$$P_{HC} = P_{PC} + V_{SC} (P_{SC} - P_{PC}) \qquad (1)$$

where P denote property, V denotes volume ratio, and the subscripts HC, PC and SC denote hybrid composite, primary composite, and secondary composite, respectively. Detail justifications for using equation (1) are given in references 2 and 3. For the present discussion, it is sufficient to say that the derivation of equation (1) requires complete hybrid response. This means: (1) perfect bond between the constituent composites, and (2) 100 percent property translation from the constituent composites to the intraply hybrid. Comparison of measured and predicted properties using equation (1) provides an indication of the effectiveness of property translation and, indirectly, of the quality of the intraply hybrid.

Elastic and strength properties of the intraply hybrids predicted using equation (1) are summarized in tables 6 to 9. For convenience of comparison, the measured properties in these tables are normalized with respect to the corresponding predicted properties. The normalized results are summarized graphically in figure 12 for elastic properties and in figure 13 for strengths. The normalized results in these figures represent a measure of the efficiency of property translation from the constituent composites to the intraply hybrid as follows: (1) unity values indicate 100 percent property translation (complete hybrid response), (2) greater-than-unity values indicated some "synergistic effect" for all the properties and/or a concentration of volume of the stronger constituent at the fracture surface for strengths, (3) less-than-unity values indicate incomplete hybrid response (partial bond between constituents) for all the properties and/or a concentration of volume of the weaker constituent at the fracture surface for strengths.

It can be seen in figure 12 that the normalized results for the elastic properties lie either slightly below or above the unity value line in general. Therefore, the intraply hybrids exhibit complete hybrid response for elastic properties. The consistantly higher-than-unity values for shear modulus (except for HMS/E//KEV/E) most probably indicate an S-glass rich region at the strain gage location.

The AS/E//S-G/E intraply hybrids show complete hybrid response (efficient property translation) for strengths except for transverse impact (TI) figure 13(a). The low translation efficiency for TI may be, in part, due to the dynamic stress transfer at the interface of the constituent composites near the cantilever end of the Izod impact specimen. The HMS/E//S-G/E intraply hybrids show low efficiency in property translation for TI and longitudinal tension (LT) strength (fig. 13(b)). The reason mentioned previously for the AS/E//S-G/E hybrid is believed to cause low efficiency for TI. The low efficiency property translation for LT strength is mainly due to partial hybrid action caused perhaps by insufficient bond between the constituents at the interface. For example, the calculated longitudinal stress in the HMS/E composite at fracture is 503 MPa (73 ksi) which is about 48 percent of its unidirectional strength (1055 MPa (153 ksi), table 1). The AS/E//KEV/E intraply also shows low efficiency in property translation, figure 13(c) while the HMS/E//KEV/E show good efficiency except for TI figure 13(d). Taken collectively, the strength data in figure 13 show the following: (1) AS/E//S-G/E and HMS/E//KEV/E intraply hybrids have high efficiency in strength translation; (2) HMS/E//S-G/E and AS/E//KEV/E intraply hybrids are inefficient in strength translation; and (3) the intraply hybrids have poor transverse impact resistance.

Based on the correlation between measured data and equation (1) it may be concluded that 8-ply thick laminates can be used to characterize the tensile, flexural and Izod impact properties of unidirectional intraply hybrids. Also, for the same reason, a specimen width of 1.27 cm (0.50 in) appears to be sufficient. Specimens from the same thin laminate should be suitable for characterizing compression properties of unidirectional intraply hybrids in compression test fixtures which provide lateral supports. Specimens from the same thin laminate should also be suitable for properties such as fatigue resistance, notch sensitivity and environmental effects. Data from all these tests should provide a broad base to verify available predictive methods as well as provide a basis for formulating new ones.

SUMMARY OF RESULTS

An investigation was conducted to characterize the tensile, flexural, and Izod impact properties of intraply hybrid composites, and to assess the effective use of the constituent composites in the intraply hybrid as well as efficiency in property translation. The primary constituent composites were graphite fiber AS/epoxy PR288 and HMS/epoxy PR288 (AS/E and HMS/E). The secondary constituent composites were S-glass fiber/epoxy PR288 and Kevlar 49-fiber/epoxy PR288 (S-G/E and KEV/E). Intraply hybrids were made from the following volume percentages of primary/secondary composite 90/10, 80/20 and 70/30 from combinations of (primary//secondary) AS/E//S-G/E, AS/E//KEV/E, HMS/E//S-G/E and HMS/E//KEV/E. The major results from this investigation are as follows:

1. Thin laminates (8-plies thick) are suitable to characterize the tensile, flexural and Izod impact properties of unidirectional intraply hybrids.
2. Stress-strain curves of these intraply hybrids exhibit linear or approximately linear behavior to fracture for longitudinal and transverse tension and nonlinear behavior for intralaminar shear. Test specimens fractured within the test gage section.
3. Intraply hybrids utilize the constituents effectively; that is, the intraply hybrid property is greater than that of its weaker constituent.
4. Intraply hybrids exhibit complete hybrid response and show high translation efficiency (100 percent or greater) in elastic properties (moduli and Poisson's ratio).
5. Intraply hybrids AS/E//S-G/E and HMS/E//KEV/E show high translation efficiency in strength (except transverse Izod impact) while AS/E//KEV/E and HMS/E//S-G/E show low translation efficiency based on predictions using approximate equations.

