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Analytical and Experimental Studies of Graphite-Epoxy and Boron-Epoxy Angle Ply Laminates in Shear

by

T. Weller

Prepared under Grant NSG-7083
for
Langley Research Center
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Page No.		line no.
II	'2/;/3' to '2.1.3'	10
III	'Lamin' to 'Lamina'	4
	insert '22' after 'transverse'	18
	'△' to '▽'	29
	'▲' to '▼'	30
IV	remove hyphen after 'core'	5
V	remove 'Laminates'	2
	'Comfiguration' to 'Configuration'	4
2	'of' to 'on'	5
	remove ')' after 'Appendix A.'	23
3	'insignificant' to 'insignificantly'	8
19	'(psi)' to '(ksi)'	
	'ult. shear fail.' to 'max. stress fail.'	
	'pund' to 'pound'	
20	'(psi)' to '(ksi)'	
	'ult. shear fail.' to 'max. stress fail.'	
23	insert '[9]' and '[14]'	
Fig. 1A	remove 'LAMINATE'	3

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ABSTRACT

The present work reports the results of a comparison study between a test program on the inelastic response under inplane shear over a wide range of 3M SP-286T3 Graphite-Epoxy and AVCO 5505/5.6 Mil. Boron-Epoxy angle-ply laminates accomplished at NASA Langley Research Center [1] and the analyses of [6], [9], [11], [12] & [14], namely RD5, SQ5, NONLIN and NOLIN respectively. This investigation is aimed at evaluating the applicability and adequacy of these analyses to predict satisfactorily the responses of angle-ply laminates. It is observed that these analytical tools are inadequate for this purpose as they fail to predict with sufficient confidence the shape of response and in particular the strength values associated with a given laminate configuration. Consequently they do not provide the sought-after information about failure mechanisms which trigger failure of a particular designed laminate. The present correlation studies favor the new modified "picture frame" of [15] as a more reliable testing apparatus for experimental generating of inplane shear responses.

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LIST OF SYMBOLS

E_{11}	Lamina Young Modulus in the 11 fiber direction.
E_{22}	Lamina Young Modulus in the transverse 22 direction.
G_{xy}	Laminate Shear Modulus.
G_{12}	Lamin Shear Modulus.
EPST0	[0°] Lamina strain in tension.
EPST90	[90°] Lamina strain in tension.
EPSC0	[0°] Lamina strain in compression
EPSC90	[90°] Lamina strain in compression
EPS45	[0°] Lamina inplane strain in shear.
SIGT0	[0°] Lamina stress in tension.
SIGT90	[90°] Lamina stress in tension
SIGC0	[0°] Lamina stress in compression.
SIGC90	[90°] Lamina stress in compression.
SIG45	[0°] Lamina inplane shear stress.
TNU12	Tension Poisson's Ratio.
CNU12	Compression Poisson's Ratio.
ϵ_{ULT11}	Lamina Ultimate strain in the 11 fiber direction.
ϵ_{ULT22}	Lamina Ultimate strain in the transverse direction.
ϵ_{ULT12}	Lamina Ultimate inplane shear strain.
γ_{xy}	Laminate shear strain.
σ_{xy}	Laminate inplane shear stress.
σ_{ULT11}	Lamina longitudinal strength.
σ_{ULT22}	Lamina transverse strength.
σ_{ULT12}	Lamina inplane shear strength.
ν_{12}	Lamina major Poisson's Ratio.

<u>Note:</u> All figures are read as follows:

△	RD5 prediction [6]
◇	RD5 predicted strength
◺	NONLIN prediction [11]&[12]
◣	NONLIN fiber failure

0 NOLIN prediction [14] ● Max. Stress Failure

▲ Max. Strain Failure

■ Quadratic Interaction Failure

——— Empirical Response of [1];

PANELS INCORR. - corresponding to shear panels where "core-effect" is neglected.

PANELS CORR. - corresponding to shear panels where "core effect" is eliminated.

TUBES NOM. THICK.- corresponding to tubes - stress calculations based on laminate nominal thickness (number of plies times nominal ply thickness).

— — — TUBES T. THICK. - corresponding to tubes - stress calculations based on laminate "true" measured thickness.

LIST OF FIGURES

1. INTRODUCTION

In [1] the empirical results of an elaborate test program accomplished at NASA Langley Research Center, aimed at investigating the nonlinear/inelastic inplane shear response of Graphite-Epoxy and Boron-Epoxy laminates over a wide range of laminate configuration, were reported.

The objectives as well as the vital importance of such an intensive test program were discussed in detail in [1] to [3], where it was pointed out that the satisfactory and efficient application of advanced composites is dependent upon the existence of sufficient information about their response to any type of loading, strength allowables and stiffnesses, as well as detecting and recognizing the mechanisms which trigger their failure. This information can either be predicted or provided experimentally.

It has been stressed in [3] that utilization of fiber composite materials in structural design incorporates the material design into the design process in an iterative manner, where for each change in loading condition to which the structural element is subject, the material has to be redesigned respectively. This process is carried out analytically (see [4] through [14]), or rather is based on empirical data and experience incorporated with analysis.

Among the essential types of loading to which aerostructures are exposed, is shear loading. The "tailoring" capacity of composites favors categorically the utilization of advanced composites for the design of optimized structures to sustain shear loading. However, recognizing that structural elements are commonly subject to a combination of loads, it appears that the "stiff" and "strong" in shear laminate will be too "weak" to withstand the other loading conditions. Consequently, this calls for an "intermediate" laminate configuration to be used to account for all the loads being introduced into the structure. Such a laminate has to be "designed" by applying one of the analyses [4] to [14]. But as already discussed in [3] the adequacy of these analyses to predict satisfactorily the response as well as the strength allowables of any laminate configuration has to be verified.

Hence it is the primary objective of the present report to correlate the experimental studies of [1] with predictions made by [6], [9], [11],

[12] and [14], and to evaluate the adequacy of these analytical tools to generate the responses and yield the strength allowables of a wide range of angle-ply laminate configurations. It was indicated in [3] that some of these analyses contain simple built-in failure mechanisms such as: maximum stress, maximum strain of quadratic interaction failure, which in the case of "good" agreement with the test results of [1] might provide a better physical insight into the failure mechanisms and critical stress combinations in the laminate which precipitate its failure. Brief descriptions of these analyses, and the accompanying computer codes, are given in [3]. For the sake of convenience they are described again in Appendix A.

2. RESULTS AND DISCUSSION

The empirical values of the ultimate inplane shear stresses and the moduli corresponding to the laminates studied and reported in [1] are presented in Table 1A for the 3M SP-286T3 Graphite-Epoxy laminates, and in Table 1B for the AVCO 5505/5.6 Mil. Boron-Epoxy laminates.
These tables also include, for comparison, the corresponding predicted values yielded by the analyses of [6], [9], [11], [12] and [14] (No values are presented in Table 1A for NONLIN analysis [11] & [12], because information on the mechanical properties and responses of both the fibers and matrix material of 3M-SP-286T3 was not available. This kind of information is required as data input for application of this computer code, see Appendix A). In [15] a so called "core effect" due to stiffening of the sandwich type shear panels by the honeycomb core was detected and discussed, and a method to eliminate this effect was proposed. The results presented in Tables 1A and 1B and the following discussion and figures are primarily based on the "corrected" results corresponding to the shear panels; i.e. "core effect" eliminated (designated PANELS CORR. in the figures). Nevertheless, the results are always compared with those corresponding to the case where this effect has been ignored, both in reducing the empirical data (designated PANELS INCORR. in the figures) and in the analytical predictions. Also as explained in [1], the experimental results experienced by the tubes are shown in the figures both for nominal laminate thickness, i.e. number of plies in laminate times lamina nominal thickness (designated TUBES NOM. THICK.

in the figures), and laminate "true" measured thickness (designated TUBES T. THICK. in the figures).

The moduli of the Graphite-Epoxy laminates (corresponding to the shear panels) are correlated with those predicted by the analysis of [14] in Fig. 1A. A similar comparison study is presented in Fig. 1B for the Boron-Epoxy laminates. Tables 1A and 1B reveal that the analyses of [9] and [14] yield identical moduli values, whereas the analyses of [6] and [11] & [12] predict slightly but insignificant different moduli values. Hence, the correlation studies shown in Figs. 1A and 1B also apply to the analyses of [6] and [11] & [12].

Tables 1A and 1B reveal, however, that considerable differences exist among the ultimate inplane shear strength predicted by the various analyses utilized for the numerical studies of the present report. In Fig. 2A the experienced experimental ultimate stresses corresponding to the Graphite-Epoxy laminates of [1] are compared with the calculated ultimate stresses of [6], [9] and [14]. A similar comparison is given in Fig. 2B for the Boron-Epoxy laminates of [1]. Note that each of these figures consists of two sub-figures; one correlating the test results of [1] with the analyses of [6] and [9], and the second one with the calculations of [14]. Such a method of presentation allows for better distinction of the ultimate values predicted by [14] where for each laminate configuration three such non-unique values are yielded, corresponding to Max. Stress, Max. Strain or Quadratic Interaction Failure (Quad. Fail.) criteria.

The results presented in Tables 1A and 1B, as well as in Figs. 1A, 1B, 2A and 2B, are discussed individually for each material and laminate configuration when a particular laminate configuration is being considered in the detailed discussion of the following sections.

2.1. GRAPHITE-EPOXY LAMINATES (3M SP-286T3)

2.1.1 Unidirectional [0°] Laminates

As described in Appendix A, the responses of the [0°] unidirectional lamina are required as data input for the analyses. In Fig. 3 the empirical responses of [1] are presented together with the reproduced responses by the computer codes, RD5 corresponding to [6] and NOLIN corresponding to [14].

The reprodu:ibility of each computer code observed in this figure will provide an assessment for further disscussions and evaluations on the comparison of the predicted responses of the angle-ply laminates with the experienced empirical ones, as well as correlating one prediction with another. Fig. 3 reveals good agreement between the responses predicted by RD5[6] and NOLIN[14], and the responses experienced by the panels and the tubes ("true" measured thickness) up to a load level which corresponds to the empirical ultimate shear stress of the panel. Beyond this stress level RD5 still follows the experimental response yielded by the tubes, whereas NOLIN deviated considerably from this response, exhibiting less nonlinearity than the tubes.

Fig. 1A and Table 1A indicate excellent correlation between the empirical modulus and the ones predicted by the analyses. Hence, reproduction is excellent. From Figs. 1A and 3 and Table 1A it appears that NOLIN Max. Stress and Quad. Fail. predict an ultimate stress which is in very good agreement with that experienced by the tubes. However, the strain corresponding to this stress is significantly lower than that yielded by the tubes. On the other hand in the case of Max. Stress this program yields a stress appreciably higher than that yielded by the tubes, at the very same failure strain of the tubes. Also the table and figures show that RD5 predicts a stress slightly higher than that experienced by the tubes but corresponding to a considerably larger strain, and SQ5[9] predicts a stress considerably higher than that observed for either the tubes or the panels.

2.1.2 [±15°] Laminates

Fig. 4 presents the experimental responses of [1] together with the predicted ones. Excellent agreement is observed between the experimental response experienced by the panels and that predicted by NOLIN. The response predicted by RD5 appears to be slightly stiffer than that yielded by the panels. However, as can be seen from this figure, as well as Fig. 2A and Table 1A, the ultimate stresses predicted by the analyses are significantly higher than the one yielded by the panels, except for the stress corresponding to NOLIN Quad. Fail. which is considerably below this experienced stress.

It appears from Fig. 1A and Table 1A that all of the analyses predict an identical shear modulus which is slightly higher than that experienced by the panels.

2.1.3 [±30°] Laminates

The experimental responses of [1], together with the predicted ones, are shown in Fig. 5. This figure reveals good agreement between the experimental response corresponding to the panels and the tubes ("true" measured thickness), and the analytical predictions in the range of stresses experienced experimentally. However, it appears from this figure, Table 1A and Fig. 2A, that the analyses predict ultimate stresses significantly above the empirical experienced ones, and with very good correlation among the stresses yielded by RD5, SQ5 and NOLIN Max. Strain, ≈46.0 ksi. NOLIN Quad. Fail. is observed to predict an ultimate stress which is noticeably lower than that predicted above, ≈42.0 ksi, and the stress corresponding to Max. Stress of this program is found to be appreciably higher than this stress, 62.5 ksi. This stress is more than twice as much as that experienced by the test specimens of [1].

Fig. 1A and Table 1A indicate that NOLIN and SQ5 predict an identical modulus which is slightly lower than that yielded by RD5. However, all of the predicted moduli are noticeably higher than the one experienced by the panels.

2.1.4 [±45°] Laminates

In Fig. 6 the empirical responses of [1] are shown together with the predicted ones. Very good correlation is found between the response predicted by NOLIN and the experimental one in the range of stresses experienced by the panels. It appears from this figure that the response predicted by RD5 correlates better with that presented for the panels, where the "core effect" is neglected. It is observed from this figure, as well as Table 1A and Fig. 2A, that the analyses predict ultimate stresses significantly higher than those experienced experimentally. The stress corresponding to SQ5 is in excellent agreement with those predicted by NOLIN Max. Strain and Quad. Fail., and the stress predicted by RD5 is identical with that yielded by NOLIN Max.

Stress. This stress of ≈65.0 ksi is higher by about 30 percent than the abovementioned predicted one (≈50.0 ksi), and about 60 percent higher than the empirical one.

It is observed from Fig. 1A and Table 1A that the various analyses predicted slightly different moduli, which are in good agreement with the modulus experienced by the tubes ("true" measured thickness), and somewhat higher than experienced by the panels.

