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

by

T. Weller

Prepared under Grant NSG-7083
for
Langley Research Center
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TECHNION-ISRAEL INSTITUTE OF TECHNOLOGY
DEPARTMENT OF AERONAUTICAL ENGINEERING
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ABSTRACT

This report presents a study aimed at evaluating the applicability and adequacy of the inelastic analyses of RD5[5], SQ5[8], NØNLIN [10]&[11] and NØLIN [13] in predicting satisfactorily the nonlinear/inelastic response of angle ply laminates. The analytical predictions are correlated with the results of a test program on the inelastic response under axial compression of a large variety of 3M SP-286T3 Graphite-Epoxy and AVCO 5505/5.6 Boron-Epoxy angle ply laminates carried out at NASA Langley Research Center [1]. These comparison studies indicate that neither of the abovementioned analyses can satisfactorily predict either the mode of response or the ultimate stress value corresponding to a particular angle ply laminate configuration. Consequently, also the simple failure mechanisms assumed in the analytical models were not verified.

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LIST OF SYMBOLS

AR	Stress field aspect ratio.
b, l	Coupon stress field dimensions, Fig. APB 1.
E_{11}	Lamina Young Modulus in the 11 fiber direction.
E_{22}	Lamina Young Modulus in the transverse 22 direction.
E_x	Laminate Young Modulus.
G_{12}	Lamina 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 Ratio.
CNU12	Compression Poisson Ratio.
x, y	Axial and transverse coordinates respectively, Fig. APB 1.
u, v	Displacements, Fig. APB 1.
δ	Axial end displacement, Fig. APB 1.
ε_{ULT11}	Lamina ultimate strain in the 11 fiber direction.
ε_{ULT22}	Lamina ultimate strain in the tranverse 22 direction.
ε_{ULT12}	Lamina ultimate inplane shear strain.
ε_x, ε_y	Laminate strains.
σ_x, σ_y	Laminate stresses.
σ_{ULT11}	Lamina longitudinal strength.
σ_{ULT22}	Lamina transverse strength.
σ_{ULT12}	Lamina inplane shear stress.
ν_{12}	Lamina major Poisson Ratio.
ν_{xy}, ν_{yx}	Laminate Poisson Ratio.

Note: All Figures Are Read As Follows:

△	RD5 Prediction [5].		
◇	RD5 Predicted Ultimate Stress.		
▽	NØNLIN Prediction [10]&[11].		
▼	NØLIN Fiber Failure.		
○	NØLIN Prediction [13] -	◉	Max. Stress Fail.
		▲	Max. Strain Fail.
		■	Quadratic Interaction Fail.
———	Empirical Response of [1].		
	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

The experimental results of an intensive test program carried out at NASA Langley Research Center and aimed at studying the nonlinear/inelasic compression response of Graphite-Epoxy and Boron-Epoxy laminates were reported in [1].

Advanced composites are increasingly being introduced into the design of primary structural components of advanced aircraft and space vehicles due to their high moduli and strength to density ratio, and particularly because of their "tailoring" capability to match and resist any type of load introduction into the structure. These characteristics propose them as an excellent, if not the number one candidate for advanced optimized structures [2].

In spite of their outstanding performances, the satisfactory and advantageous application of composite materials is limited unless there exist reliable analytical tools to predict and provide the response and design allowables of any "tailored" laminate with full confidence, i.e. verified by ample experimental evidence.

Theoretical studies include assumptions which can only be postulated when they are based on sound experimental evidence and then have to be verified experimentally. As a matter of fact theoretical studies were derived, [3] through [13], but all of them lacked the experimental background to justify both the assumptions made in their derivation and their adequacy to predict the response of laminated materials.

In the present report the experimental studies of [1] are correlated with the predictions of [5], [8], [10], [11] and [13], and the adequacy for satisfactory application of these analytical tools to generate and predict the response, as well as strength allowables, of different laminate configurations is evaluated. Some of these analyses, for example [5], [8] and [13], consider and account for simplified failure criteria, such as Max. Stress or Strain and Quadratic Interaction Failure for the laminate, and hence in the case of "good" agreement with the empirical investigation of [1], might allow for a better physical insight into failure mechanisms and critical stress combinations which trigger failure of the laminate. A brief description of the computer codes of [5], [8], [10], [11] and [13] follows in the next section.

2. NUMERICAL STUDIES

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]. These codes are known as RD5 or ULTIMATE, SQ5, NØNLIN and NØLIN and they are based on the analyses of [5], [8], [10]&[11] and [13] respectively. The main features of these programs follow.

2.1. COMPUTER CODES

2.1.1 RD5 - ULTIMATE[5]

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. This information in conjuction with a generalized Hook's low provides the laminate response. In addition to the response the program furnishes for each stage of loading the instantaneous stiffnesses and Poisson ratios.

2.1.2 SQ5[8]

Provides the stress allowables for a particular laminate based upon the maximum strain theory of failure. It is based on a coupled inplane and bending-point stress analysis of the 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.

2.1.3 NØNLIN[10]&[11]

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 into 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.

2.1.4 NØLIN[13]

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 Quadratic Interaction Fail. of an individual lamina. Hence it assumes that lamina failure precipitates overall failure of the laminate.

The codes of [5], [8] and [13] 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 A 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 [14].

3. RESULTS AND DISCUSSION

In Tables 1A and 1B experimental values of the ultimate stresses and moduli in compression corresponding to the laminates tested and reported in [1] are represented, together with the predicted values of the analyses of [5], [8], [10], [11] and [13]. (No values are given in Table 1A for NØNLIN [10]&[11] because of lack of information both on the fiber and matrix material of 3M SP-286T3. This information is required as data input for the application of this computer code).

In Fig. 1A the moduli observed for the Graphite-Epoxy laminates (coupons) are correlated with the predicted moduli by [8] and [13]. A similar comparison is shown in Fig. 1B for the Boron-Epoxy laminates (including the moduli predicted by [10]&[11]). Tables 1A and 1B reveal that the analyses of [8] and [13] yield identical moduli values, whereas the analysis of [5] predicts slightly but insignificantly different moduli values. Consequently, the comparisons presented in Figs. 1A and 1B also apply to the analysis of [5].