6. Intraply hybrids AS/E//S-G/E exhibit a synergistic effect in longitudinal tension (strength greater than either constituent); AS/E//KEV/E and HMS/E//KEV/E exhibit a synergistic effect in longitudinal flexure.

7. Intraply hybrids AS/E//S-G/E show appreciable improvements in longitudinal impact resistance (about 100 percent and greater compared to AS/E) accompanied by increases in longitudinal tensile and flexural strengths and no reduction in modulus or in intralaminar shear strength.

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TABLE 1. - UNIDIRECTIONAL PROPERTIES OF CONSTITUENT COMPOSITES, EXPERIMENTALLY MEASURED

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Composite			
	AS/E	HMS/E	S-G/E	KEV 49/E
Longitudinal strength, ksi	213.7	152.6	192.3	186
Transverse strength, ksi	10.4	2.88	11.2	4.1
Intralaminar shear strength, ksi	13.0	6.5	10.7	6.5
Longitudinal strain, percent	1.12	0.535	2.84	1.73
Transverse strain, percent	0.83	0.300	0.57	-0.76
Intralaminar shear strain, percent	5.17	0.96	4.13	[a]2.36
Longitudinal modulus, 10^6 psi	18.2	26.5	6.95	11.2
Transverse modulus, 10^6 psi	1.28	0.95	2.17	0.80
Shear modulus, 10^6 psi	0.600	0.779	0.644	0.41
Major Poisson's ratio	0.32	0.25	0.30	0.44
Minor Poisson's ratio	0.05	0.022	0.075	0.029
Flex strength (longitudinal), ksi	230.3	122.5	318	105
Flex strength (transverse), ksi	17.8	[a]7	21.2	5.8
Izod impact (longitudinal), in-lb/in^2	241.3	[a]84	1260.0	790.8
Izod impact (transverse), in-lb/in^2	41.3	[a]5	69.6	25.2

[a]Estimated.

Most data based on average value of three specimens, 2 gages each, back-to-back.

TABLE 2. - MEASURED PROPERTIES OF INTRAPLY HYBRIDS AS/E//S-G/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)	
	90/10	80/20
Longitudinal tensile strength, ksi	265	191
Transverse tensile strength, ksi	10.8	9.5
Intralaminar shear strength, ksi	14.4	12.3
Longitudinal tensile strain, percent	1.3	1.06
Transverse tensile strain, percent	0.74	0.63
Intralaminar shear strain, percent	3.03	3.05
Longitudinal modulus, 10^6 psi	20	17.8
Transverse modulus, 10^6 psi	1.6	1.7
Shear modulus, 10^6 psi	1.12	0.925
Major Poisson's ratio	0.31	0.30
Minor Poisson's ratio	0.03	0.03
Flex strength (longitudinal), ksi	263	275
Flex strength (transverse), ksi	21.3	22.7
Izod impact (longitudinal), in-lb/in^2	388	522
Izod impact (transverse), in-lb/in^2	18.3	26.7

TABLE 3. - MEASURED PROPERTIES ON INTRAPLY HYBRIDS HMS/E//S-G/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)		
	90/10	80/20	70/30
Longitudinal tensile strength, ksi	84.7	81.3	109
Transverse tensile strength, ksi	5.0	4.2	6.1
Intralaminar shear strength, ksi	8.15	8.09	9.5
Longitudinal tensile strain, percent	0.38	0.31	0.45
Transverse tensile strain, percent	0.36	0.34	0.35
Intralaminar shear strain, percent	1.40	0.84	0.70
Longitudinal modulus, 10^6 psi	30.4	29.6	24.1
Transverse modulus, 10^6 psi	1.4	1.5	1.9
Shear modulus, 10^6 psi	0.87	1.38	1.3
Major Poisson's ratio	0.30	0.32	0.27
Minor Poisson's ratio	0.014	0.02	0.027
Flex strength (longitudinal), ksi	109	148	153
Flex strength (transverse), ksi	7.9	10.6	13.1
Izod impact (longitudinal), in-lb/in^2	324	453	618
Izod impact (transverse), in-lb/in^2	5.7	12.0	12.6

TABLE 4. - MEASURED PROPERTIES OF INTRAPLY HYBRIDS AS/E//KEV/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)		
	90/10	80/20	70/30
Longitudinal tensile strength, ksi	196	204	205
Transverse tensile strength, ksi	8.4	6.7	5.4
Intralaminar shear strength, ksi	10.5	11.6	10.9
Longitudinal tensile strain, percent	0.38	1.13	1.01
Transverse tensile strain, percent	0.40	0.54	0.45
Intralaminar shear strain, percent	[a]2.72	2.89	[a]3.44
Longitudinal modulus, 10^6 psi	18.5	17.8	16.8
Transverse modulus, 10^6 psi	1.4	1.4	1.2
Shear modulus, 10^6 psi	0.78	0.81	0.64
Major Poisson's ratio	0.32	0.33	0.30
Minor Poisson's ratio	0.015	0.045	0.03
Flex strength (longitudinal), ksi	205	246	253
Flex strength (transverse), ksi	7.4	12.9	10.1
Izod impact (longitudinal), in-lb/in^2	302	376	408
Izod impact (transverse), in-lb/in^2	11.1	9.4	9.6

[a]Estimated.