2.1.5 [0°/90°] Laminates

Fig. 7 presents the empirical responses of [1] together with the predicted ones. As one might expect, the analyses predict a response which is identical with that yielded earlier for the [0°] unidirectional laminates of Fig. 3. The experienced experimental responses are, however, different from the ones experienced both by the [0°] panels and tubes. This difference is mainly pronounced by the high straining capability experienced in the experiments with this laminate configuration, where the [0°/90°] panels yielded a strain which is almost seven times that experienced by the [0°] panels, and the [0°/90°] tubes carried a strain which is about 60 percent higher than that sustained by the [0°] tubes. This high straining performance resulted, of course in higher ultimate stress values (for magnitudes see Table 1A). It is also seen from Fig. 7 that the response predicted by RD5 agrees excellently with the empirical one in the range of RD5 existence. Hence, reproducibility of data input is better than that observed for the [0°] unidirectional laminate. Also NOLIN predictions correlate better with the test results in the lower range of stress values. Referring to the discussion in Appendix A it should be borne in mind that the analyses utilize the [0°] unidirectional lamina responses as data input and as such the data input includes Max. Stress and Strain values corresponding to this laminate to detect failure of the laminate. The present results of Fig. 7, Table 1A and Fig. 2A indicate that predictions based on this type of information lead to wrong allowables for the [0°/90°] laminate. (Note that the "corrected" response of the panels isn't extended beyond $\gamma_{xy} \approx 0.35$ because of lack of information on the core response beyond this strain. See reduction of core response in [15]).

The above discussion also explains the differences between the predicted moduli and the experimental ones appearing in Table 1A and Fig. 1A. The analyses reproduce the unidirectional properties, whereas the cross-plied [0°/90°] laminate is slightly and insignificantly stiffer.

2.1.6 [0°/±45°/90°] Laminates

Fig. 8 presents the experimental responses of [1] together with the ones predicted by the analyses. Very good correlation is observed between the response predicted by RD5 and the empirical one in the range of experienced experimental stresses. Good agreement with the experimental response is also observed for the response predicted by NOLIN. It appears from this figure, Table 1A and Fig. 2A, that the ultimate stresses corresponding to SQ5 and NOLIN Max. Strain and Quad. Fail. agree very well and correlate very well with the stress experienced by the panels. The stresses corresponding to RD5 and NOLIN Max. Stress are significantly above the experimental ultimate stress and are in good agreement.

It is seen in Table 1A and Fig. 1A that SQ5 and NOLIN predict an identical modulus with the one experienced by the panels. This modulus is insignificantly lower than that predicted by RD5.

2.2. BORON-EPOXY LAMINATES (AVCO 5505/5.6 Mil. Dia.)

In addition to the analyses of [6], [9] and [14], the experimental results of [1] corresponding to this material are also compared with the analytical predictions of [11] & [12]. The results obtained by the computer code of this analysis, NONLIN, should not however be treated with the same confidence as those yielded by the other analyses studied herein, because the data input for the matrix material of the composite, required for this analysis, was not provided. Instead, available data about the matrix reported in the literature [11] was utilized. Also note that this analysis does not predict allowables, except for the case when the fibers in any of the lamina reach their ultimate stress. Hence, no such values appear in either Table 1B or Fig. 2B.

2.2.1 Unidirectional [0°] Laminates

Like for the [0°] Graphite-Epoxy laminates, the reproduction capability of the algorithms of the computer codes are again evaluated. The empirical responses of [1] together with the reproduced ones by the computer codes of Appendix A are shown in Fig. 9. This figure reveals "fair" correlation between the experienced experimental response and the calculated responses; in the low stress-strain range, i.e. almost linear range, RD5 and NOLIN agree very well with the empirical response, whereas only good correlation is observed for NONLIN with the experimental results. With further increase in stress values, at the region of the knee of the experimental response, RD5 agrees with the test results, whereas NOLIN exhibits only fair correlation with the empirical response, experiencing more pronounced nonlinearity. At this level of stresses NONLIN starts deviating considerably from the test results. In the high straining range of the empirical response, Fig. 9 reveals better correlation of NOLIN than of RD5 with test results.

Fig. 1B and Table 1B indicate very good reproduction of the shear modulus by the computer codes, except for NONLIN. Also, Table 1B and Fig. 2B reveal that NOLIN predicts the experienced ultimate shear stress for all of the failure criteria, though at a lower strain value. RD5 yields a stress which is a little higher than the experimental one but which corresponds to a considerably higher strain value, and SQ5 a very high ultimate stress about three times that of the empirical one.

2.2.2 [±15°] Laminates

The empirical responses of [1] are presented, together with the predicted ones, in Fig. 10. Very good agreement is observed for NOLIN with the empirical response in the range of existence of test results. Good correlation is also seen between RD5 and NONLIN and the experimental response, where these predicted responses exhibit a slightly stiffer response than experienced empirically. These responses correlate better with the response corresponding to the panels, where the "core effect" was ignored (also to the tubes with "true" measured thickness). It is also found from this figure, Table 1B and Fig. 2B, that NOLIN Quad. Fail. predicts the empirical ultimate stress, whereas

NOLIN Max. Strain and RD5 yield slightly higher ultimate stresses. SQ5 is observed to predict a considerably higher ultimate stress and NOLIN Max. Stress yields a very high stress which is about twice that of the empirical one.

It is observed in Table 1B and Fig. 1B that all of the analyses predict an identical shear modulus lower than the experimental one.

2.2.3 [±30°] Laminates

The experimental responses of [1] are shown in Fig. 11 together with the predicted ones. It is observed that all of the predicted responses agree very well with the empirical response. It is seen from this figure, Table 1B and Fig. 2B, that RD5, SQ5 and NOLIN Max. Strain predict an ultimate stress which is a little higher than the experimental one. NOLIN Quad. Fail. yields a stress which is appreciably higher than the abovementioned ones, and NOLIN Max. Stress predicts an ultimate stress which is twice as high as the empirical one.

It is observed in Table 1B and Fig. 1B that RD5, SQ5 and NOLIN predict a shear modulus of 6.32×10^6 psi, which is slightly higher than the 6.19×10^6 psi experienced experimentally, and the 6.25×10^6 psi yielded by NONLIN.

2.2.4 [±45°] Laminates

The predicted responses are compared with the empirical ones of [1] in Fig. 12. Agreement between the analytical predictions and experimental response is very good, except for very high stresses, where the empirical response deviates slightly from a linear type of behavior. Also a peculiar type of behavior is observed for RD5 for stress levels higher than those corresponding to Max. Strain Fail. of NOLIN. A jump in strain, without affecting the slope of response with further increasing stresses, is observed. Similar behavior is revealed for the [±45°] Graphite-Epoxy laminates of Fig. 6. It is seen from Fig. 12, Table 1B and Fig. 2B that the ultimate stresses predicted by NOLIN Max. Strain and SQ5 are in very good agreement; however, they are appreciably lower than the empirical one. The stress yielded by NOLIN Quad. Fail. is slightly higher than the experimental one, and the stresses calculated by NOLIN Max. Stress and RD5 are considerably higher than the one experienced experimentally.

It is found from Table 1B and Fig. 1B that NONLIN predicts a modulus value identical with the experimental ones, whereas RD5, SQ5 and NOLIN predict identical moduli which are slightly larger than the empirical one.

2.2.5 [0°/90°] Laminates

Fig. 13 presents the empirical responses of [1] together with the predicted ones. Like for the [0°/90°] Graphite-Epoxy laminates of Fig. 7 and as one may anticipate, the predicted responses are identical with those yielded for the [0°] laminates of Fig. 9. Again, like for the Graphite-Epoxy laminates, such an identity, however, does not exist between the empirical results of the [0°] and [0°/90°] laminates. Again, the [0°/90°] laminate appears to experience a significantly higher straining capability relative to the unidirectional [0°] laminates (0.43 relative to 0.27), followed by a noticeable increase in ultimate stress. Note, however, that the differences between the responses of the [0°] and [0°/90°] laminates corresponding to the present material are not as pronounced as for the Graphite-Epoxy laminates. This similarity in behavior of the two studied materials, which is in contrast to the analyses, calls for further analytical studies, in particular investigatigation of failure mechanisms which appear to be different for the two laminate configurations ([0°] unidirectional and [0°/90°] cross-plied).

Fig. 13 reveals very good correlation of RD5 with the experimental response in the less pronounced nonlinear range, whereas NOLIN deviates from the empirical response at early stress levels and exhibits more emphasized nonlinearity up to predicted failure. A similar trend of behavior is experienced by RD5 in the nonlinear region, and good agreement with NOLIN is observed in Fig. 13. NONLIN agrees with the empirical response only in the linear range and then deviates from the experimental response, exhibiting a much stiffer response. (Note that the "corrected" response of the panels isn't extended beyond $\gamma_{xy} \approx .35$ because of lack of information on the core response beyond this strain).

It is seen from Fig. 2B and Table 1B that the predicted ultimate stresses by NOLIN and RD5 are considerably below the empirical one as a result of the discussion above, whereas SQ5 yields a significantly higher ultimate stress (see also discussion of [0°/90°] Graphite-Epoxy laminates). Fig. 1B and Table 1B indicate that RD5, SQ5 and NOLIN predict a shear modulus which is slightly higher than the experimental one and lower than the one yielded by NONLIN.

2.2.6 [0°/±45°/90°] Laminates

Fig. 14 presents the predicted responses together with the empirical ones of [1]. Very good agreement is observed among the various analyses predictions, and between the analyses and experienced experimental response, except for high stress levels. This deviation in correlation may, however, be explained by the unexpected behavior of the test results in the range of high stress levels. The curvature of the empirical curve becomes concave rather than convex, which is in contrast to the common experience. It is also observed in this figure, as well as Fig. 2B and Table 1B, that NOLIN Max. Strain and SQ5 predict very similar ultimate stresses which are very low relative to the empirical ultimate stress. NOLIN Quad. Fail. predicts a strength value which is considerably below the empirical one, and Max. Stress of this program yields a stress just a little lower than that experienced experimentally. RD5 on the other hand yields a strength value which is appreciably higher than the empirical one.

It is seen from Table 1B and Fig. 1B that all of the analyses predict an identical modulus which is slightly higher than the experimental one.

3. CONCLUSIONS

(a) Present studies indicate "fair" to "excellent" correlation of the predicted modes of response by the various analyses utilized in the numerical studies, namely: RD5, SQ5, NONLIN and NOLIN with the empirical responses experienced by the shear panels of [1].

(b) The analyses appear to be inadequate to predict the strength allowables corresponding to the variety of angle-ply laminates investigated in the present work. Hence, the assumed built-in failure mechanisms are not verified and therefore are not necessarily the actual mechnisms which precipitate failure of the laminates. This is best revealed when comparing the experimental results of the [0°] and [0°/90°] laminates between themselves, and with the analytical predictions.

(c) Present studies favor categorically the "modified picture frame" and consequently the shear panels, for experimentation of composite materials under inplane shear. However, further recent studies with this apparatus indicate that the empirical results can be improved by strengthening the tension corrers of the panels to avoid stress concentrations whenever they appear, thus increasing the experienced stress allowables.

(d) [0°] laminates experience experimentally different shear responses from those observed for [0°/90°] laminates. The latter are characterized by a very high straining capacity relative to the unidirectional ones.

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APPENDIX A

In the present numerical studies, four computer codes were utilized to predict analytically the stress-strain response of the variety of laminates tested and reported in [1]. Namely, these codes are known as RD5 or ULTIMATE, **SQ5, NONLIN** and NOLIN, and they are based on the analyses of [6], [9], [11] & [12] and [14] respectively. The main features of these programs are:

RD5-ULTIMATE [6]

Predicts the stress-strain response to ultimate failure for a plane unisotropic laminate with mid-plane symmetry, consisting of orthotropic laminae with nonlinear stress-strain responses. This analysis assumes that any degradation occurring due to lamina yielding or failure is restricted to that lamina and has no influence on the adjacent laminae. The technique of analysis requires the stress-strain responses of the individual unidirectional lamina. The information, in conjuction with a generalized Hook's law, provides the laminate response. In addition to the response, the program furnishes, for each stage of loading, the instantaneous stiffnesses and Poisson's ratio.

NONLIN [11] & [12]

This is a micro/macro analysis utilizing the discrete finite element method (D.E.M.) to determine the nonlinear response of a laminate subjected to inplane loading. The inelastic effective properties of a unidirectional rectangular, and square arrays of elastic fibers introduced in an inelastic matrix, are generated with the aid of the D.E.M. method. The obtained properties are then used on the macro level in conjuction with an inelastic laminate analysis. The analysis is based on an incremental plasticity theory and consequently is very complicated relative to the other analyses. The analysis does not include any type of built-in failure mechanisms.

SQ5 [9]

Provides the stress allowables for a particular laminate based upon the maximum strain theory of failure. It is based on the coupled inplane and bending point stress analysis of a laminate. The laminate constitutive equations are derived from the laminae constitutive relations. Then it is used to determine the mid-plane strains and curvatures arising from the inplane stress and moment resultants. These are then applied to determine the stresses and strains in each layer of the laminate.

NOLIN [14]

Generates the nonlinear stress-strain response of a symmetric laminate under inplane loading by relating its behavior to the nonlinear responses of the unidirectional laminae. The nonlinear response of the individual lamina is defined by a Ramberg-Osgood type of representation, and material nonlinearities are represented by deformation type theory. As a starting point for its application, the analysis requires the input of the nonlinear transverse and inplane shear responses of the unidirectional laminae. Then the appropriate Ramberg-Osgood parameters are calculated to formulate an interaction expression for simultaneous application of transverse and inplane shear stresses. The analysis predicts ultimate stress values corresponding to Max. Stress, Max. Strain and Quad. Int. Fail. of an individual lamina. Hence it assumes that lamina failure precipitates overall failure of the laminate.