Tables 1A and 1B reveal considerable differences among the ultimate compression stresses predicted by the different analyses. The calculated ultimate strength values are compared with the empirical ones of [1], in Fig. 2A for the Graphite-Epoxy laminates, and in Fig. 2B for the Boron-Epoxy ones. Each of these figures consists of two sub-figures, one correlating the test results of [1] with the analyses of [5] and [8], and the second with the predictions of [13]. The figures are presented in such a manner as to allow for better distinction of the predicted ultimate values of [13], where three different such values are yielded for each laminate corresponding to Max. Stress, Max. Strain and Quadratic Interaction modes of failure of the laminate.

The results presented in Tables 1A and 1B and Figs. 1A, 1B, 2A and 2B will be discussed individually for each material and laminate configuration, when a particular laminate is being considered in the following discussions and evaluations of analytical predictions vs. observed test results.

Before proceeding with the discussion, the following remarks and comments on the presentation of Figs. 3 to 20 of this report should be noted; each figure consists of the test results reproduced from [1] and the analytical predictions of RD5[5], NØNLIN [10]&[11] (only for Boron-Epoxy laminates) and NØLIN[13]. The reproduced test results include the response experienced by the coupons and two plots corresponding to the tubes; one when nominal thickness is considered and designated Tubes Nom. Thick. in the figures, and the second when "true" measured thickness is accounted for and designated Tubes T. Thick. in the figures.

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

3.1.1 Unidirectional [0°] Laminates

The experimental response of [1] is presented, together with the predicted ones, by RD5[5] and NØLIN[13] in Fig. 3. As already mentioned earlier, the analyses of [5] and [13] require the unidirectional [0°] and [90°] lamina responses in tension, compression and shear as data input, or rather data library for application of their computer codes. This type of information for the compression response was extracted from the experimental compression response of the [0°] compression coupons of [1]. Hence Fig. 3 assists in evaluating the capability of the computer codes RD5[5] and NØLIN[13] to reproduce the stress-strain response of the [0°] unidirectional lamina. This of course might affect the predicted responses of the angle ply laminates and their correlation with the empirical responses of [1]. It is observed from Fig. 3 that RD5 reproduces excellently the compression branch of the lamina, whereas reproduction of the tension branch is very good in the range of low stress-strain levels and becomes poorer with increase in stress values, displaying less nonlinearity than that experienced by the coupons. This nature of behavior depends very much upon reproduction of the unidirectional [90°] lamina response in tension by RD5. Fig. 3 also reveals that the NØLIN code does not reproduce so well either the lamina compression branch or its tension branch. This stems from the analysis of [13], which assumes a perfectly elastic response of the lamina up to failure in the so called 11 direction, i.e. fiber direction. As already stated this might influence the predicted responses of the angle ply laminates.

It is seen from Table 1A and Fig. 1A that RD5 yields an ultimate stress which is slightly higher than that experienced experimentally (200.ksi compared with 191.ksi, respectively). NØLIN Max. Stress and Quadratic Interaction Fail. predict a lower stress value than the experimental one, 180.ksi, and NØLIN Max. Strain Fail. yields a higher strength value than experienced both experimentally and by RD5 209.ksi. This ultimate stress is also predicted by SQ5[8].

3.1.2 [±15°] Laminates

The experimental responses of [1], together with the predicted ones, [5] and [13], are shown in Fig. 4. It appears from Fig. 4 that there is good agreement between RD5 and NØLIN predictions, as well as very good correlation between the empirical compression branch corresponding to the coupons and the theoretical predictions. It is also observed that once the "true" measured thickness of the tubes is accounted for, the tube compression response correlates well with that experienced by the coupons; however, the "true" ultimate stresses yielded by the tubes are significantly lower than those obtained for the coupons (see also Table 1A). Fig. 4 also reveals that there is no correlation between the theoretical predictions of the tension branch and the coupon tension branch. The predictions display more pronounced nonlinearity than do the coupons.

Fig. 1A and Table 1A indicate that the analyses of [5], [8] and [13] yielded an identical modulus of 13.24×10^6 psi, which is slightly lower than that of 13.94×10^6 psi experienced by the coupons. It is observed in Fig. 2A and Table 1A that the ultimate stress predicted by SQ5[8] is in excellent agreement with that yielded by the coupons (117.ksi). Also, RD5[5] predicts an ultimate strength value of 105.ksi, which is lower than that experienced by the coupons and in very good agreement with NØLIN[13] Max. Strain Fail. (106.ksi). It also appears that NØLIN Quad. Fail. predicts a low strength value relative to the coupons (92.9 ksi), and Max. Stress yields a higher stress value (140.ksi) than that observed for the coupons. As has already been stated earlier it is observed in Table 1A that the tubes sustained a low ultimate strength value independent of whether nominal or "true" thickness is considered.

3.1.3 [±30°] Laminates

The experimental responses of [1], as well as the predicted ones, are presented in Fig. 5. It is observed that RD5[5] and NØLIN[13] predictions are in good agreement. It appears that these predictions display more pronounced nonlinearity and considerably lower strength values (see Table 1A) than those experienced experimentally by the coupons. It is also observed in this figure that once the "true" thickness is being considered for the tubes, their compression branch of the response is in good agreement with the predicted ones. However, very "poor" ultimate stresses are then experienced by them (see Table 1A). Comparing the tension branch of the responses predicted by the analyses with those experienced empirically it is seen that the tubes, when "true" thickness is accounted for, respond similarly to the theoretical predictions, whereas the coupons respond with a completely different behavior; higher stiffness and not as much as pronounced nonlinearity.

The results of Table 1A and Fig. 1A show that the analyses yield identical moduli of 5.76×10^6 psi which are noticeably lower than those experienced by both the coupons (6.87×10^6) and the tubes (6.55×10^6 when "true" thickness is accounted for). Regarding the ultimate stresses, it is found that the coupons sustained appreciably higher strength values (59.1 ksi) than were predicted by the analyses: 48.7 by SQ5[8], 40.0 by RD5[5] and 43.4, 37.6 & 28.8 by NØLIN[13] Max. Stress, Max. Strain and Quad. Fail. respectively. Also the strength experienced by the coupons is almost twice as high as that yielded by the tubes.