TABLE 5. - MEASURED PROPERTIES OF INTRAPLY HYBRIDS HMS/E//KEV/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)		
	90/10	80/20	70/30
Longitudinal tensile strength, ksi	103	105	110
Transverse tensile strength, ksi	4.6	5.0	5.3
Intralaminar shear strength, ksi	7.99	7.97	7.52
Longitudinal tensile strain, percent	0.37	0.38	0.43
Transverse tensile strain, percent	0.40	0.43	0.52
Intralaminar shear strain, percent	1.44	1.42	1.59
Longitudinal modulus, 10^6 psi	26.8	26.9	25.9
Transverse modulus, 10^6 psi	1.4	1.1	1.0
Shear modulus, 10^6 psi	0.745	0.549	0.659
Major Poisson's ratio	0.33	0.27	0.35
Minor Poisson's ratio	0.02	0.02	0.017
Flex strength (longitudinal), ksi	205	130	130
Flex strength (transverse), ksi	7.4	9.7	10.1
Izod impact (longitudinal), in-lb/in^2	190	196	177
Izod impact (transverse), in-lb/in^2	11.1	5.7	5.7

TABLE 6. - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR INTRAPLY HYBRID AS/E//S-G/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)								
	90/10			80/20			70/30		
	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]
Modulus, 10^6 psi									
Longitudinal tensile	20.0	17.1	17.0	17.8	15.9	11.9	-----	14.8	--------
Transverse tensile	1.6	1.4	14.3	1.7	1.5	13.3	-----	1.5	--------
Shear	1.12	0.60	86.7	0.925	0.61	51.6	-----	0.61	--------
Poisson's ratio	0.31	0.32	-3.1	0.30	0.32	-6.3	-----	0.31	--------
Strength, ksi									
Longitudinal tensile	265	212	25.0	191	209	-8.6	-----	193	--------
Transverse tensile	10.8	10.5	2.9	9.5	10.6	-10.4	-----	10.6	--------
Intralaminar shear	14.4	12.8	12.5	12.3	12.5	-1.6	-----	12.3	--------
Longitudinal flexure	263	239	10.0	275	248	-10.9	-----	257	--------
Transverse flexure	21.3	18.1	17.7	22.7	18.5	22.7	-----	18.8	--------
Thin specimen									
Izod impact, in-lb/in^2									
Longitudinal	328	343	-4.4	522	445	17.3	-----	547	--------
Transverse	18.3	44.1	-58.5	26.7	47.0	-43.2	-----	49.8	--------

[a]With respect to predicted value.

TABLE 7. - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR INTRAPLY HYBRID HMS/E//S-G/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)								
	90/10			80/20			70/30		
	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]
Modulus, 10^6 psi									
Longitudinal tensile	30.4	24.5	24.1	29.6	22.6	31.0	24.1	20.6	17.0
Transverse tensile	1.4	1.1	27.3	1.5	1.2	25.0	1.9	1.3	46.1
Shear	0.87	0.77	13.0	1.38	0.75	84.0	1.3	0.74	75.7
Poisson's ratio	0.30	0.32	-6.3	0.32	0.32	0.0	0.27	0.31	-12.9
Strength, ksi									
Longitudinal tensile	84.7	157	-46.1	81.3	161	-49.5	109	165	-33.9
Transverse tensile	5.0	3.7	35.1	4.2	4.5	-6.7	6.1	5.4	13.0
Intralaminar shear	8.15	6.9	18.1	8.09	7.3	10.8	9.5	7.8	21.8
Longitudinal flexure	109	142	-23.2	148	162	-8.6	153	181	-15.5
Transverse flexure	7.9	8.4	-5.9	10.6	9.8	8.2	13.1	11.3	15.9
Thin specimen Izod impact, in-lb/in^2									
Longitudinal	324	202	60.4	453	319	42.0	618	437	41.4
Transverse	5.7	11.5	-50.4	12.0	17.9	-33.0	12.6	24.5	-48.6

[a]With respect to predicted value.