The codes of [6], [9] and [14] require the existence of lamina unidirectional stress strain responses as vital information for their application. Such information can be generated on a micro level, but is usually obtained experimentally. In Appendix B the stress-strain responses corresponding to the unidirectional laminae of 3M SP-286T3 Graphite-Epoxy and Avco 5505/5.6 Mil. Dia. Boron-Epoxy, which were the prepreged materials used to fabricate the specimens of [1], are presented. The tension responses were generated by SWRI, the manufacturer of the test specimens of [1]. The compression and shear responses were reproduced from the experimental responses yielded by the [0°] and [90°] unidirectional laminates of [1] and [2].

APPENDIX B

It has been pointed out in the section on the Numerical Studies that the computer codes RD5[6] and NOLIN[14]require the existence of the unidirectional [0°] and [90°] laminae responses in tension, compression and shear for their application. The images of these data inputs or library input data are presented in Tables APB-1A and APB-1B as being input into RD5 code. In addition to the data in these Tables, also required by NOLIN, the information presented in Table APB-2 has to be provided to operate NOLIN code. (Instead of feeding NOLIN with the stress-strain input data for the responses, one may use the Ramberg-Osgood parameters as explained in [14] and thus avoid the utilizing of curve fitting algorithms to generate these parameters.)

The mechanical properties given in Table APB-2 are also required as data input by SQ5 code, [9].

It was mentioned in the section on Results and Discussion that the input data for the matrix material of the AVCO 5505 Boron-Epoxy laminates was taken from [11]and [12]. The mechanical properties are as follows:

Young Modulus of Matrix	510000. psi
Shear Modulus of Matrix	200000. psi
Poisson's Ratio of Matrix	.310

and the equivalent stress/equivalent strain curve is reproduced from these references:

ES1 = 5000	SL1 = 10^6
ES2 = 10000	SL2 = $.5x10^6$
ES3 = 15000	SL3 = $.19x10^6$
ES4 = 20000	SL4 = $.10x10^6$
ES5 = 25000	SL5 = 3230
ES6 = 30000	SL6 = 0.

The Boron Fiber properties are provided by the manufacturer, and are as follows:

Young Modulus of Fiber	$58. \times 10^6$ psi
Shear Modulus of Fiber	23.75×10^6 psi
Poisson's Ratio of Fiber	.200
Fiber Tension Ultimate	500. ksi
Fiber Compression Ultimate	750. ksi

TABLE 1A Inplane Shear Response - Comparison of Experimental Ultimate Stresses and Moduli with Analytical Predictions of RD5[6], SQ5[9], NONLIN [11]&[12], and NOLIN[14]

GRAPHITE-EPOXY LAMINATES (3M SP-286T3)

Laminate Configuration	TEST TESULTS OF [1]						ANAL RD5 [6]		ANAL SQ5 [9]		ANAL NONLIN [11]&[12]		ANAL NOLIN[14]			
	Shear Panels			Shear Tubes									Ult. Shear Stress (psi)			
	Ult.Shear Stress "core effect" (ksi)	Ult.Shear Stress no "core effect" (ksi)	Gxy Shear Mod. ($x10^6$psi)	Ult.Shear Stress nom. thick (ksi)	Ult.Shear Stress measured thick (ksi)	Gxy ($x10^6$psi)	Ult. Shear Stress (ksi)	Gxy ($x10^6$psi)	Ult. Shear Stress (ksi)	Gxy ($x10^6$psi)	Ult. Shear Stress (ksi)	Gxy ($x10^6$psi)	ult. shear fail.	max. strain fail.	quad. inter. fail.	Gxy ($x10^6$psi)
[0°]	8.87 11.0	= 6.10	0.57 (0.90)	10.7 12.4	6.90 8.66	0.94 [0.64]	9.00 (11.5)	0.55 (0.89)	12.5_{12} (14.4)	0.57 (0.90)			8.10_{12} (10.0)	9.83_{12} (13.10)	8.10 (10.0)	0.57 (0.90)
[±15°]	24.8 27.2	=23.8	1.38 (1.71)	27.8 32.6	22.6 26.0	2.25 [1.82]	32.0 (32.0)	1.49 (1.75)	35.7_{22} (32.1)	1.49 (1.74)			28.2_{12} (24.3)	33.0_{22} (29.6)	20.1 (19.0)	1.49 (1.74)
[±30°]	30.1 35.6	=28.2	3.14 (3.47)	28.9 38.9	22.0 29.4	4.91 [3.68]	46.0 (48.0)	3.39 (3.47)	46.1_{22} (47.2)	3.33 (3.41)			62.5_{22} (60.4)	45.6_{22} (46.4)	41.7 (40.3)	3.33 (3.41)
[±45°]	44.2 30.7	=41.5	4.09 (4.42)	41.3 53.9	28.6 36.7	6.28 [4.31]	66.0 (66.0)	4.33 (4.33)	51.6_{22} (51.6)	4.30 (4.30)			65.9_{22} (65.9)	50.7_{22} (50.7)	51.7 (51.7)	4.24 (4.24)
[0°/90°]	17.6 18.1	-	0.60 (0.93)	9.40 11.6	8.23 11.3	0.60 [0.55]	8.50 (12.0)	0.55 (0.89)	12.5_{12} (14.4)	0.57 (0.90)			8.10_{12} (10.0)	9.83_{12} (13.1)	8.10 (10.0)	0.57 (0.90)
[0°/±45°/90°]	27.4 31.4	=29.3	2.41 (2.74)	27.2 39.2	20.3 25.0	3.29 [2.32]	38.0 (40.0)	2.44 (2.61)	28.9_{22} (30.9)	2.41 (2.57)			36.8_{22} (29.8)	28.5_{22} (30.4)	29.0 (29.8)	2.41 (2.57)

nom. thick - Nominal Thickness

( ) - "Core Effect" neglected (in unidirectional lamina input).

[ ] - Corrected for measured thickness.

A_{11} - Failure in compression/or tension in lamina 11 direction.

A_{22} - Failure in compression/or tension in lamina 22 direction.

A_{12} - Failure in shear.

1" (inch) = $2.540x10^{-2}$ metre (m)

1 pound force = 4.448222 Newton (N)

1 kip = 10^3 pund force

1 psi = $6.894757x10^3$ Pascal (Pa)

1 ksi = 10^3 psi

TABLE 1B Inplane Shear Response - Comparison of Experimental Ultimate Stresses and Moduli with Analytical Predictions of RD5[6], SQ5[9], NONLIN [11]&[12], and NOLIN[14]

BORON-EPOXY LAMINATES (AVCO 5505/5.6 MIL. DIA.)

Laminate Configuration	TEST RESULTS OF [1]						ANAL RD5 [6]		ANAL SQ5 [9]		ANAL NONLIN [11]&[12]		ANAL NOLIN[14]			
	Shear Panels			Shear Tubes									Ult. Shear Stress (psi)			
	Ult.Shear Stress "core effect" (ksi)	Ult.Shear Stress no "core effect" (ksi)	Gxy Shear Mod. ($\times10^6$ psi)	Ult.Shear Stress nom. thick (ksi)	Ult.Shear Stress measured thick (ksi)	Gxy ($\times10^6$ psi)	Ult. Shear Stress (ksi)	Gxy ($\times10^6$ psi)	Ult. Shear Stress (ksi)	Gxy ($\times10^6$ psi)	Ult. Shear Stress (ksi)	Gxy ($\times10^6$ psi)	ult. shear fail.	max. strain fail.	quad. inter. fail.	Gxy ($\times10^6$ psi)
[0°]	8.44 9.38	= 5.60	0.66 (0.93)	6.93 8.33	4.99 5.69	1.07 [0.73]	6.50 (11.0)	0.65 (0.94)	17.8_{12} (25.1)	0.66 (0.93)		0.70	5.60_{12} (9.40)	5.60_{12} (10.7)	5.60 (9.40)	0.66 (0.93)
[±15°]	35.5 43.6	=31.6	2.70 (2.97)	32.4 39.1	22.0 26.8	4.06 [2.77]	35.0 (40.0)	2.54 (2.75)	41.8_{22} (45.1)	2.55 (2.75)		2.55	61.1_{11} (63.0)	56.5_{22} (39.1)	31.8 (34.0)	2.55 (2.75)
[±30°]	52.7 57.0	=52.0	6.19 (6.46)	20.3 52.0	16.8 36.2	10.0 [7.21]	55.0 (60.0)	6.31 (6.39)	59.8_{22} (60.5)	6.32 (6.39)		6.25	100.4_{11} (99.3)	58.1_{22} (58.7)	67.0 (68.6)	6.32 (6.39)
[±45°]	72.3 81.7	=78.9	8.10 (8.57)	20.6 45.1	12.5 26.5	13.3 [7.94]	100. (95.0)	8.20 (8.20)	67.4_{22} (67.4)	8.22 (8.22)		8.10	93.8_{22} (93.8)	66.0_{22} (66.0)	83.1 (83.1)	8.21 (8.21)
[0°/90°]	11.2 11.5		0.60 (0.87)	7.19 8.28	7.06 8.13	0.64 [0.62]	6.50 (11.0)	0.65 (0.94)	17.8_{12} (25.1)	0.66 (0.93)		0.70	5.60_{12} (9.40)	5.60_{12} (10.7)	5.60 (9.40)	0.66 (0.93)
[0°/±45°/90°]	48.6 54.2	=51.2	4.36 (4.63)	18.3 28.7	11.6 19.2	5.31 [3.79]	60.0 (55.0)	4.43 (4.57)	36.4_{22} (37.5)	4.43 (4.57)		4.40	49.2_{22} (50.6)	35.0_{22} (36.0)	43.7 (45.0)	4.43 (4.57)

nom. thick. - Nominal Thickness

( ) - "Core Effect" neglected (in unidirectional lamina input).

[ ] - Corrected for measured thickness.

A_{11} - Failure in compression/or tension in lamina 11 direction.

A_{22} - Failure in compression/or tension in lamina 22 direction.

A_{12} - Failure in shear.

1" (inch) = 2.540×10^{-2} metre (m)

1 pound force = 4.448222 Newton (N)

1 kip = 10^3 pound force

1 psi = 6.894757×10^{3} pascal (Pa)

1 ksi = 10^3 psi

TABLE AP1A INPUT LIBRARY DATA FOR MATERIAL 2 - - 3MSP286T-3(A-S)

SIGT0	EPST0	SIGT90	EPST90	SIGC0	EPSC0	SIGC90	EPSC90
0.13500E 05	0.80000E-03	0.90000E 03	0.60000E-03	0.22500E 05	0.14000E-02	0.46000E 04	0.25000E-02
0.26500E 05	0.16000E-02	0.18000E 04	0.12000E-02	0.45000E 05	0.28000E-02	0.90000E 04	0.50000E-02
0.40500E 05	0.24000E-02	0.26700E 04	0.18000E-02	0.67500E 05	0.42000E-02	0.13250E 05	0.75000E-02
0.54500E 05	0.32000E-02	0.34800E 04	0.24000E-02	0.87200E 05	0.56000E-02	0.16800E 05	0.10000E-01
0.69000E 05	0.40000E-02	0.42700E 04	0.30000E-02	0.10670E 06	0.70000E-02	0.20500E 05	0.12500E-01
0.83500E 05	0.48000E-02	0.50800E 04	0.36000E-02	0.12560E 06	0.84000E-02	0.23750E 05	0.15000E-01
0.97500E 05	0.56000E-02	0.58300E 04	0.42000E-02	0.14440E 06	0.98000E-02	0.26600E 05	0.17500E-01
0.11150E 06	0.64000E-02	0.66200E 04	0.48000E-02	0.16250E 06	0.11200E-01	0.29100E 05	0.20000E-01
0.12550E 06	0.72000E-02	0.73600E 04	0.54000E-02	0.17300E 06	0.12600E-01	0.31400E 05	0.22500E-01
0.13950E 06	0.80000E-02	0.81000E 04	0.60000E-02	0.19400E 06	0.14000E-01	0.33500E 05	0.25000E-01
0.0	0.88000E-02	0.0	0.66000E-02	0.0	0.15400E-01	0.0	0.27500E-01
0.0	0.96000E-02	0.0	0.72000E-02	0.0	0.16800E-01	0.0	0.30000E-01

SIG45	EPS45	TNU12	CNU12	TNU21	CNU21
0.12540E 04	0.22000E-02	0.31400E 00	0.24000E 00	0.27911E-01	0.27477E-01
0.25080E 04	0.44000E-02	0.31600E 00	0.26000E 00	0.29169E-01	0.28473E-01
0.37620E 04	0.66000E-02	0.31800E 00	0.27500E 00	0.26349E-01	0.29089E-01
0.51000E 04	0.88000E-02	0.31900E 00	0.28000E 00	0.24609E-01	0.28256E-01
0.58500E 04	0.11000E-01	0.32000E 00	0.30000E 00	0.23246E-01	0.31877E-01
0.64000E 04	0.13200E-01	0.32000E 00	0.31500E 00	0.23835E-01	0.30333E-01
0.69600E 04	0.15400E-01	0.32000E 00	0.32500E 00	0.22857E-01	0.27590E-01
0.74000E 04	0.17600E-01	0.32000E 00	0.33000E 00	0.24076E-01	0.25525E-01
0.77500E 04	0.19800E-01	0.32000E 00	0.33500E 00	0.22552E-01	0.26150E-01
0.80500E 04	0.22000E-01	0.31900E 00	0.34000E 00	0.2248[illegible]E-01	0.26656E-01
0.0	0.24200E-01	0.0	0.0	0.0	0.0
0.0	0.26400E-01	0.0	0.0	0.0	0.0