3.1.4 [±45°] Laminates

Fig. 6 presents the empirical responses of [1], together with those predicted by [5], and [13]. This figure displays good agreement between the linear portion of the compression branches of the responses predicted by the analyses, and those experienced by the coupons and tubes (when "true" thickness is being considered). It is observed in this figure that NØLIN[13] predicts significantly less pronounced nonlinearity than RD5, and correlates well with the response corresponding to the tubes ("true" thickness). It is also seen from this figure that the coupons experienced a significantly higher compression stressing and straining capacity than was predicted by the analyses. The compression response of the tubes, when nominal thickness is considered, behaves very similarly to that of the coupons; exhibiting, however, a considerably lower strength value (see Table 1A). Comparing the predicted and empirical tension branches of the responses, it is seen that they display a similar behavior to that already experienced and discussed for the compression branches.

It appears from Table 1A and Fig. 1A that the analyses predict a modulus of 2.04×10^6 psi, which is noticeably lower than the 2.27×10^6 experienced by the coupons. Also Table 1A and Figs. 2A and 6 indicate that the coupons experienced considerably higher ultimate stresses (3.82 ksi) than were predicted by the analyses; a maximum value of 31.3 by RD5[5], and a minimum of 16.2 by NØLIN Max. Stress. Note that Table 1A includes two values for RD5, 31.3 ksi and (60.)↑. The second value of 60. defines the ultimate stress according to the computer code of this analysis; however, this stress value is associated with very high, unresonable and unacceptable strain values. The stress of 31.3 generated by the computer code was found to be the last one corresponding to acceptable strain values. It is also seen from Table 1A that the ultimate stress corresponding to the tubes is close to that predicted by RD5[5], when nominal thickness is considered, and to that yielded by SQ5[8] when "true" thickness i accounted for.

3.1.5 [±60°] Laminates

The responses of [1] and those predicted by the analyses of [5] and [13] are shown in Fig. 7. It is seen from this figure that the responses predicted by the analyses are slightly and insignificantly different and correlate fairly well with the response experienced by the coupons. However, the coupons display considerably higher stressing and straining capability, both in compression and tension, than do the analytical predictions. It is also observed in this figure that the compression branch of the response corresponding to the tubes when "true" thickness is accounted for correlates very well with the analytical predictions. Good agreement of the tension branch corresponding to the tubes with the numerical studies is also found.

Fig. 1A and Table 1A indicate a predicted modulus of 1.61×10^6 psi by SQ5[8] and NØLIN[13] which is slightly higher than 1.58×10^6 yielded by RD5[5]. These moduli values are noticeably lower than 1.72×10^6 experienced by the coupons and 1.79×10^6 obtained for the tubes ("true" thickness). As mentioned already above, in the discussion on Fig. 7, the predicted ultimate stresses are considerably lower than those experienced by the coupons (see Table 1A and Fig. 2A). It is found in Table 1A that the coupons sustained a strength value of 37.6 ksi compared with the highest ultimate value of 30.8 predicted by SQ5[8] and the lowest value of 19.5 yielded by NØLIN Max. Stress [13]. It is also observed in this Table that the tubes, when nominal thickness is being considered, experienced higher ultimate stresses than those predicted analytically. However, once their "true" thickness is taken into account, they experience a strength of 22.1 ksi, which is in very good agreement with 22.3 and 23.3 ksi calculated with NØLIN Max. Strain and Quad. Fail. respectively, and with 23.8 ksi predicted by RD5[5].

3.1.6 [±75°] Laminates

The experimental responses of [1] are displayed together with the analyticl predictions of [5] and [13], in fig. 8. Good correlation is observed in Fig. 8 between the prediction of NØLIN[13] and the response experienced by the coupons. Good agreement is also observed between the prediction of RD5[5] and NØLIN[13] in the low stress-strain range, while with increase in stress, RD5 responds less nonlinearly than does NØLIN. This discussion also applies to comparison of the RD5 prediction with the coupon response. It is also seen from this figure that the tubes (nominal thickness) respond very similarly to the analytical predictions and the coupons, experiencing, however, considerably low stress-strain values relative to either the coupons or analytical predictions (see Table 1A).

Comparing the moduli predicted by the analyses, it is seen from Table 1A and Fig. 1A that SQ5[8] and NØLIN[13] yielded an identical modulus of $1.81x10^6$ psi, which is slightly higher than $1.75x10^6$ calculated with RD5[5]. These moduli values are lower than $1.91x10^6$ experienced by the coupons and in very good agreement with $1.75x10^6$ yielded by the tubes when nominal thickness is being considered. Once "true" thickness is accounted for, very poor correlation with analytical predictions is found ($1.20x10^6$). It is observed in Fig. 2A and Table 1A that the empirical ultimate stress of 36.0 ksi experienced by the coupons is in good agreement with 37.5 yielded by RD5[5] and 32.5 predicted by NØLIN Max. Stress and Max. Strain [13]. SQ5[8] is found to predict a considerably high stress of 48.9 ksi and NØLIN Quad. Fail. a relatively low stress of 29.8 ksi. The tubes appear to sustain considerably low stress values (21.4 ksi for nominal thickness).

3.1.7 [90°] Laminates

Like for the [0°] laminates, the experimental responses of this laminate configuration are utilized as data input for the computer codes of the different analyses [5], [8] and [13]. Hence, evaluation of the empirical responses of [1], which are presented in Fig. 9 together with the predicted or rather reproduced ones, indicate the degree of "effectiveness" of the analytical models on which the computer codes are based, at least in reproducing the data input. Very good agreement is observed between NØLIN [13] and the experimental response experienced by the coupons. RD5[5] is seen to follow the empirical response in the range of low stress-strain levels but, with increase in stress values, displays less nonlinearity than either the coupons or NØLIN. It is also seen from Fig. 9, as well as Table 1A, that the tubes experience considerably lower stress-strain values and a less stiffer compression response relative to the coupons.

Table 1A reveals that RD5[5] predicts a modulus of $1.84x10^6$psi, which is slightly lower than that of $1.91x10^6$ experienced by the coupons. Fig. 2A and Table 1A indicate very good agreement between the strength of 34.4 ksi yielded by the coupons and 35.0 by RD5;

good correlation with NØLIN[13] predictions: 32.0, 33.2 & 32.0 ksi for Max. Stress, Max. Strain and Quad. Fail. respectively; and no correlation with SQ5[8] ultimate stress of 47.8 ksi.