TABLE 8. - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR INTRAPLY HYBRID AS/E//KEV 49/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)								
	90/10			80/20			70/30		
	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]
Modulus, 10^6 psi									
Longitudinal tensile	18.5	17.5	5.7	17.8	16.8	6.0	16.8	16.1	4.3
Transverse tensile	1.4	1.2	16.7	1.4	1.2	16.7	1.2	1.1	9.1
Shear	0.78	0.58	34.5	0.81	0.56	44.6	0.64	0.54	18.5
Poisson's ratio	0.32	0.33	-3.0	0.33	0.34	-2.9	0.30	0.36	-16.7
Strength, ksi									
Longitudinal tensile	196	211	-7.1	204	208	-1.9	205	205	0.0
Transverse tensile	8.4	9.8	-14.3	6.7	9.1	-26.4	5.4	8.5	-36.5
Intralaminar shear	10.5	12.3	-14.6	11.6	11.7	-0.9	10.9	11.1	-1.8
Longitudinal flexure	205	218	-6.0	246	205	20.0	253	193	31.1
Transverse flexure	7.4	16.6	-55.4	12.9	15.4	-16.2	10.1	14.2	-289
Thin specimen Izod impact, in-lb/in^2									
Longitudinal	190	296	-35.8	376	351	7.1	408	406	0.5
Transverse	11.1	39.7	-72.0	9.4	38.1	-75.3	9.6	36.5	-73.7

[a]With respect to predicted value.

TABLE 9. - COMPARISON OF MEASURED AND PREDICTED PROPERTIES FOR INTRAPLY HYBRID HMS/E//KEV 49/E

[Conversion factors: ksi = 6.89 MPa; 10^6 psi = 6.89 GPa.]

Property	Percent constituents (primary/secondary)								
	90/10			80/20			70/30		
	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]	Measured	Predicted	Percent[a]
Modulus, 10^6 psi									
Longitudinal tensile	26.8	25.0	7.2	26.9	23.4	15.0	25.9	21.9	18.3
Transverse tensile	1.4	0.94	48.9	1.1	0.92	19.6	1.0	0.91	9.9
Shear	0.745	0.742	0.4	0.549	0.705	-22.1	0.659	0.668	-1.3
Poisson's ratio	0.33	0.27	22.2	0.27	0.29	-6.9	0.35	0.31	12.9
Strength, ksi									
Longitudinal tensile	103	156	-34.0	105	159	-34.0	110	163	-32.5
Transverse tensile	4.6	3.0	53.3	5.0	3.1	61.3	3.2	3.2	0.0
Intralaminar shear	7.99	6.5	22.9	7.97	6.5	22.6	7.52	6.5	15.7
Longitudinal flexure	205	121	69.4	130	119	9.2	130	117	11.1
Transverse flexure	7.4	6.9	7.2	9.7	6.8	42.6	10.1	6.6	53.0
Thin specimen Izod impact, in-lb/in^2									
Longitudinal	190	155	22.6	196	225	-12.9	177	296	-40.2
Transverse	11.1	7.0	58.6	5.7	9.0	-36.7	5.7	11.9	-52.1

[a]With respect to predicted value.

$$P_{IH} = V_{PC}P_{PC} + V_{SC}P_{SC}$$

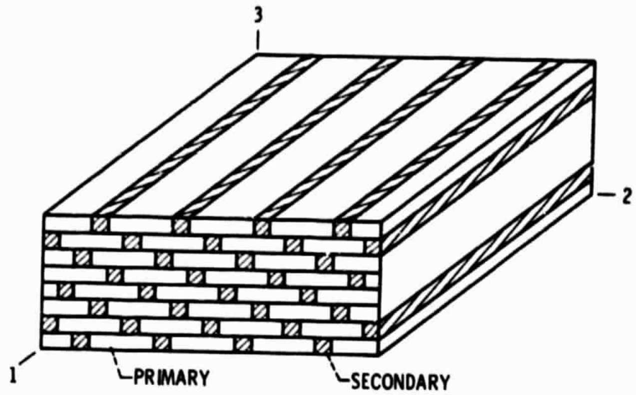

Figure 1. - Schematic of unidirectional intraply hybrid composite and approximate equation for property translation efficiency.

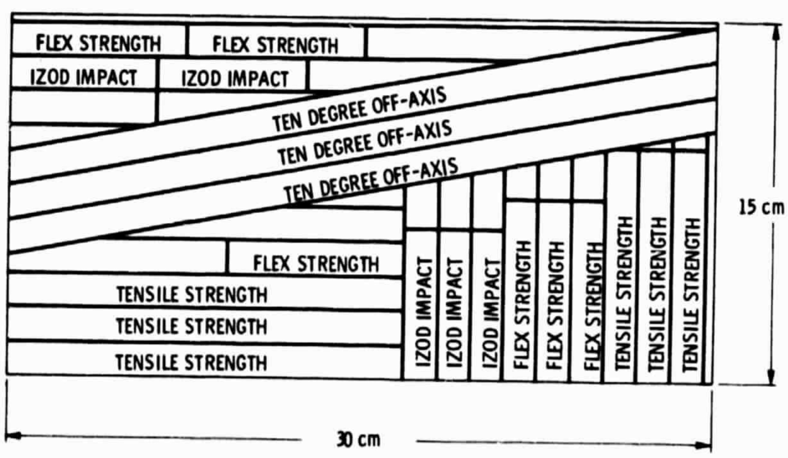

Figure 2. - Laminate cutting plan.