TABLE APB1B INPUT LIBRARY DATA FOR MATERIAL 1 - - AVCO 5505/5.6

SIGT0	EPST0	SIGT90	EPST90	SIGC0	EPSC0	SIGC90	EPSC90
0.21700E 05	0.70000E-03	0.11500E 04	0.40000E-03	0.31270E 05	0.10000E-02	0.44800E 04	0.15000E-02
0.43400E 05	0.14000E-02	0.23000E 04	0.80000E-03	0.62540E 05	0.20000E-02	0.89500E 04	0.30000E-02
0.65100E 05	0.21000E-02	0.33500E 04	0.12000E-02	0.93810E 05	0.30000E-02	0.13150E 05	0.45000E-02
0.86800E 05	0.28000E-02	0.43400E 04	0.16000E-02	0.12508E 06	0.40000E-02	0.16800E 05	0.60000E-02
0.10850E 06	0.35000E-02	0.52700E 04	0.20000E-02	0.15635E 06	0.50000E-02	0.20200E 05	0.75000E-02
0.13020E 06	0.42000E-02	0.61800E 04	0.24000E-02	0.18762E 06	0.60000E-02	0.23100E 05	0.90000E-02
0.15190E 06	0.49000E-02	0.70600E 04	0.28000E-02	0.22100E 06	0.70000E-02	0.25750E 05	0.10500E-01
0.17360E 06	0.56000E-02	0.78500E 04	0.32000E-02	0.25400E 06	0.80000E-02	0.28000E 05	0.12000E-01
0.19530E 06	0.63000E-02	0.84500E 04	0.36000E-02	0.28800E 06	0.90000E-02	0.31000E 05	0.13500E-01
0.21700E 06	0.70000E-02	0.89000E 04	0.40000E-02	0.34000E 06	0.10000E-01	0.31700E 05	0.15000E-01
0.0	0.77000E-02	0.0	0.44000E-02	0.0	0.11000E-01	0.0	0.16500E-01
0.0	0.84000E-02	0.0	0.48000E-02	0.0	0.12000E-01	0.0	0.18000E-01

SIG45	EPS45	TNU12	CNU12	TNU21	CNU21
0.17820E 04	0.27000E-02	0.22700E 00	0.26400E 00	0.21052E-01	0.25215E-01
0.33200E 04	0.54000E-02	0.22700E 00	0.26600E 00	0.21052E-01	0.25350E-01
0.42500E 04	0.81000E-02	0.22700E 00	0.26800E 00	0.19222E-01	0.23997E-01
0.46500E 04	0.10800E-01	0.22400E 00	0.26800E 00	0.17884E-01	0.20855E-01
0.48500E 04	0.13500E-01	0.22400E 00	0.27000E 00	0.16800E-01	0.19572E-01
0.50500E 04	0.16200E-01	0.22400E 00	0.27200E 00	0.16439E-01	0.16817E-01
0.52200E 04	0.18900E-01	0.22400E 00	0.27500E 00	0.15897E-01	0.14555E-01
0.53500E 04	0.21600E-01	0.23000E 00	0.28000E 00	0.14653E-01	0.12727E-01
0.55000E 04	0.24300E-01	0.23300E 00	0.29000E 00	0.11274E-01	0.17059E-01
0.56000E 04	0.27000E-01	0.22700E 00	0.32000E 00	0.82380E-02	0.28718E-02
0.0	0.29700E-01	0.0	0.0	0.0	0.0
0.0	0.32400E-01	0.0	0.0	0.0	0.0

TABLE APB-2 Unidirectional Lamina Properties Utilized In The Predictions Of SQ5 9 and NOLIN 14

	3M SP-286T3 GRAPHITE-EPOXY	AVCO 5505/5.6 Mil BORON-EPOXY
(E_{11}) Tension	16.87×10^6 psi	31.00×10^6 psi
(E_{11}) Compression	16.07×10^6 psi	31.27×10^6 psi
(E_{22}) Tension	1.52×10^6 psi	2.88×10^6 psi
(E_{22}) Compression	1.91×10^6 psi	2.98×10^6 psi
(G_{12})	0.57×10^6 psi	0.66×10^6 psi
(σ_{ULT11}) Tension	140. ksi	220. ksi
(ε_{ULT11}) Tension	.008	.008
(σ_{ULT11}) Compression	180. ksi	340. ksi
(ε_{ULT11}) Compression	.013	.0113
(σ_{ULT22}) Tension	8. ksi	8.9 ksi
(ε_{ULT22}) Tension	.006	.00405
(σ_{ULT22}) Compression	32. ksi	32. ksi
(ε_{ULT22}) Compression	.025	.015
(σ_{ULT12})	8.1 ksi	5.6 ksi
(ε_{ULT12})	.022	.0275
(ν_{12}) Compression	.230	.267
(ν_{12}) Tension	.298	.216

1" (inch) = 2.540×10^{-2} metre (m)

1 pound force = 4.448222 Newton (N)

1 kip = 10^3 pound force

1 psi = 6.894757×10^3 pascal (Pa)