3.1.8 [0°/90°] Laminates

Fig. 10 presents the empirical responses of [1] and those predicted by the analyses. It is observed that in the region corresponding to low stress-strain values there is very good correlation between the analyses and the empirical compression branch corresponding to the coupons. However, with increase in stress-strain values the response of RD5[5] deviates slightly from the empirical one, while that predicted by NØLIN[13] becomes pronouncedly nonlinear. This behavior of NØLIN might be explained by recalling the nature of reproduction observed earlier in Fig. 3 for the [0°] unidirectional laminate. It is also seen from this figure that the analytical predicted tension branches are stiffer than the tension response displayed by the coupons. However, RD5 agrees better than NØLIN with the test results.

Table 1A and Fig. 1A reveal very good correlation of the empirical modulus of 8.79×10^6 psi with the calculated ones: 8.82×10^6 by SQ5[8] and NØLIN[13], and 8.99×10^6 by RD5[5]. Table 1A and Fig. 2A indicate that the ultimate stresses predicted by RD5, SQ5 and NØLIN Max. Strain: 110., 115. and 112. ksi respectively, are in very good agreement with 115. ksi experienced by the coupons. The stress of 107. ksi yielded by NØLIN Quad. Fail. is in good agreement with the test results, and that corresponding to Max. Stress, 96.2 ksi is appreciably lower. It is found from Table 1A and Figs. 2A and 10 that the tubes sustained very low stress-strain values relative to either the coupons or analytical predictions.

3.1.9 [0°/±45°/90°] Laminates

The experimental responses of [1], together with the analytical predictions, are shown in Fig. 11. It is observed that RD5[5] correlates well with NØLIN[13] displaying very good agreement for low and moderate stress-strain levels. Fig. 11 also displays good agreement between the response experienced by the coupons and the analytical predicted responses. However, the coupon response appears to behave to some extent less nonlinearly and more stiffely than predicted (see Table 1A and Fig. 1A). It is also observed in this figure that the tubes (nominal thickness) respond similarly to the coupons but sustain very low stresses (see Table 1A).

Fig. 1A and Table 1A indicate that SQ5[8] and NØLIN[13] predict a modulus of 6.32×10^6 psi which is lower than 6.42×10^6 predicted by RD5[5] and 6.74 experienced by the coupons. It also appears from Table 1A and Fig. 2A that the coupons sustained a considerably higher ultimate stress (97.8 ksi) than that predicted by the analyses (85.0 ksi by RD5, 82.1 by SQ5 and 68.7, 79.2 and 64.8 by NØLIN Max. Stress, Max. Strain and Quad Fail respectively).

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

In addition to the analyses of [5], [8] and [13], the empirical results of [1] corresponding to this material are compared with the predicted response by the analysis of [10]&[11]. The results yielded by the computer code of this analysis, NØNLIN, should not, however, be treated with the same degree of confidence as those of the other analyses, because the data input for the matrix material of this composite required in the analysis was not provided. Hence, available information about the matrix reported in the literature [10] was adopted. Also note that no ultimate stress values appear either in Table 1B* or Fig. 2B because the analysis of [10]&[11] does not predict ultimate stresses, except for the case when the fibers in any of the laminae reach their assigned strength values.

3.2.1 <u>Unidirectional [0°] Laminates</u>

Like in the case of the unidirectional [0°] Graphite-Epoxy laminates, the reproduction capability of the computer codes are again evaluated. The empirical response of [1], together with the reproduced ones, are presented in Fig. 12. It is observed that the compression branch of RD5[5] correlates very well with the experiments except in the neighbourhood of ultimate stress values; NØLIN[13] deviates slightly from the empirical one at high stress-strain levels because, as already mentioned earlier, it does not allow for nonlinear behavior in the 11 fiber direction, and NØNLIN[10]&[11] is seen to be in very good agreement with NØLIN. The tension branch of RD5 and NØLIN are almost identical and agree with the coupon response except for high stress-strain levels when they display less nonlinearity than that experienced by the coupons. The tension branch of NØNLIN is observed to exhibit less nonlinear effects than either RD5 or NØLIN.

Table 1B and Fig. 2B reveal very good agreement between the experimental ultimate stress, 342. ksi, and the strength predicted by RD5[5] and NØLIN Max. Stress and Quad. Fail. [13], 340. ksi by all of the three. SQ5 and NØLIN Max. Strain are observed to yield a slightly higher strength than that experienced empirically, 353. ksi. It is seen from Table IB. and Fig. 1B that except for NØNLIN all the analyses predict the experimental modulus of $31.27\text{x}10^6$ psi. NØNLIN yields a slightly lower modulus of $31.20\text{x}10^6$.

3.2.2 [±15°] Laminates

Fig. 13 presents the experimental responses of [1] and the predicted ones. It is observed that all of the analyses predict almost identical compression branches, which are in very good agreement with the response yielded by the coupons for low stress-strain values, and that expeienced by the tubes when "true" thickness is accounted for. With increase in stress-strain values the coupons respond more nonlinearly than predicted by the analyses. Also RD5[5] displays more nonlinear behavior than NØNLIN[10]&[11] and NØLIN[13]. Reffering to the tension branch of the responses, it appears that neither of the predicted responses agrees with the experimental responses. Very good correlation is observed between RD5 and NØLIN in the low stress-strain range whereas with increase in stress-strain levels NØLIN displays slightly more pronounced nonlinear behavior. At very high stress values this behavior inverts, and RD5 displays very strong nonlinear effects. NØNLIN is seen to respond more linearly but less stiffly than either RD5 or NØLIN, except for high stress values, where an opposite trend is observed.

It is seen from Table 1B and Fig. 1B that RD5[5], SQ5[8] and NØLIN[13] yield a modulus of $25.26\text{x}10^6$ psi, which is slightly higher than 24.96×10^6 predicted by NØNLIN [10]&[11], and also higher than 23.65×10^6 experienced by the coupons. Table 1B and Fig. 2B reveal good agreement between the ultimate stress of 139. ksi experienced by the coupons, and 133. predicted by SQ5[8]. Also, the strength of 150. ksi yielded by RD5[5] correlates well with that sustained by the coupons. It is seen in Table 1B that only one strength value was predicted by NØLIN. This ultimate strength value of 104. ksi is appreciably lower than the empirical one. Only one value was obtained due to the fact that it was impossible to achieve convergence of the solution with the algorithm which solves the nonlinear equations of this computer code. It is found from Table 1B, Fig. 2B and Fig. 13 that the tubes sustained very low ultimate stresses relative to either the coupons or the analytical predictions.