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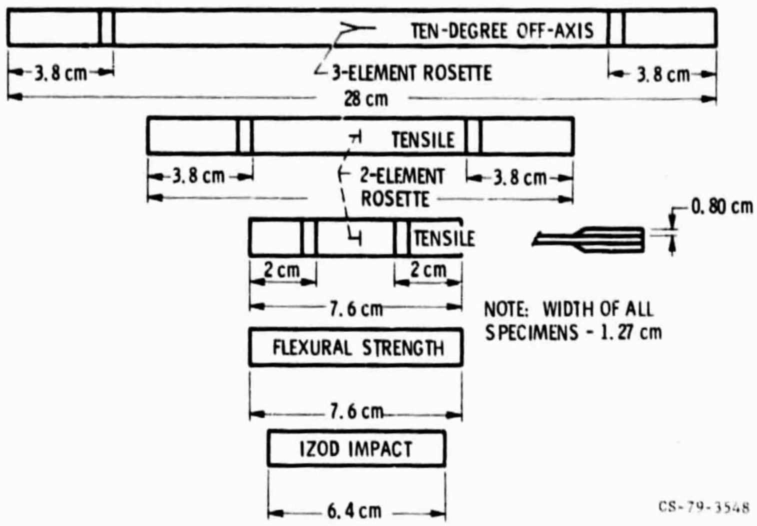

Figure 3. - Specimen and instrumentation details.

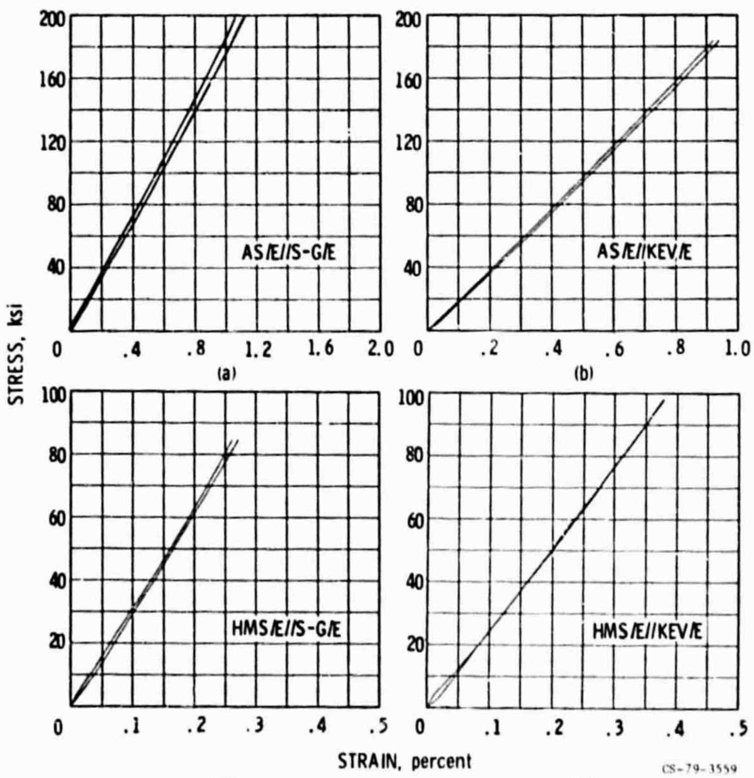

Figure 4. - Longitudinal tensile stress-strain curves of intraply hybrid composites (80/20, volume percent of constituent composites; ksi - 6.89 MPa).

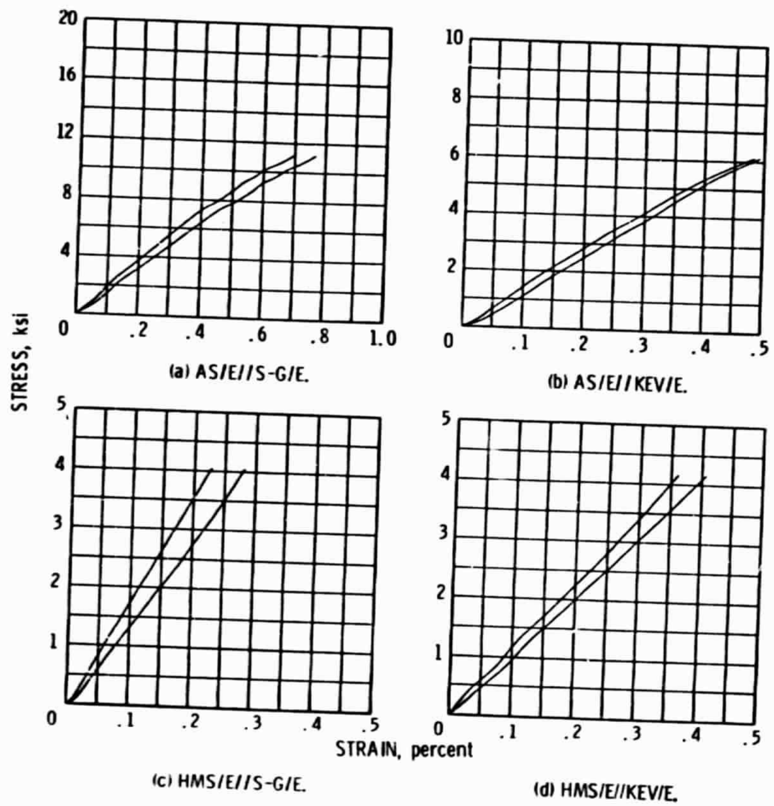

Figure 5. - Transverse tensile stress-strain curves of intraply hybrid composites (80/20, volume percent of constituent composites; ksi = 6.89 MPa).