1 ksi = 10^3 psi

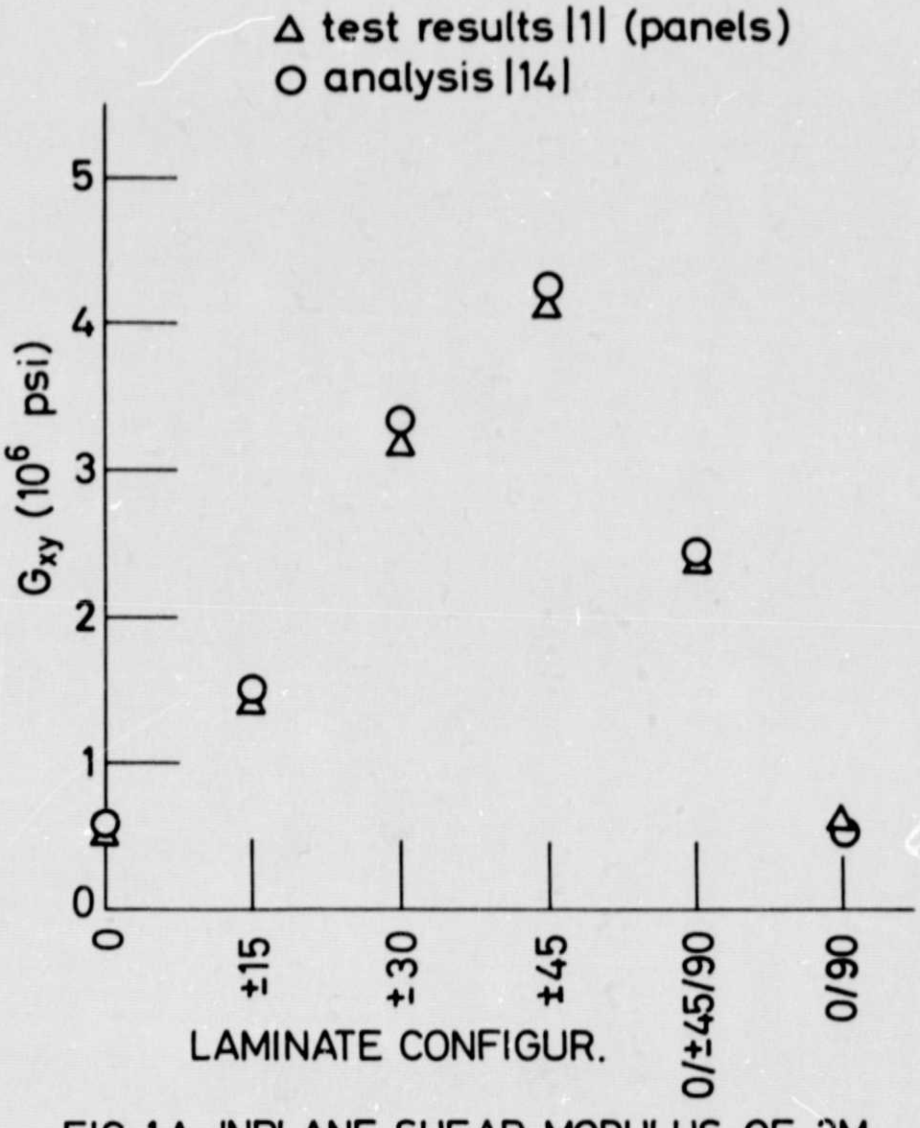

FIG. 1A INPLANE SHEAR MODULUS OF 3M SP-286T3 GRAPHITE-EPOXY LAMINATE AS A"FUNCTION" OF LAMINATE CONFIGURATION

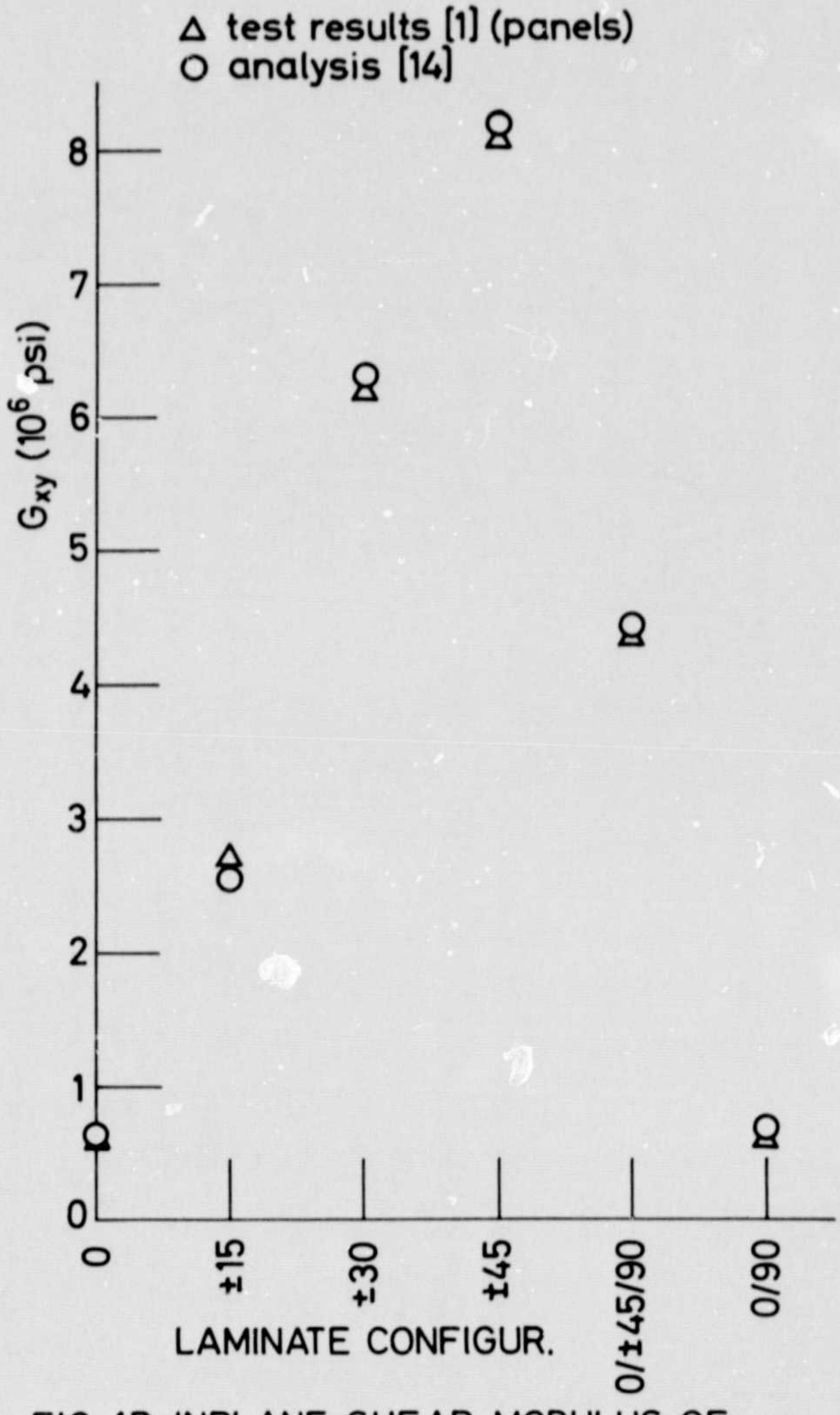

FIG. 1B INPLANE SHEAR MODULUS OF 5505/5.6 MIL. DIA. BORON-EPOXY AS A "FUNCTION" OF LAMINATE CONFIGURATION

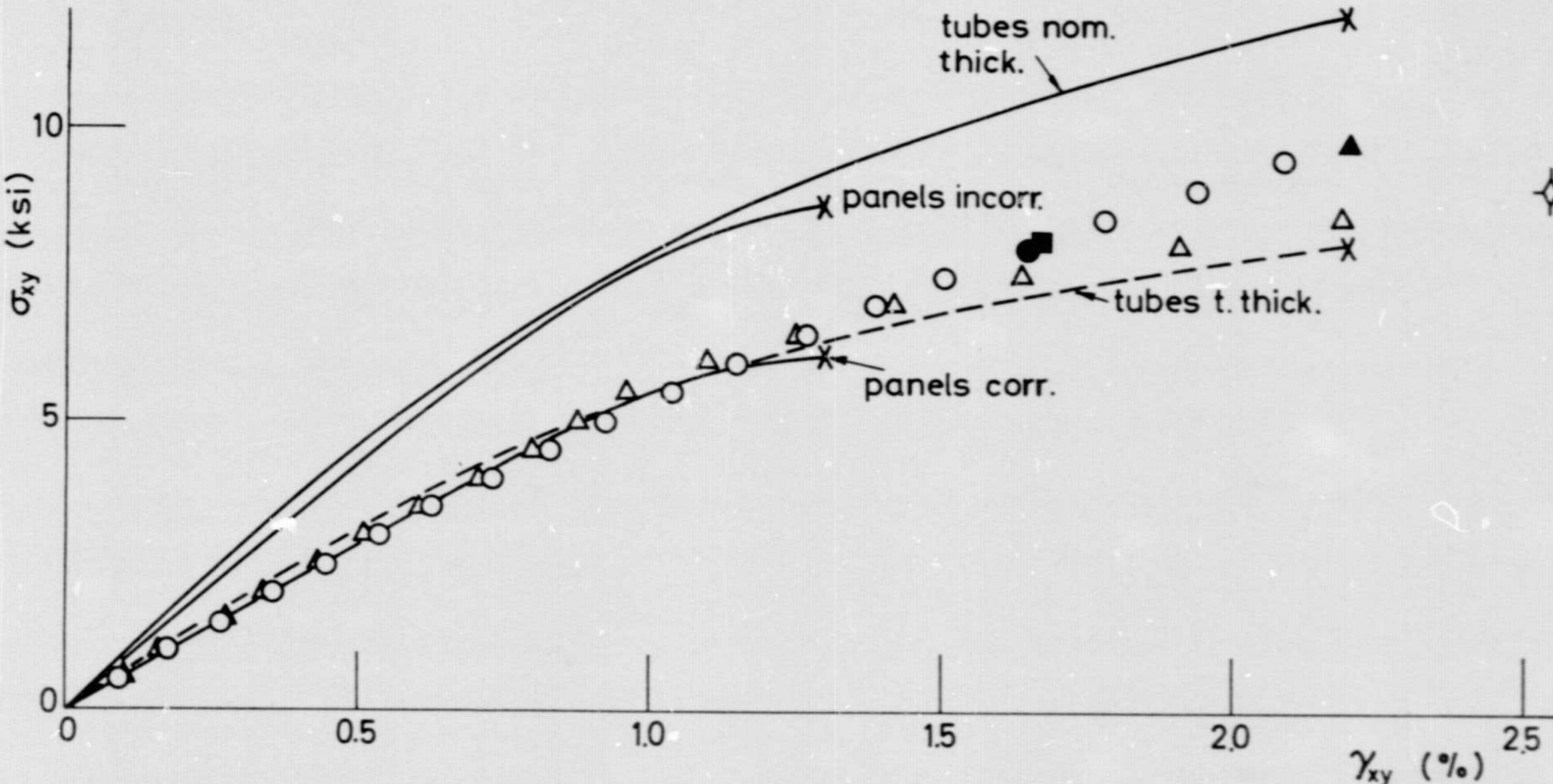

FIG. 3 SHEAR RESPONSE OF 0° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

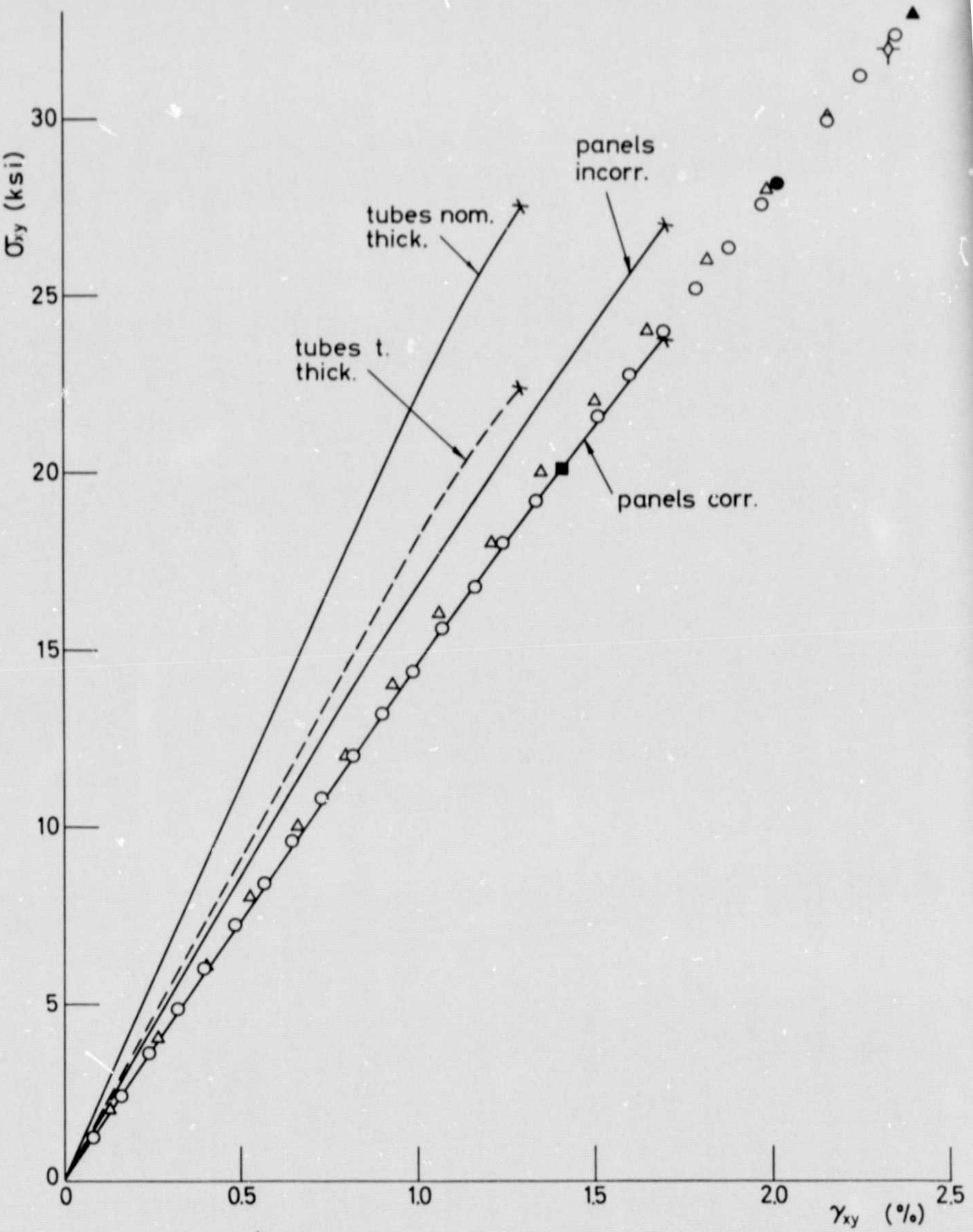

FIG. 4 SHEAR RESPONSE OF ±15° 3M SP-286T3 GRAPHITE EPOXY LAMINATES

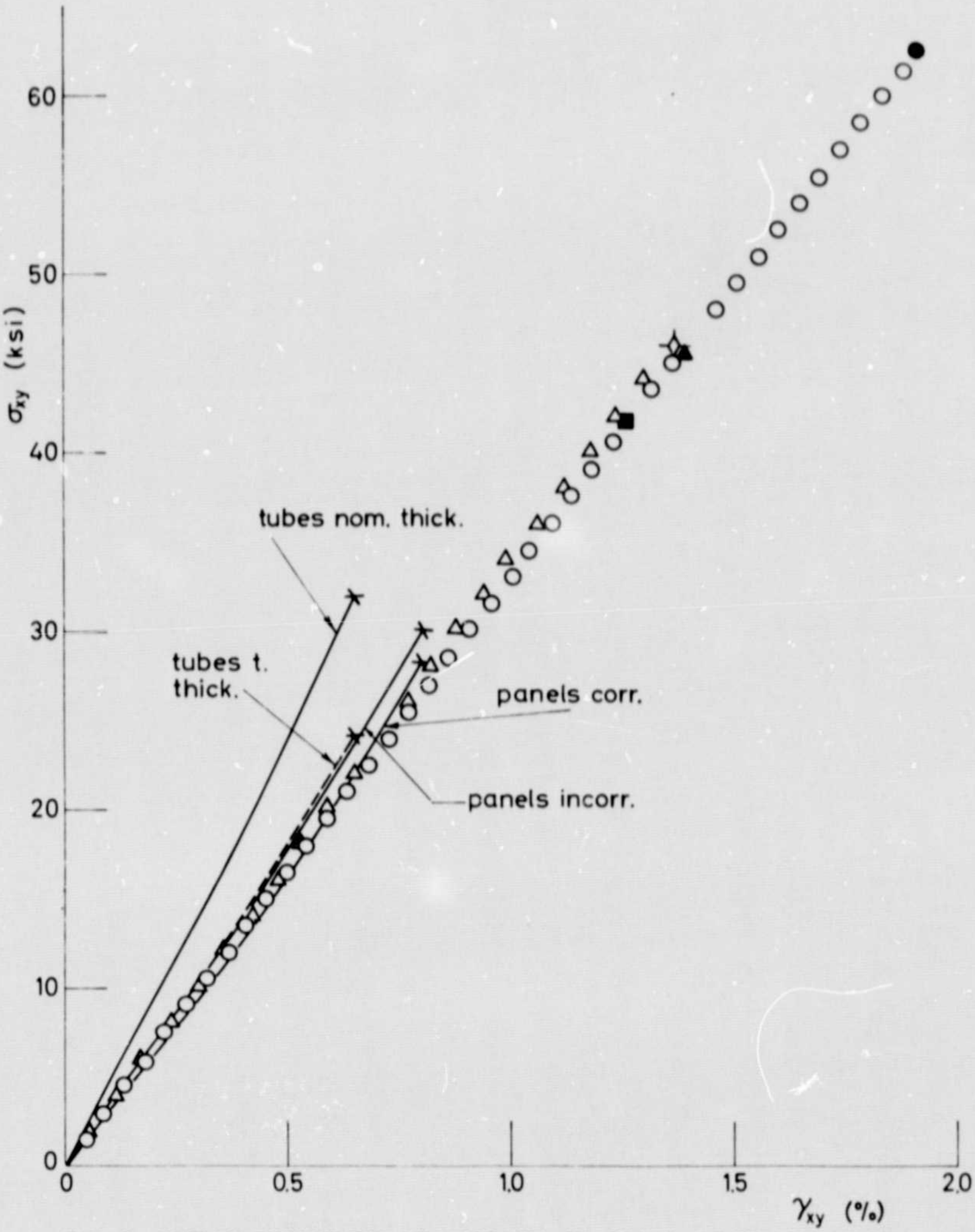

FIG. 5 SHEAR RESPONSE OF ±30° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