3.2.3 [±30°] Laminates

It was reported in [1] that two batches of coupons were manufactured and delivered for testing for this type of laminate configuration and when tested they displayed completely different responses. Hence, the empirical response corresponding to each batch is presented separately, together with the responses predicted by the analyses in Figs. 14A and 14B. Fig. 14B reveals immediately that there is no correlation between the analyses and the response experienced by the coupons, and as such won't be discussed any further. Fig. 14A displays very good agreement between the compression branch experienced by the coupons and that corresponding to the tubes when nominal thickness is considered. However, it is observed in this figure as well as Table 1B that the tubes experienced very low ultimate stresses relative to the coupons. Referring to the tension branch of the experimental responses it is observed that the coupons and tubes respond completely differently, one from another. It appears from Fig. 14A that the analytical predictions agree one with another only in the very low stress-strain range. At a stress level of about 20.0 ksi, which corresponds to the ultimate stress of the tubes when "true" thickness is accounted for, NØLIN[13] response deviates from the responses predicted by RD5[5] and NØNLIN [10]&[11] while displaying initiation of pronounced nonlinearity. At a stress level of about

35.0 ksi a similar behavior is observed for the response of RD5, which deviates from NØNLIN and also displays initiation of pronounced nonlinearity. The above discussion applies to both the compression and tension branches of the analytical predictions. Correlation of the predicted responses with the empirical ones indicates "fair" agreement with the response yielded by the tubes (nominal thickness). No correlation is observed with the response experienced by the coupons. This is rather emphasized in the pronounced nonlinear region of the responses, where the coupons display a very high stressing and straining capacity realtive to the analyses of RD5 and NØLIN. The mode of the response predicted by NØNLIN is observed to differ from that corresponding to the coupons as it displays less stiff behavior in the range of stresses corresponding to the almost linear response of the coupons, and "weak" nonlinear behavior in the range of high stresses, which is associated with the pronounced nonlinear behavior of the coupons.

It appears from Table 1B and Fig. 1B that the coupons experienced a modulus of $10.98\text{x}10^{6}$ psi, which is noticeably higher than $9.23\text{x}10^{6}$ predicted by RD5[5], SQ5[8] and NØLIN[13]. It is also found that NØNLIN [10]&[11] predicted an even lower modulus of $8.87\text{x}10^{6}$ psi. As already discussed above and as can be seen from Table 1B and Fig. 2B the analyses predict ultimate stresses which are significantly lower than 58.9 ksi sustained by the coupons. It is also observed in Table 1B that no ultimate stress was generated by RD5[5]. (The last stress value corresponding to acceptable strains is 42.5 ksi, and above this stress the calculated stresses are associated with unacceptable strain values).

3.2.4 [±45°] Laminates

Fig. 15 presents the experimental responses of [1] together with the predicted ones. In the range of low stress-strain values good correlation is found for the tubes ("true" thickness) with the analytical predictions, but with increase in stress-strain values the analyses of RD5[5] and NØLIN[13] predicted more pronounced nonlinear behavior than that experienced by the tubes, whereas NØNLIN [10]&[11] displays less emphasized nonlinear behavior and also displays a tendency to follow the response experienced by the tubes when nominal thickness is considered. No correlation between the response experienced by the coupons and either of the predicted responses is observed in Fig. 15. The coupons are found to sustain a considerably higher stress-strain capacity than that predicted analytically (see also Table 1B and Fig. 2B). This is also observed to be true when correlating either representation of the responses experienced by the tubes with the predicted responses, in spite of the fact that the tubes display a considerably low stressing capacity relative to the coupons. (Note that the straining capability of the tubes is of the same magnitude of that experienced by the coupons).

Fig. 1B and Table 1B indicate that NØNLIN [10]&[11] predicts a modulus of 2.57×10^6 psi, which is in very good agreement with 2.53 experienced by the coupons. RD5[5], SQ5[8] and NØLIN[13] yield a lower modulus of 2.46×10^6, which is in good agreement with 2.39×10^6 experienced by the tubes ("true" thickness).

Comparing the ultimate stresses predicted by the different analyses with the empirical strength values experienced by the coupons, it is found from Table 1B and Fig. 2B that SQ5[8] predicts a strength of 35.6 ksi, which is in very good agreement with 35.1 experienced by the coupons. NØLIN[13] yields very low strength values, which are even considerably lower than those experienced by the tubes. RD5[5] again generates meaningless stresses (see discussion above on the [±30°] laminates).

3.2.5 [±60°] Laminates

The empirical responses of [1], together with the predicted ones, are presented in Fig. 16. "Poor" correlations is observed among the responses predicted by the different analyses. Fig. 16 displays good agreement between the responses experienced by the tubes ("true" thickness) and the coupons, however, the coupons exhibit appreciably higher stressing and straining capability than do the tubes. Also, it is observed in this figure that NØNLIN [10]&[11] correlates well with the experimental responses, except for high stress levels where it predicts less nonlinear behavior than that observed experimentally.

It is observed in Fig. 16 that in the range of low stresses and strains the response of NØLIN[13] also agrees with the empirical responses; however, at a very low stress of about 10.0 ksi it deviates from the empirical one and displays strong nonlinear behavior. As can be seen from Fig. 16 this results in a considerably lower stressing and straining capability relative to the coupons. Correlating the response predicted by RD5[5] with the experimental ones it is observed in Fig. 16 that its response is stiffer and less nonlinear than that observed for the coupons.

Table 1B and Fig. 1B indicate that RD5[5], SQ5[8] and NØLIN[13] yield a modulus of 2.21×10^6 psi, which is noticeably higher than 1.84×10^6 predicted by NØNLIN [10]&[11]. These moduli are higher than 1.62×10^6 observed for the coupons.

Comparing the ultimate stresses predicted by the different analyses with the experimental strength values, it is seen from Table 1B and Fig. 2B that SQ5[8] predicts a high strength of 50.0 ksi compared with 31.8 experienced by the coupons, whereas NØLIN[13] predicts relatively low strength values: 17.3 for Max. Stress, 18.0 for Max. Strain and 20.5 ksi for Quad. Fail. No ultimate was generated by RD5 (see discussion on [±30°] laminates). It appears from Table 1B and Figs. 2B and 16 that the tubes (nominal thickness) yielded the highest ultimate stress for this particular laminate.