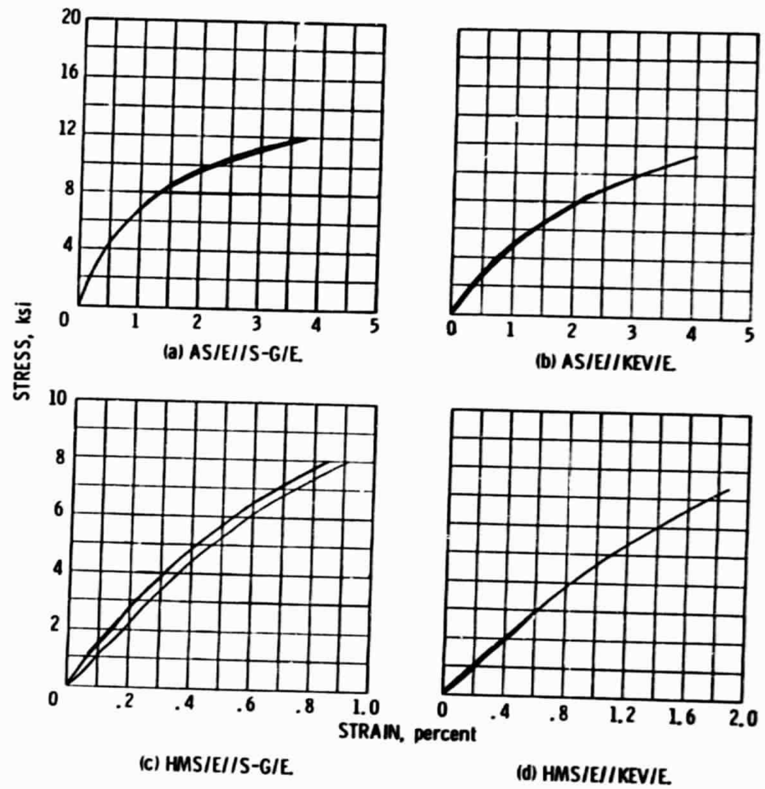

Figure 6. - Intralaminar shear stress-strain curves (10^0 off-axis) of intraply hybrid composites (80/20, volume percent of constituent composites; ksi = 6.89 MPa).

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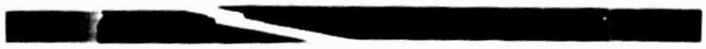

(a) INTRALAMNAR SHEAR (10° OFF-AXIS).

(b) LONGITUDINAL TENSION.

(c) TRANSVERSE TENSION.

Figure 7. - Fractured specimens of intraply hybrid composite (80/20 volume percent-As/E//S-G/E).

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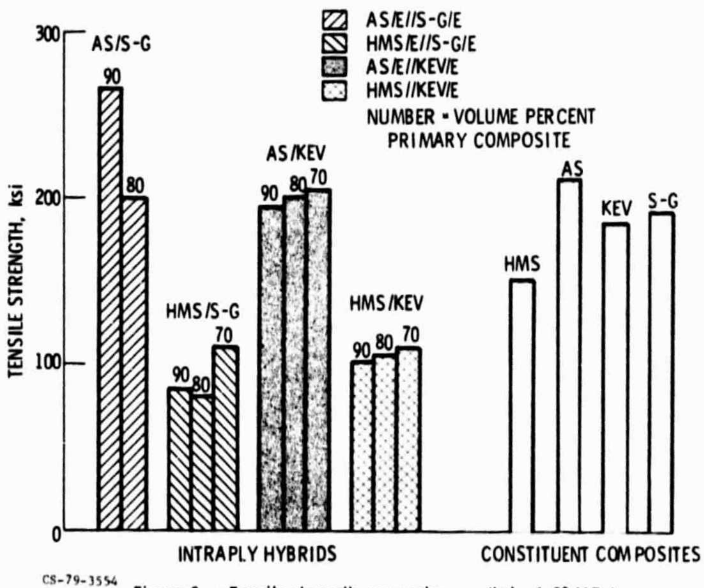

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Figure 8. - Tensile strength comparisons. (ksi = 6.89 MPa)