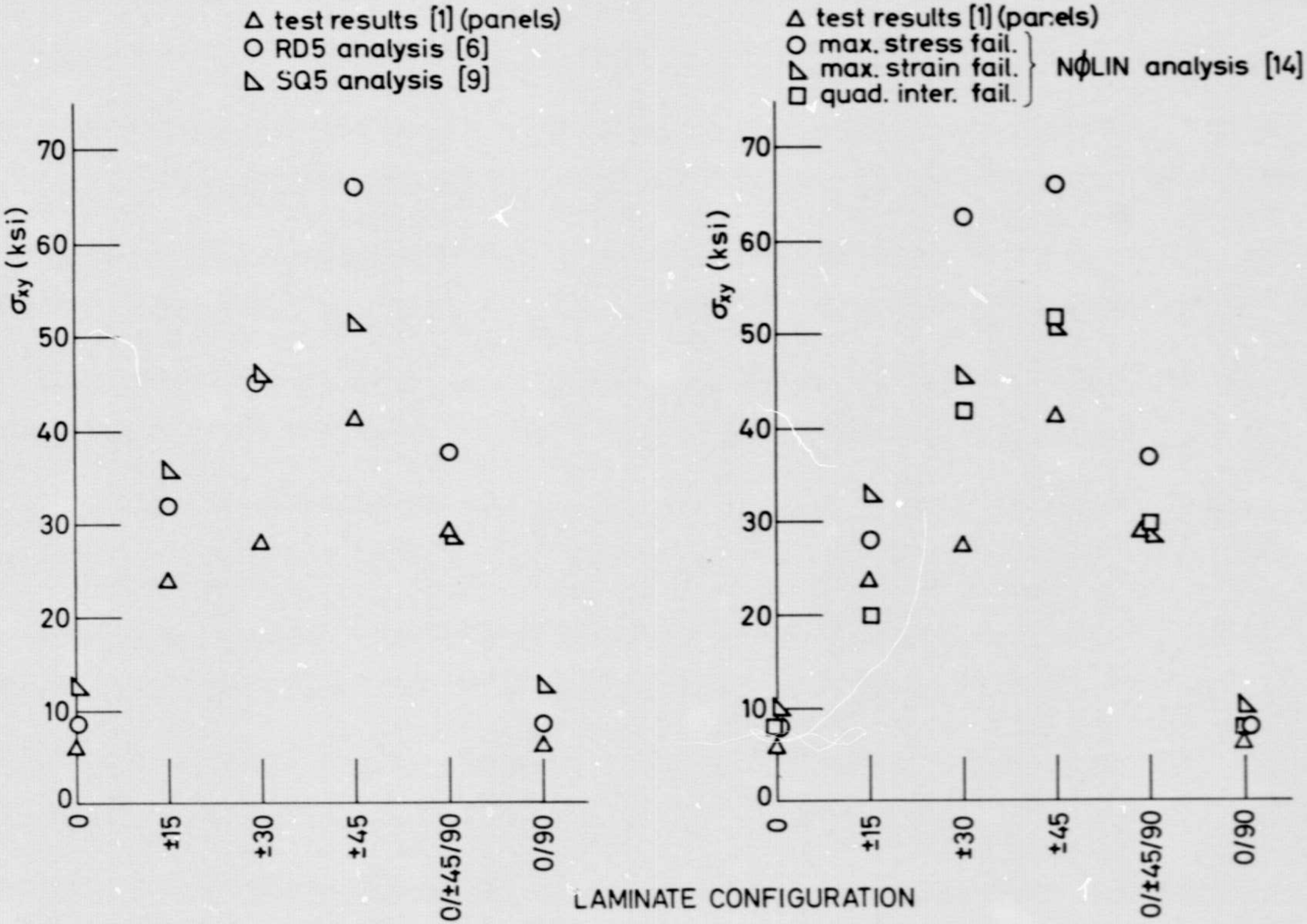

FIG. 2A ULTIMATE INPLANE SHEAR STRESS OF 3M SP-286T3 GRAPHITE-EPOXY AS A "FUNCTION" OF LAMINATE CONFIGURATION

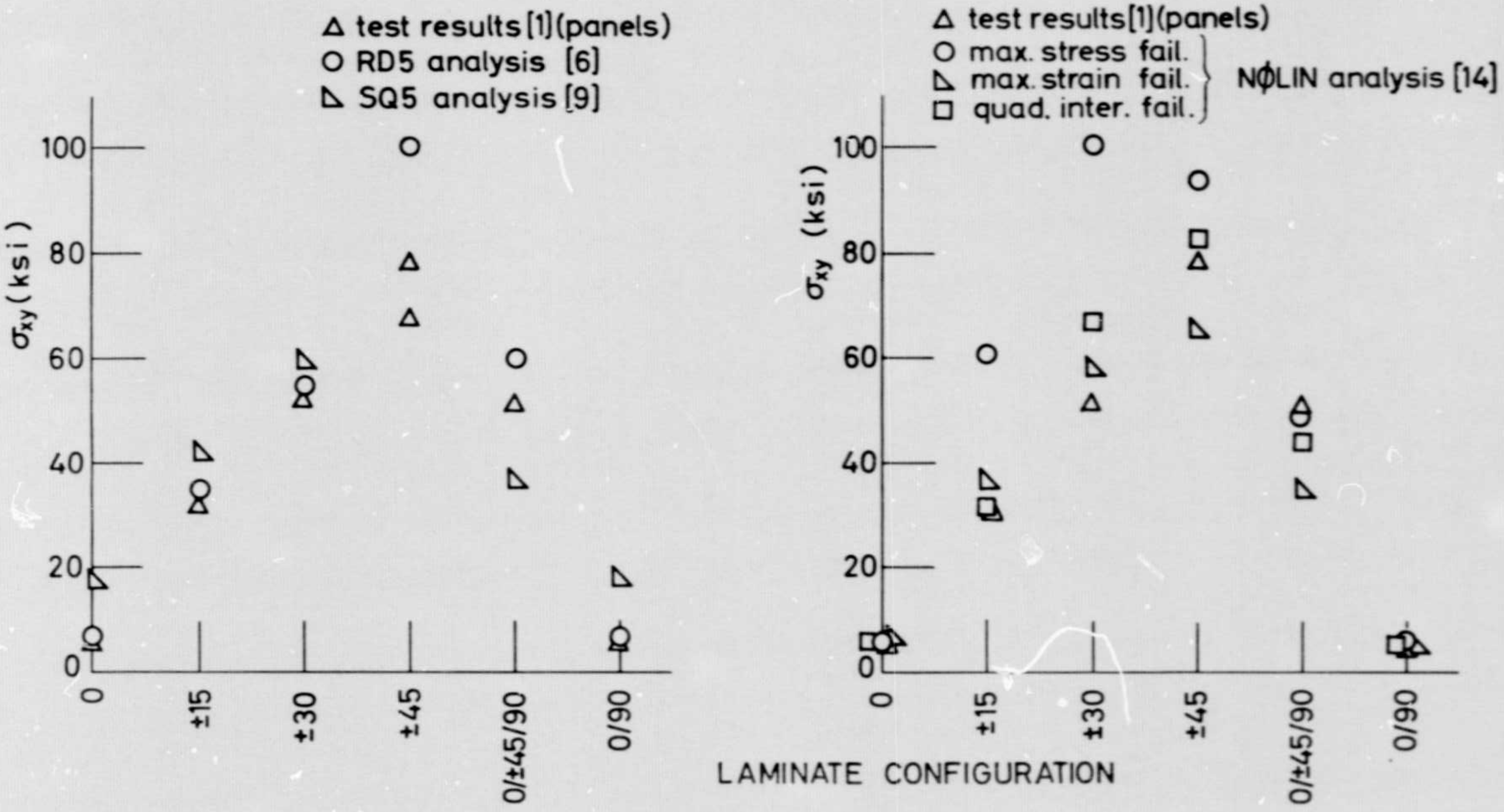

FIG. 2B ULTIMATE INPLANE SHEAR STRESS OF AVCO 5505/5.6 MIL. DIA. BORON-EPOXY AS A "FUNCTION" OF LAMINATE CONFIGURATION

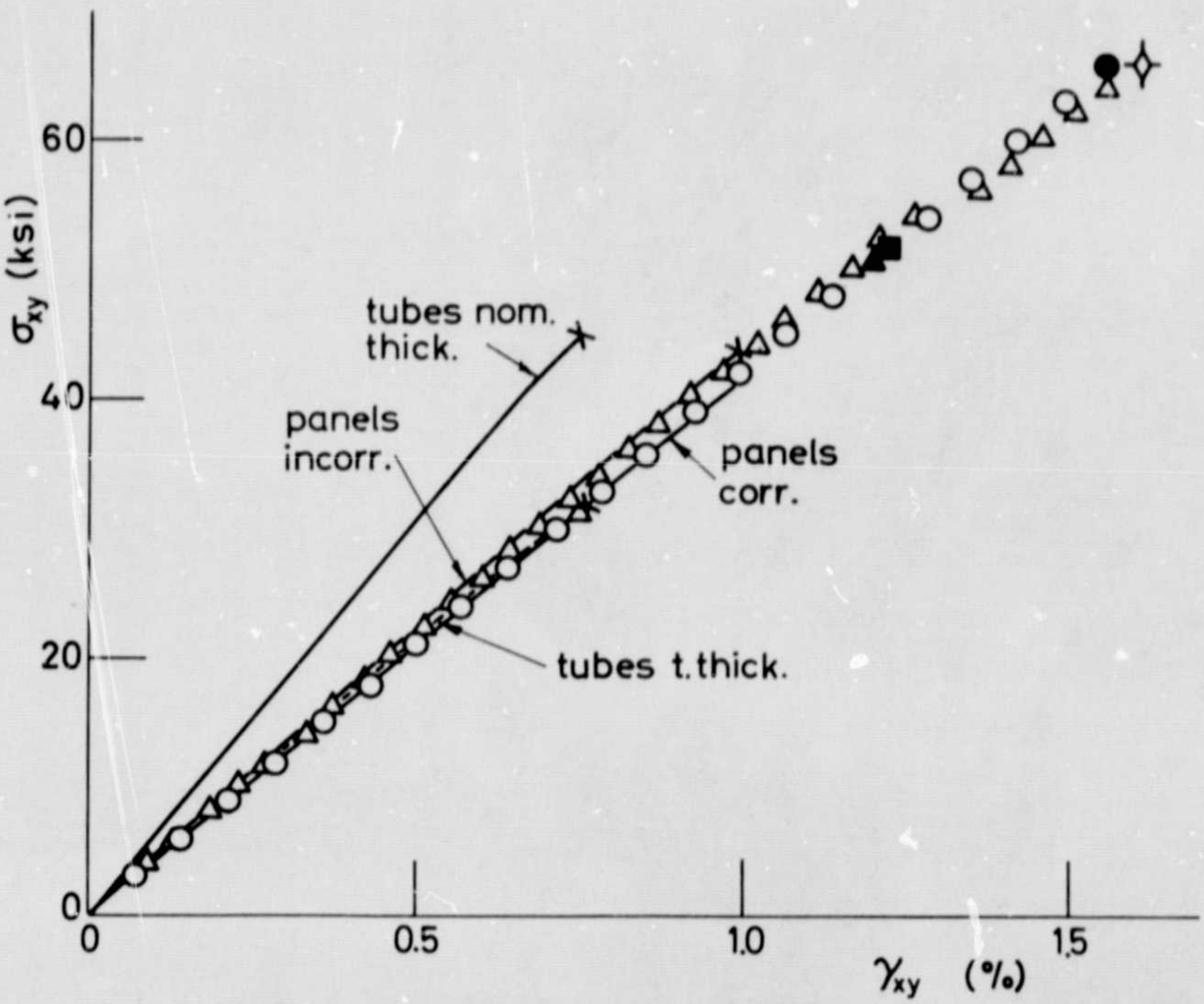

FIG. 6 SHEAR RESPONSE OF ±45° 3M SP-286T3 GRAPHITE EPOXY LAMINATES

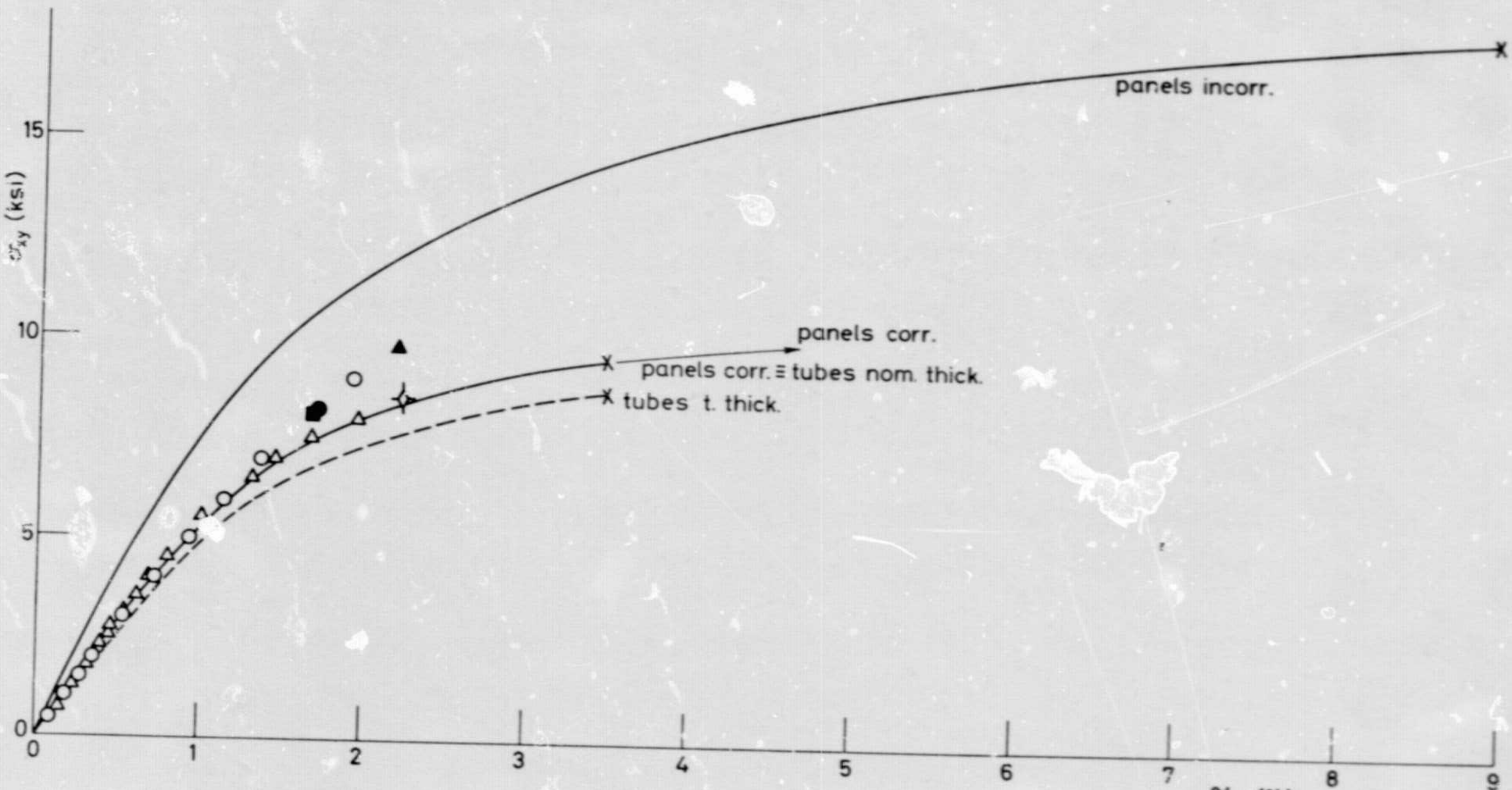

FIG. 7 SHEAR RESPONSE OF 0/90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