3.2.6 <u>[±75°] Laminates</u>

Fig. 17 presents the experimental response of [1] together with the predicted ones. No agreement among the different predicted responses is observed in this figure. Good agreement between the compression branch corresponding to the coupons and RD5[5] is observed; very good correlation in the almost linear range of response, whereas with increase in stress RD5 responds less nonlinearly than do the coupons. Good agreement of NØLIN[13] response with the coupons is also observed in Fig. 17 in the range of low stresses and strains (linear range); however, with increase in stresses the response of NØLIN deviates from the empirical one while displaying an appreciably more pronounced nonlinear response. The response predicted by NØNLIN

[10]&[11] is observed to display more emphasized nonlinear behavior than NØLIN, and does not agree with either the experimental response or RD5 and NØLIN predictions. In regards to the tension branch of the responses it is observed in Fig. 17 that there is good agreement among the different analyses, and between the analyses and experimental response. (Note that tubes are not presented in the present evaluation. See [1]).

Table 1B and Fig. 1B indicate that the experimental modulus of 2.79×10^6 is in very good agreement with 2.76×10^6 calculated with RD5, SQ5 and NØLIN. NØNLIN is found to predict a lower modulus of 1.97×10^6 psi. It appears from Table 1B and Fig. 2B that the empirical ultimate stress of 34.8 ksi is considerably lower than 44.6 predicted by SQ5[8], and is in good agreement with the strength value of 31.9 yielded by NØLIN Max. Stress [13]. NØLIN Max. Strain and Quad. Fail. are found to predict low ultimate stress values, 26.4 and 28.5 ksi respectively. Again, like for the [±30°] laminate no ultimate stress was predicted by RD5[5].

3.2.7 [90°] Laminates

As with the [0°] unidirectional laminates, the reproduction capability of the different computer codes is evaluated. In Fig. 18 the empirical responses of [1] are presented with the predicted ones. It is observed that in the range of moderate stress-strain levels reproduction by both RD5[5] and NØLIN[13] is very good. With increase in stress levels both predictions deviate from the empirical response experienced by the coupons, while displaying a less nonlinear behavior than that observed for the coupons, a trend which is more emphasized for NØLIN. It is also observed in this figure that there is good agreement between the experimental responses corresponding to the tubes (nominal thickness) and coupons; however, the tubes sustain a considerably lower ultimate stress than that experienced by the coupons (see also Table 1B). Referring to NØNLIN response [10]&[11], it is seen from Fig. 18 that this analysis predicts an appreciably lower stressing capacity than that observed for the coupons and predicted by the other analyses. This response is found to be in very good agreement with that experienced by the tubes when "true" thickness is accounted for. Comparing the tension branch of the predicted responses, as well as the empirical ones of Fig. 18, very good agreement is found.

It appears from Table 1B and Fig. 1B that RD5[5], SQ5[8] and NØLIN[13] reproduce the modulus of $2.98x10^6$ psi experienced by the coupons, whereas NØNLIN [10]&[11] predicts a considerably lower modulus of $2.05x10^6$. Comparing the ultimate stresses yielded by the different analyses with the empirical ones, it is found from Table 1B and Fig. 2B that the stresses of 32.0 ksi predicted by NØLIN Max. Stress and Quad. Fail. are in very good agreement with 31.7 experienced by the coupons. Good correlation is also observed between the empirical stress and 34.1 ksi predicted by NØLIN Max. Strain. It is also observed in Table 1B that RD5 yields a similar stress of 34.0 ksi for the last acceptable strain value.

3.2.8 [0°/90°] Laminates

The experimental responses of [1] and the ones predicted by the analyses are presented in Fig. 19. Comparison of the analytical predictions with the response experienced by the coupons reveals very good agreement between the empirical response and RD5[5] as well as very good agreement with the predictions of NØNLIN [10]&[11] and NØLIN[13] in the range of moderate stress-strain values. With increase in stress-strain levels NØNLIN and NØLIN, which predict almost identical responses, display some minor nonlinear behavior which is not observed for the coupons. Note that NØNLIN and NØLIN yield strength values which are in good agreement with that predicted by the coupons, whereas RD5 yields an appreciably lower stress (see Table 1B and Fig. 2B). It is also observed in Fig. 19 that once the "true" thickness of the tubes is accounted for they respond wimilarly to the coupons but fail at a considerably lower strength value (see Table 1B).

It is found from Table 1B and Fig. 1B that NØNLIN yields the lowest modulus, $16.67x10^6$ psi, NØLIN and SQ5 predict a modulus of $17.15x10^6$ which is in very good agreement with the empirical one of $17.17x10^6$, and RD5 yields a slightly higher modulus of $17.21x10^6$.

Table 1B and Fig. 2B indicate very good agreement between the strength of 230. ksi observed for the coupons and 220. yielded by NØNLIN. Also it is observed that all other analyses predict lower ultimate stress values than that experienced by the coupons.

3.2.9 [0°/±45°/90°] Laminates

In Fig. 20 the experimental responses of [1] are shown together with the ones predicted by the analyses. Very good agreement is observed between the response yielded by the coupons and those predicted by the analyses, in particular the one calculated with NØNLIN [10]&[11]. No correlation is observed in Fig. 20 between the response observed for the coupons and either version of the responses experienced by the tubes.

It is seen from Fig. 1B and Table 1B that NØNLIN predicts a modulus of $11.62x10^6$ psi which is slightly higher than $11.47x10^6$ experienced by the coupons and slightly lower than 11.87 yielded by either SQ5[8] or NØLIN[13], and $11.92x10^6$ predicted by RD5[5]. Comparing the ultimate stresses experienced empirically and those predicted analytically, it appears from Table 1B and Fig. 2B that NØNLIN strength of 141. ksi is in good agreement with 158. ksi observed for the coupons, whereas NØLIN[13], in spite of its very good agreement with the coupons mentioned above, yields a stress of 125. ksi for Max. Strain and lower stresses of 121. and 113. ksi for Max. Stress and Quad. Fail. respectively. It is also observed that RD5[5] predicts a noticeably lower ultimate of 130 ksi and SQ5[8] a strength of 134.