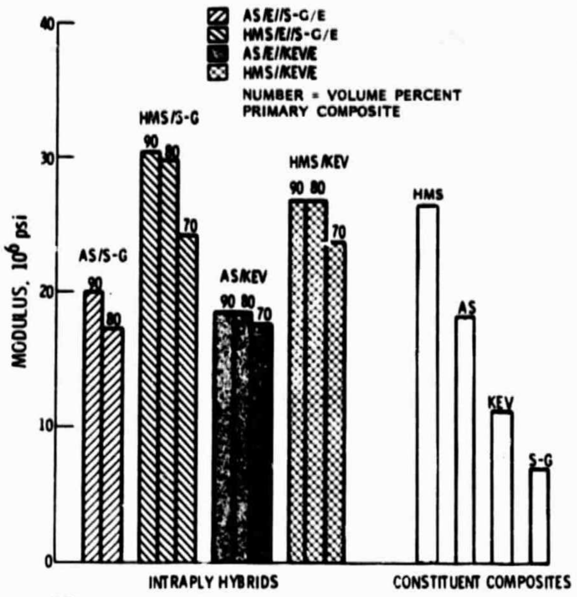

Figure 9. - Tensile modulus comparisons. (10^6 psi = 6.89 GPa)

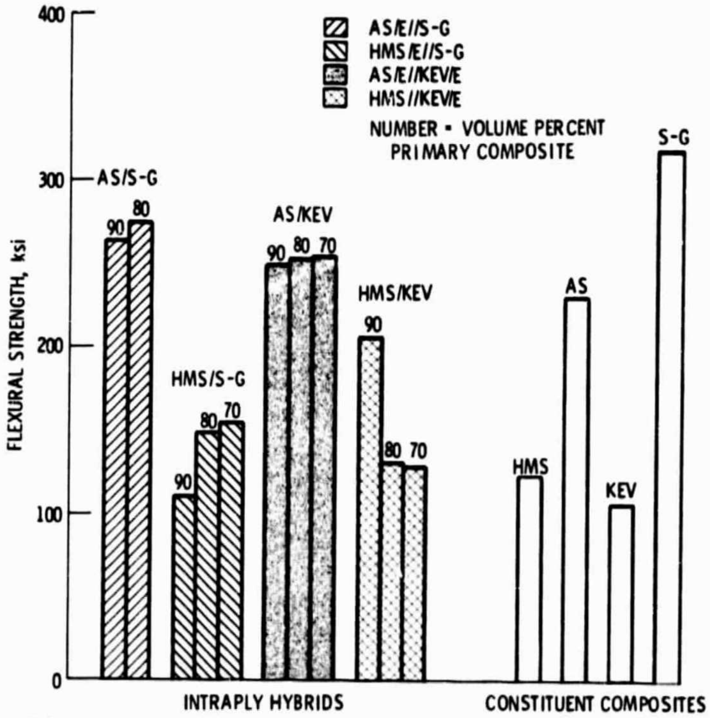

Figure 10. - Flexural strength comparisons.

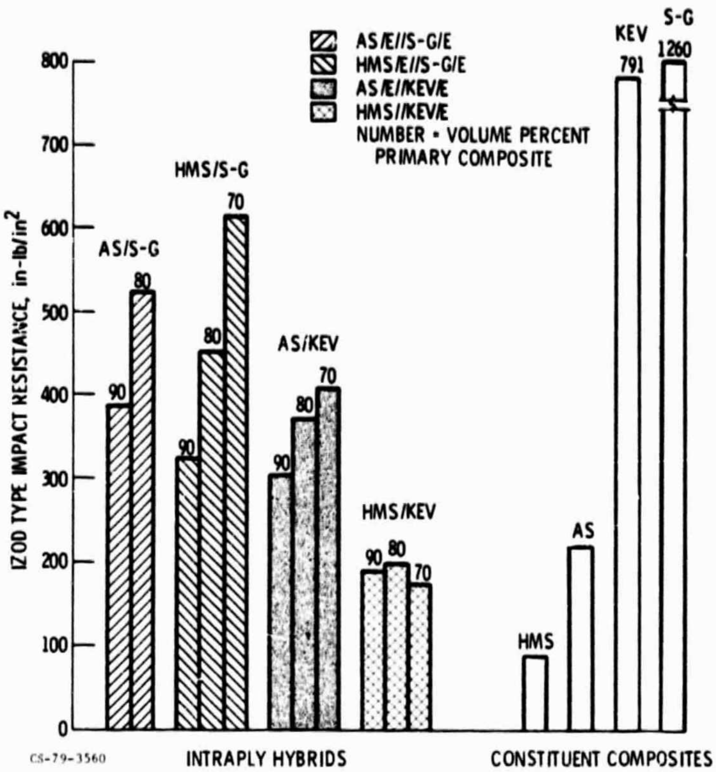

Figure 11. - IZOD type impact comparisons. (in-lb/in^2 = 0.1458 cm N/cm^2)