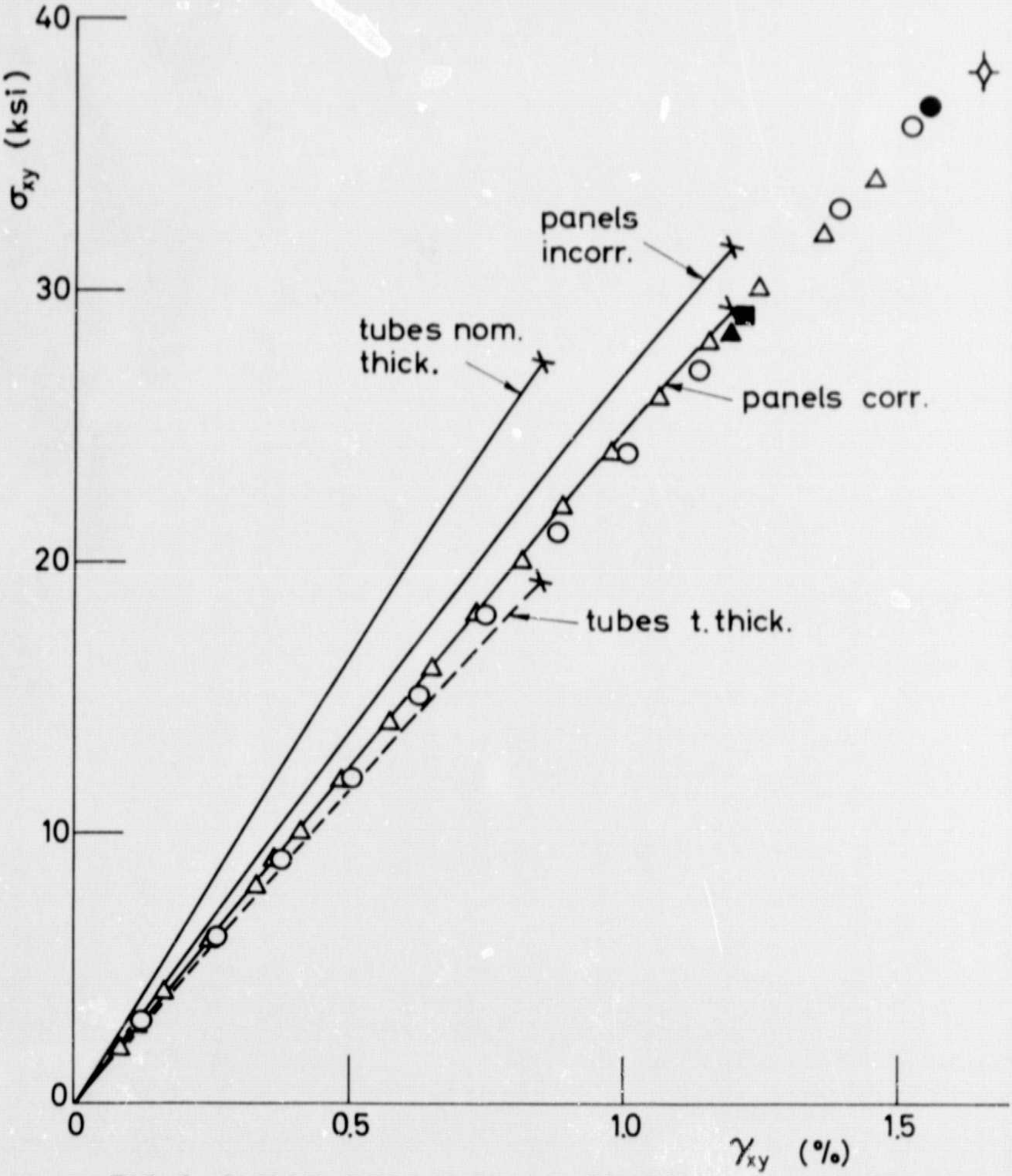

FIG. 8 SHEAR RESPONSE OF 0/±45/90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