4. CONCLUSIONS

(a) None of the analyses, namely RD5[5], SQ5[8], NØNLIN[10]&[11] and NØLIN[13], utilized in the present comparison studies is found to be adequate to predict satisfactorily the compression response of angle-ply laminates.

(b) As mentioned in the text of this report the responses corresponding to the unidirectional laminates, which were experienced by the compression coupons of [1], were utilized as data input for the computer codes RD5, SQ5 and NØLIN. It is observed from the present comparison studies for the angle-ply laminates that in spite of this the predicted response with these codes do not favor the responses experienced by the coupons better than the ones observed for the tubes. For some laminate configurations better correlation is observed with the responses yielded by the tubes.

(c) Present numerical studies indicate that no unique compression responses were predicted by the various analyses employed in the present comparison studies for the large variety of laminate configurations invesrigated. For some laminate configurations considerably different responses were predicted for the same laminate by the various analyses.

(d) The analyses were found to be inadequate to predict the ultimate stresses of the angle-ply laminates. The built-in failure mechanisms in the analytical models were not verified by the test results because of very poor correlation between the calculated strength values and those observed experimentally.

(e) The very good correlation of the predicted moduli with the empirical ones, and the pronounced disagreement among the predicted ultimate stresses, niether verifies nor contradicts the influence of the edge effects discussed in Appendix B. In view of the arguments in this Appendix, and the lack of success of a sound test program with the compression tubes of [1], coupons having different dimensions than those employed in [1] should further be tested to accomplish the objectives of the test program of [1] and present comparison studies and evaluations.

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APPENDIX A

It has been pointed out in the section on the Numerical studies that the computer codes RD5[5] and NØLIN[13] 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 data input are presented in Tables APA-1A and APA-1B as being input into RD5 code. In addition to the data in these Tables, also required by NØLIN, the information presented in Table APA-2 has to be provided to operate the NØLIN code. (Instead of feeding NØLIN with the stress-strain data input for the responses, one may use the Ramberg-Osgood parameters as explained in [13] and avoid the utilizing of curve fitting alegorithms to generate these parameters.)

The mechanical properties given in Table APA-2 are also required as data input by SQ5 code.

It was mentioned in the section on Results and Discussion that the data input for the matrix material of the AVCO 5505 Boron-Epoxy laminates was taken from [10]&[11]. The mechanical properties are as follows:

Young Modulus of Matrix	510,000. psi
Shear Modulus of Matrix	200,000. psi
Poisson's Ratio of Matrix	.310

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

ES1	=	5,000	SL1	=	10^6
ES2	=	10,000	SL2	=	$.5x10^6$
ES3	=	15,000	SL3	=	$.19x10^6$
ES4	=	20,000	SL4	=	$.10x10^6$
ES5	=	25,000	SL5	=	3,230
ES6	=	30,000	SL6	=	0.

The Boron fiber properties are Provided by the manufacturer and are as follows:

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

APPENDIX B

It has been mentioned in [1] that edge effects might be induced far away from the loaded boundaries of the coupons resulting in an uneven stress-strain distribution even for a coupon loaded uniformally. This kind of behavior was experienced by all the angle ply laminates of [1].

When the coupon is loaded in a manner described in Fig. APB1, allowing for a uniform axial displacement, $u = (-\delta)$, and completely restraining the lateral displacement, $v = 0$, along the loaded boundaries, $\pm l/2$, it is anticipated that the coupon width or rather its aspect ratio, $AR = l/b$, will have an appreciable influence on the stress-strain distribution of angle-ply laminates possessing high Poisson's ratios.

With the prescribed boundary conditions the specimen might experience an induced transverse stress, approaching in the limit a stress of:

$$\sigma_y = \sigma_x \nu_{yx}$$

A wide specimen will contain a wide zone of continuous fibers subject to this high degree of lateral restraint. Consequently, this zone will result in both higher stresses and stiffnesses than the regions close to the free edges of the coupon, where the filaments are noncontinuous, and hence shear the load from the termination of one diagonal fiber into the begining of an adjecant one through the matrix. This, of course, will result in an unknown uneven stress-strain field which renders wide specimens unsuitable for application. The stress is picking up towards the center and hence is higher than the average stress utilized to present the response of such specimens. On the other hand, too narrow specimens will be affected primarily and subject to the edge effect which will reduce both their strength and stiffness.

A numerical study was carried out to determine the actual lateral edge effect combined with Poisson's ratio and to define the "best aspect ratio", i.e. the minimum length of the coupon, l, free of lateral boundary influence, at least along its center line transverse to the direction of applied compression. SNAP computer code, [15], was used for this purpose and the obtained results are presented in Fig. APB-2. The coupons of [1] have an aspect ratio, AR≈.75, which according to Fig. APB-2 is too short to eliminate the lateral boundary influence.

The above discussion calls for a different type of specimen. Indeed, tubes were also tested and reported in [1]. A tube is free of the free edge region, but on the other hand is susceptible to another deficiency: if the radial displacements at the loaded boundaries are prevented from expanding to allow for Poisson's expansion, high bending stresses develop at the restrained boundaries. These stresses might precipitate early local failure at the specimen edges or might be superimposed on the compressive stresses in case the tube is too short, again bringing about failure at a stress lower than the ultimate one corresponding to the tested laminate.

TABLE 1A Compression Response - Comparison of Experimental Ultimate Stresses and Moduli With Analytical Predictions of RD5[5], SQ5[8], NØNLIN[10]&[11] and NØLIN[13]