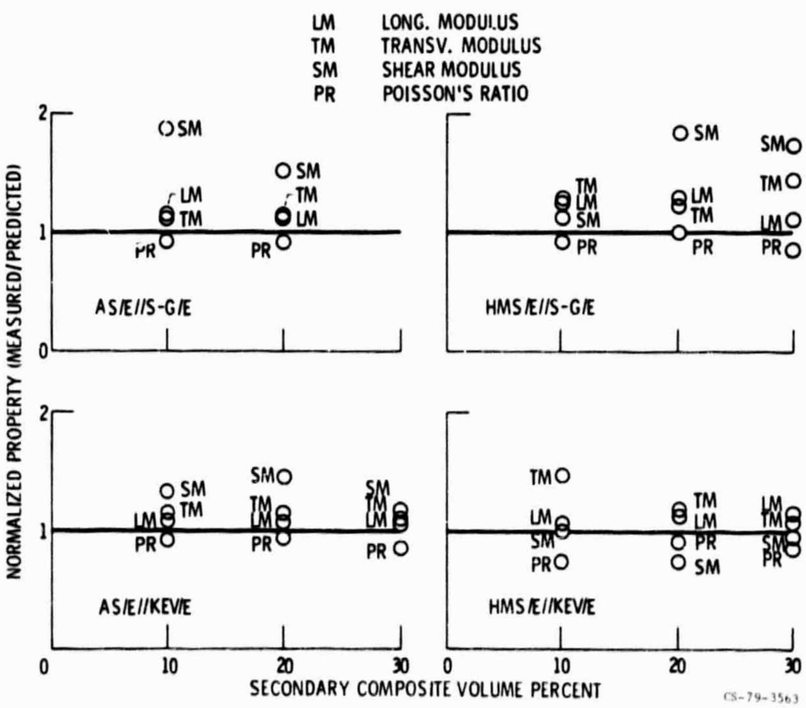

Figure 12. - Elastic property translation efficiency summary of intraply hybrids (average of three replicates).

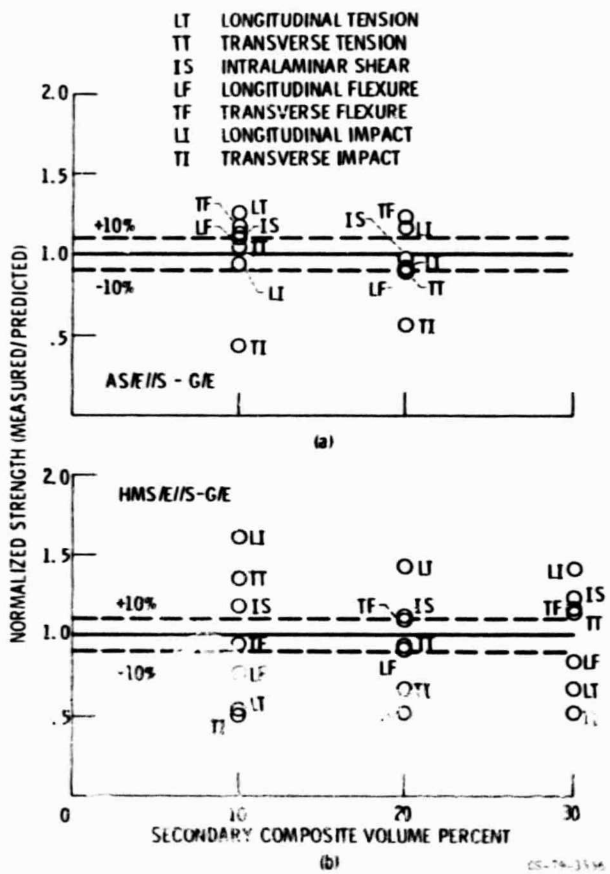

Figure 13. - Strength translation efficiency summary of intraply hybrids (average of three replicates).

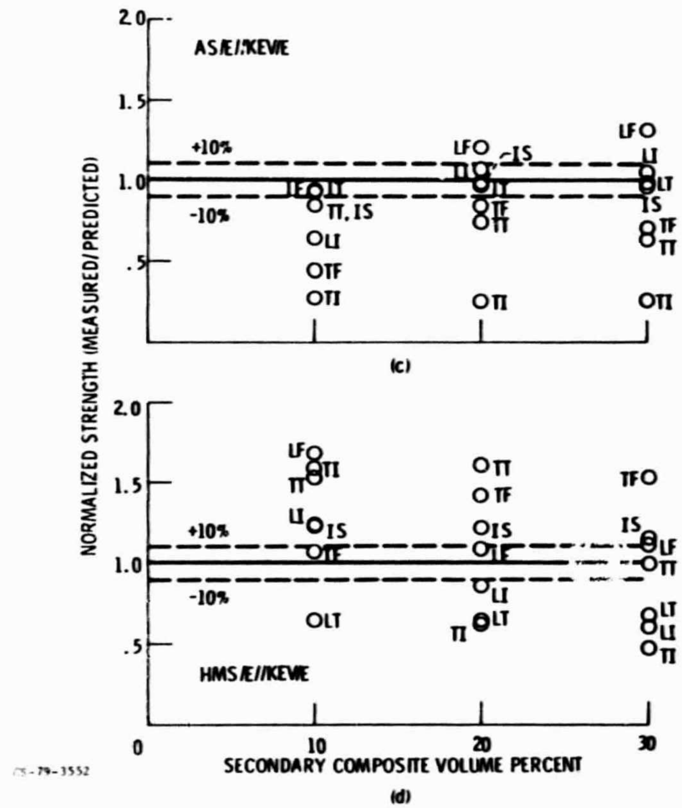

Figure 13. - Concluded.