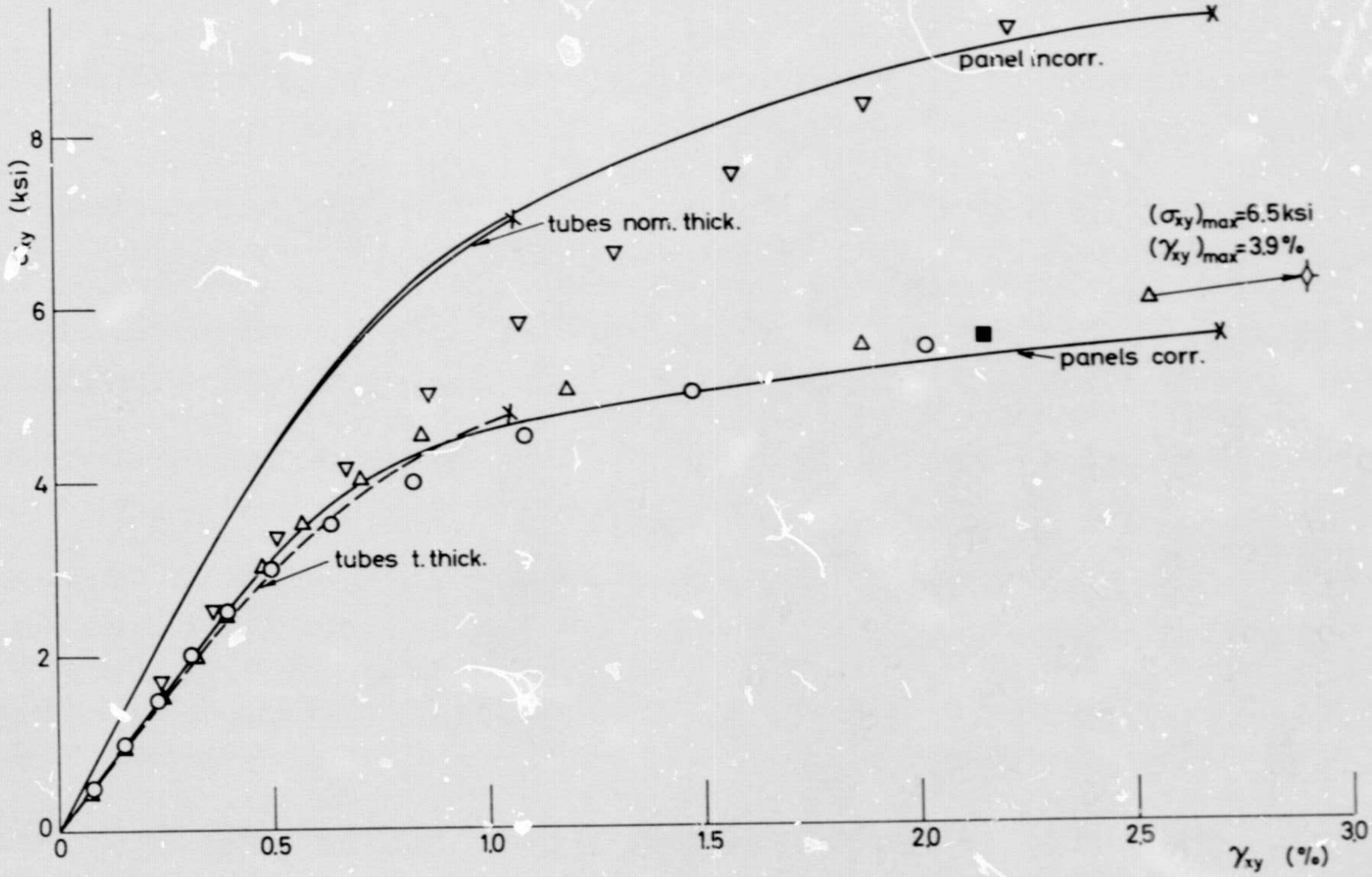

FIG. 9 SHEAR RESPONSE OF 0° AVCO 5505 5.6 MIL BORON-EPOXY LAMINATES

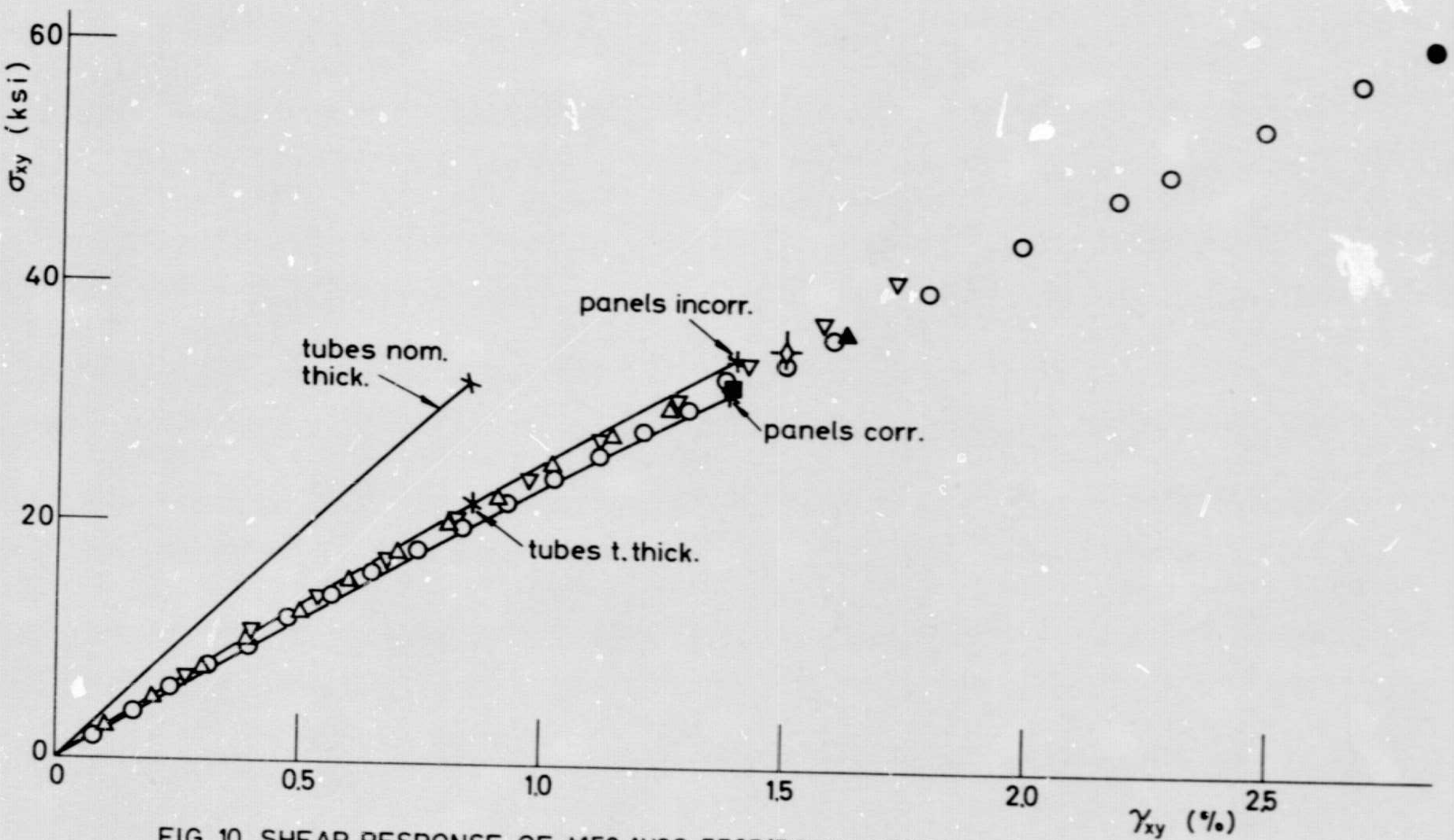

FIG. 10 SHEAR RESPONSE OF ±15° AVCO 5505/5.6 MIL BORON EPOXY LAMINATES

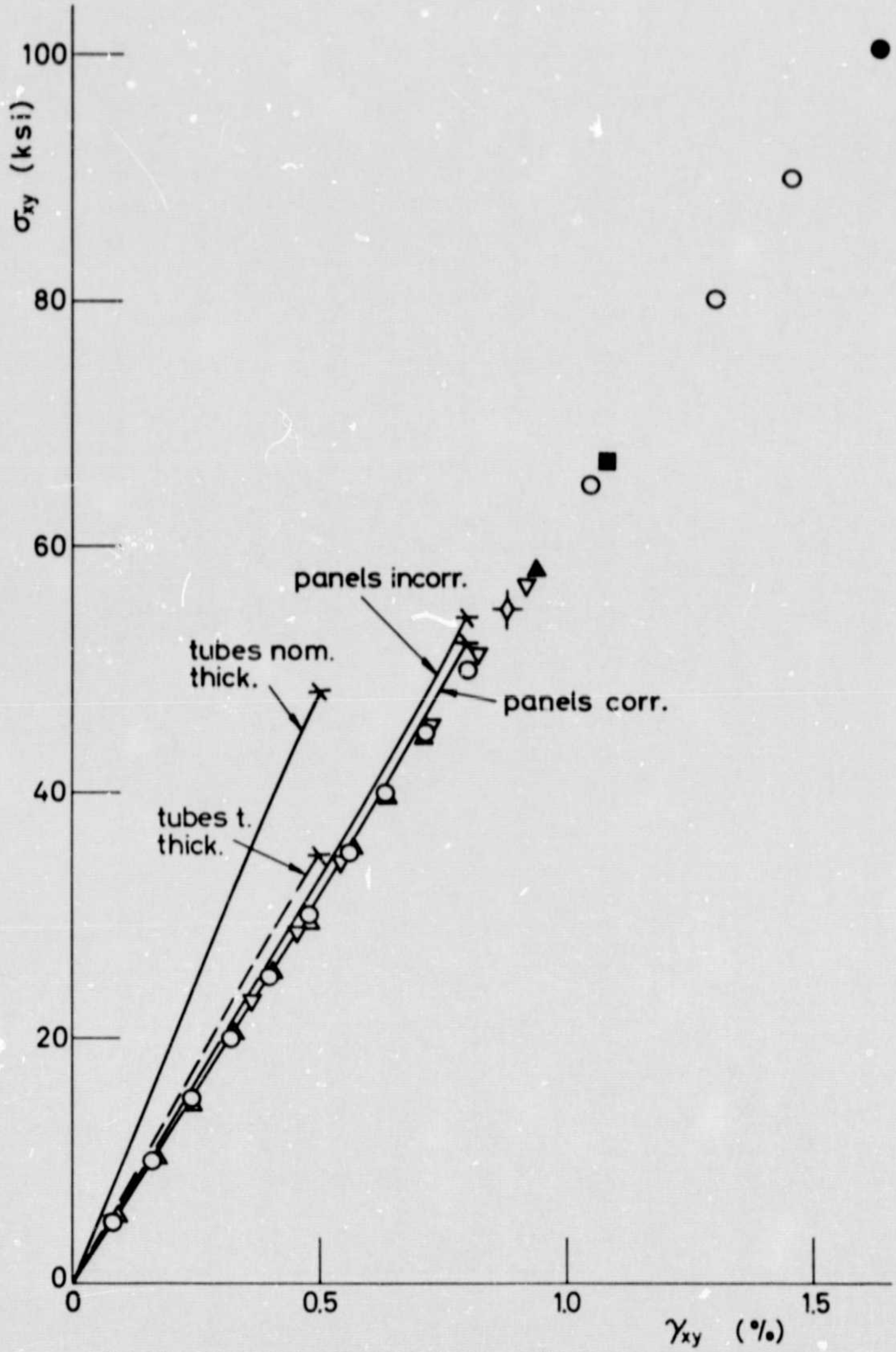

FIG. 11 SHEAR RESPONSE OF ±30° AVCO 5505/5.6 MIL. BORON-EPOXY LAMINATES

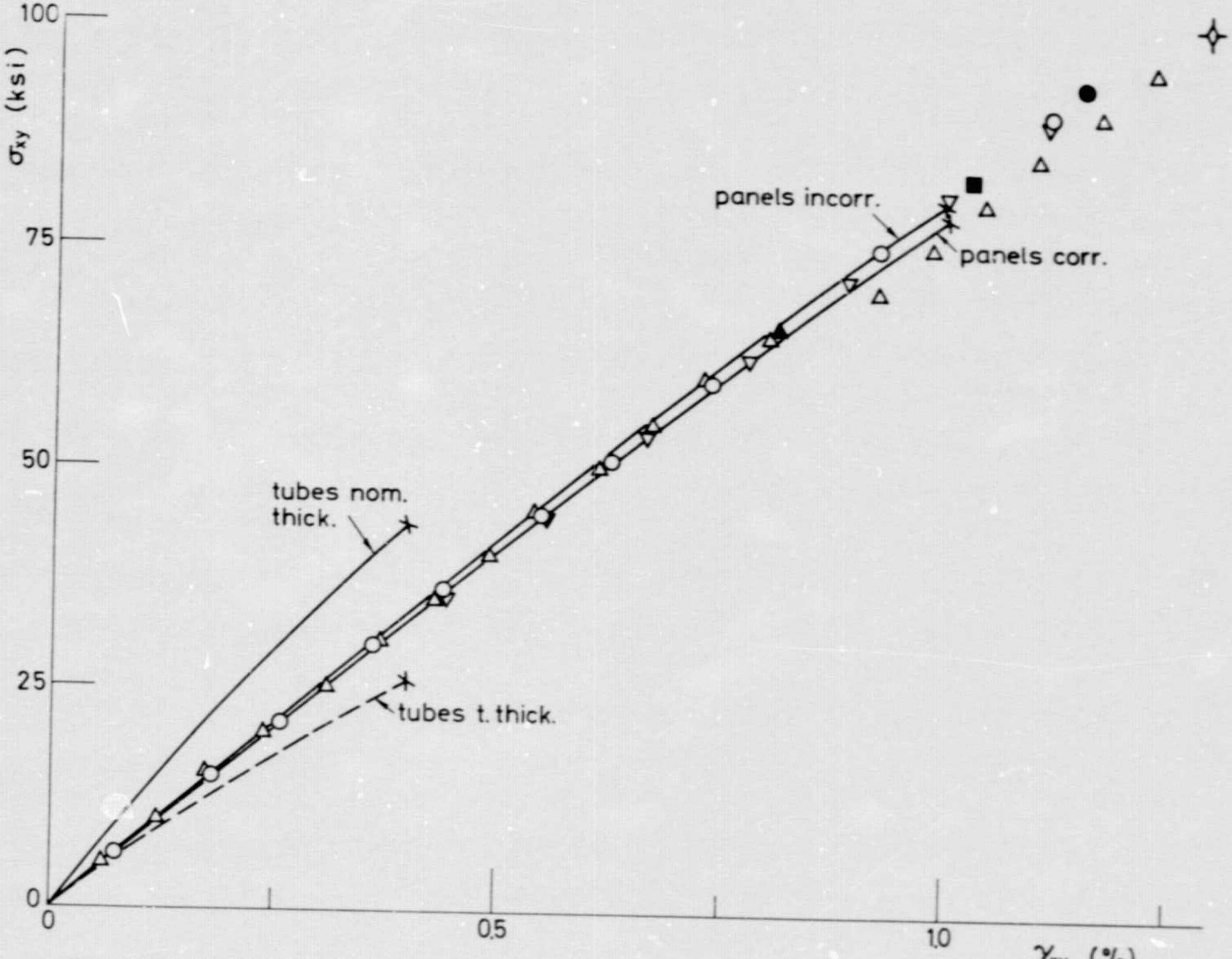

FIG. 12 SHEAR RESPONSE OF ±45° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES

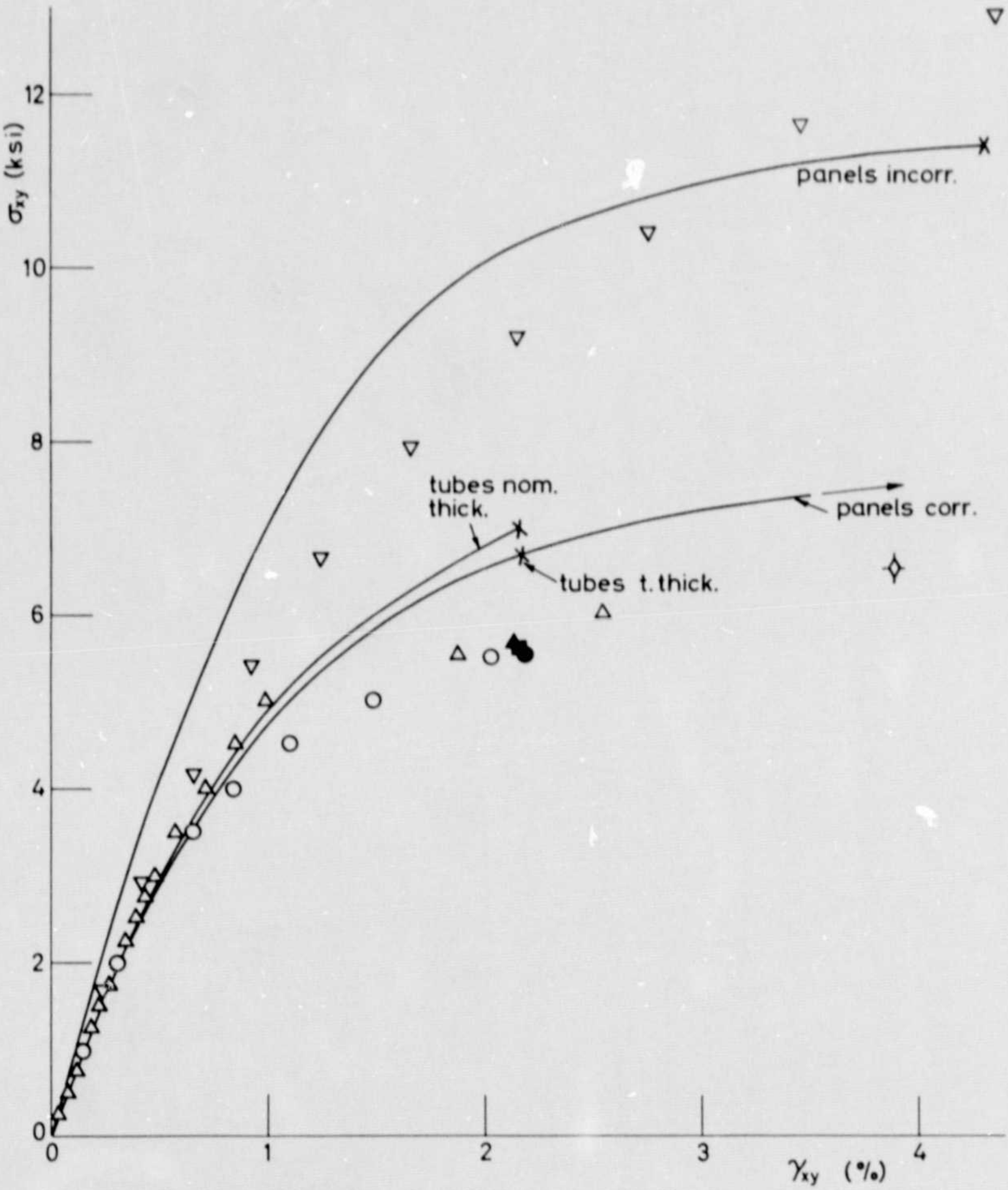

FIG. 13 SHEAR RESPONSE OF 0/90° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES

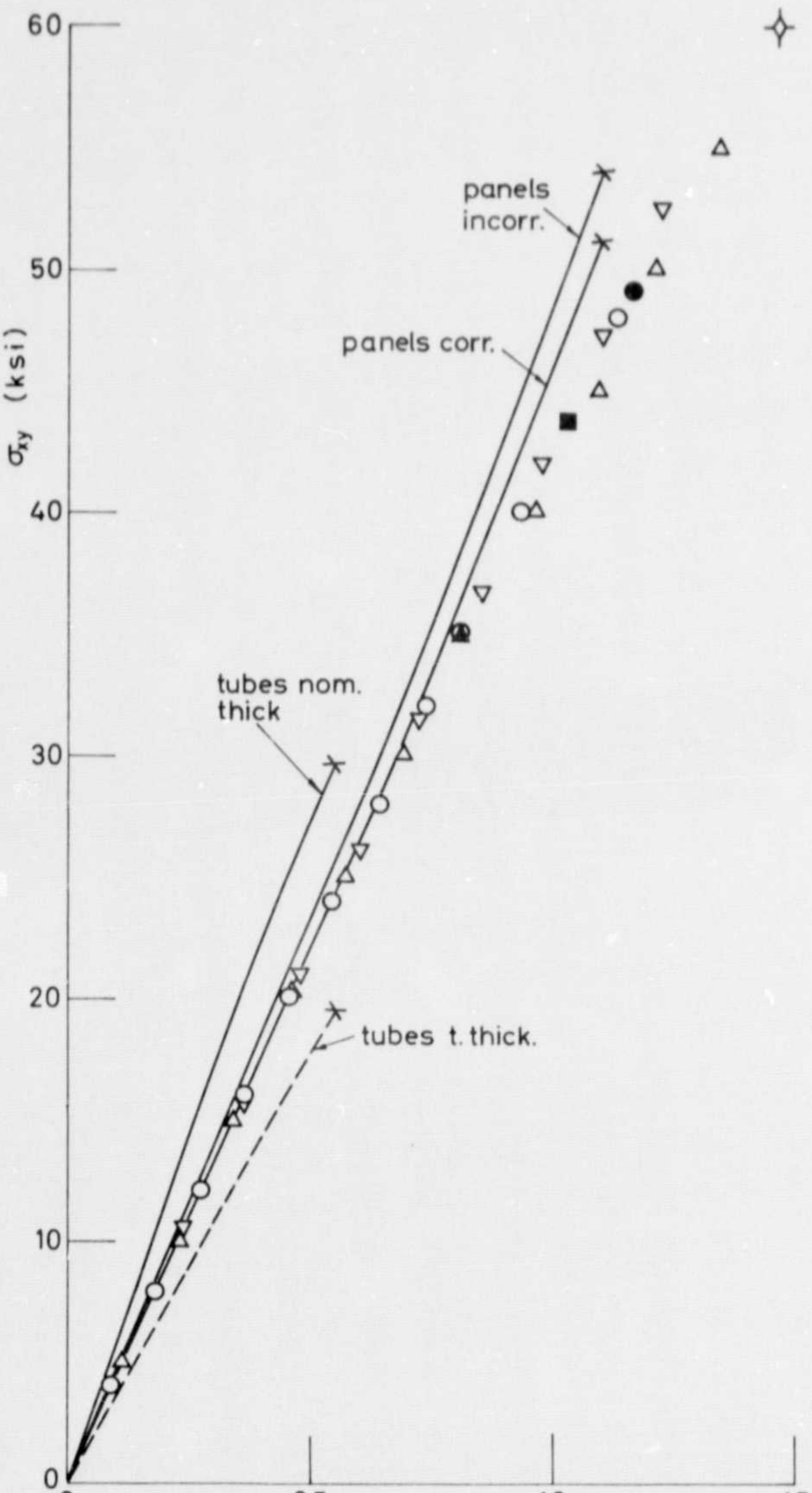

FIG 14 SHEAR RESPONSE OF 0/±45/90° AVCO 5505/5.6 MIL BORON-EPOXY LAMINATES