GRAPHITE-EPOXY LAMINATES - 3m SP-286T3															
Laminate Configuration	TEST RESULTS OF [1]					ANAL RD5 [5]		ANAL. SQ5 [8]		ANAL. NØNLIN [10]&[11]		ANAL. NØLIN [13]			
	Compression Coupons		Compression Tubes									Ult. Comp. Stress (ksi)			
	Ult. Comp. Stress (ksi)	E_x Comp. Mod (x10^6psi)	Ult. Comp. Stress Nom. Thick. (ksi)	Ult. Comp. Stress Measured Thick. (ksi)	E_x (x10^6psi)	Ultimate Comp. Stress (ksi)	E_x (x10^6psi)	Ultimate Comp. Stress (ksi)	E_x (x10^6psi)	Ultimate Comp. Stress (ksi)	E_x (x10^6psi)	Max. Stress Fail.	Max. Strain Fail.	Quad. Interac. Fail.	E_x (x10^6psi)
[0°]	164. 191.	16.07	—	—	—	200.	16.09	$209._{11}$	16.07			$180._{11}$	$209._{11}$	180.	16.07
[±15°]	115. 117.	13.94	66.4 105.	51.0 82.6	18.42 [14.25]	105	13.24	$117._{22}$	13.24			$140._{22}$	$106._{22}$	92.9	13.24
[±30°]	54.8 59.1	6.87	29.2 35.7	24.6 28.6	8.11 [6.55]	40.0	5.75	48.7_{22}	5.76			43.4_{12}	37.6_{22}	28.8	5.76
[±45°]	37.4 38.2	2.27	28.3 28.9	22.4 23.4	3.12 [2.51]	31.3 (60)†	2.03	25.1_{12}	2.04			16.2_{12}	19.7_{12}	17.5	2.04
[±60°]	35.4 37.6	1.72	22.2 32.1	16.3 22.1	2.51 [1.79]	23.8	1.58	30.8_{12}	1.61			19.5_{12}	22.3_{12}	23.3	1.61
[±75°]	31.2 36.0	1.91	19.4 21.4	13.4 15.0	1.75 [1.20]	37.5	1.75	48.9_{22}	1.81			32.5_{22}	32.5_{22}	29.8	1.81
[90°]	33.0 34.4	1.91	15.5 24.1	10.2 18.0	1.52 [1.01]	35.0	1.84	47.8_{22}	1.91			32.0_{22}	33.2_{22}	32.0	1.91
[0°/90°]	111. 115.	8.79	29.4 49.3	28.7 42.2	8.35 [7.79]	110.	8.99	$115._{11}$	8.83			96.2_{11}	$112._{11}$	107.	8.83
[0°/±45°/90°]	89.8 97.8	6.74	38.2 47.6	29.1 35.9	7.77 [5.71]	85.	6.42	82.1_{11}	6.32			68.7_{11}	79.2_{11}	64.8	6.32

[ ] 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.

( )† Ultimate stress values corresponding to very high unreasonable strain values; upper number - last stress value which corresponds to an acceptable strain value.

1" (inch) = 2.540×10^{-2} meter (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 1B Compression Response - Comparison of Experimental Ultimate Stresses and Moduli With Analytical Predictions of RDS[5], SQ5[8], NØNLIN[10]&[11] and NØLIN[13].

BORON-EPOXY LAMINATES (AVCO 5505/5.6 MIL. DIA.)															
Laminate Configuration	TEST RESULTS OF [1]					ANAL RDS [5]		ANAL. SQ5 [8]		ANAL. NØNLIN [10]&[11]		ANAL. NØLIN [13]			
	Compression Coupons		Compression Tubes									Ult. Comp. Stress (ksi)			
	Ult. Comp. Stress (ksi)	E_x Comp. Mod. ($x10^6$ psi)	Ult. Comp. Stress Nom. Thick. (ksi)	Ult. Comp. Stress Measured Thick. (ksi)	E_x ($x10^6$ psi)	Ultimate Comp. Stress (ksi)	E_x ($x10^6$ psi)	Ultimate Comp. Stress (ksi)	E_x ($x10^6$ psi)	Ultimate Comp. Stress (ksi)	E_x ($x10^6$ psi)	Max. Stress Fail.	Max. Strain Fail.	Quad. Interac. Fail	E_x ($x10^6$ psi)
[0°]	263. 342.	31.27	—	—	—	340.	31.28	353.$_{11}$	31.27	**	31.20	340.$_{11}$	353.$_{11}$	340.	31.27
[±15°]	133. 139.	23.65	83.5 91.8	57.6 68.0	37.49 [26.85]	150.	25.27	133.$_{22}$	25.26	**	24.96	***	104.$_{22}$	***	25.26
[±30°]	94.7 | 55.5 96.1 | 58.9	13.57 | 10.98	29.0 30.6	20.6 22.4	11.11 [8.00]	42.5 (NO.ULT.OBT.)	9.23	44.5$_{22}$	9.23	**	8.87	32.1$_{22}$	24.6$_{22}$	24.6	9.23
[±45°]	33.7 35.1	2.53	25.5 28.0	19.4 20.4	3.23 [2.39]	13.5 (NO.ULT.OBT.)	2.46	35.6$_{12}$	2.46	**	2.57	11.2$_{12}$	11.5$_{12}$	11.5	2.46
[±60°]	30.8 31.8	1.62	33.1 38.7	23.4 26.4	3.97 [2.72]	30.0 (NO.ULT.OBT.)	2.21	50.0$_{22}$	2.21	**	1.84	17.3$_{12}$	18.0$_{12}$	20.5	2.21
[±75°]	33.3 34.8	2.79	27.4 31.1	19.9 21.4	—	36.0 (64.)†	2.76	44.6$_{22}$	2.76	**	1.97	31.9$_{22}$	26.4$_{22}$	28.5	2.76
[90°]	29.8 31.7	2.98	17.8 21.7	12.6 14.3	3.39 [2.32]	34.0 (38.)†	2.99	44.7$_{22}$	2.98	**	2.05	32.0$_{22}$	34.1$_{22}$	32.0	2.98
[0°/90°]	179. 230.	17.7	206. 233.	138. 157.	25.34 [17.73]	190.	17.21	194.$_{11}$	17.15	220.*	16.67	176.$_{11}$	184.$_{11}$	201.	17.15
[0°/±45°/90]	146. 158.	11.47	137. 147	88.1 87.4	16.65 [10.20]	130.	11.92	134.$_{11}$	11.87	141.*	11.62	121.$_{11}$	125.$_{11}$	113.	11.87

* Fiber failure in 0 degree layer.

** Calculations exceeded maximum observed experimental strain values.

*** Solution does not converge.

( )† Ultimate stress values corresponding to very high unreasonable strain values; upper number - last stress value which corresponds to an acceptable strain value.

[ ] 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} meter (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

LE.APA-1A 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	0.17900E 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	0.22482E-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 APA 1B. 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

ORIGINAL PAGE IS OF POOR QUALITY

TABLE APA-2 Unidirectional Lamina Properties Utilized In The Predictions Of SQ5[9] and NØLIN[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	.007
(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})	0.22	.0275
(ν_{12})Compression	.230	.267
(ν_{12})Tension	.298	.216

1" (inch) = 2.540×10^{-2} meter (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

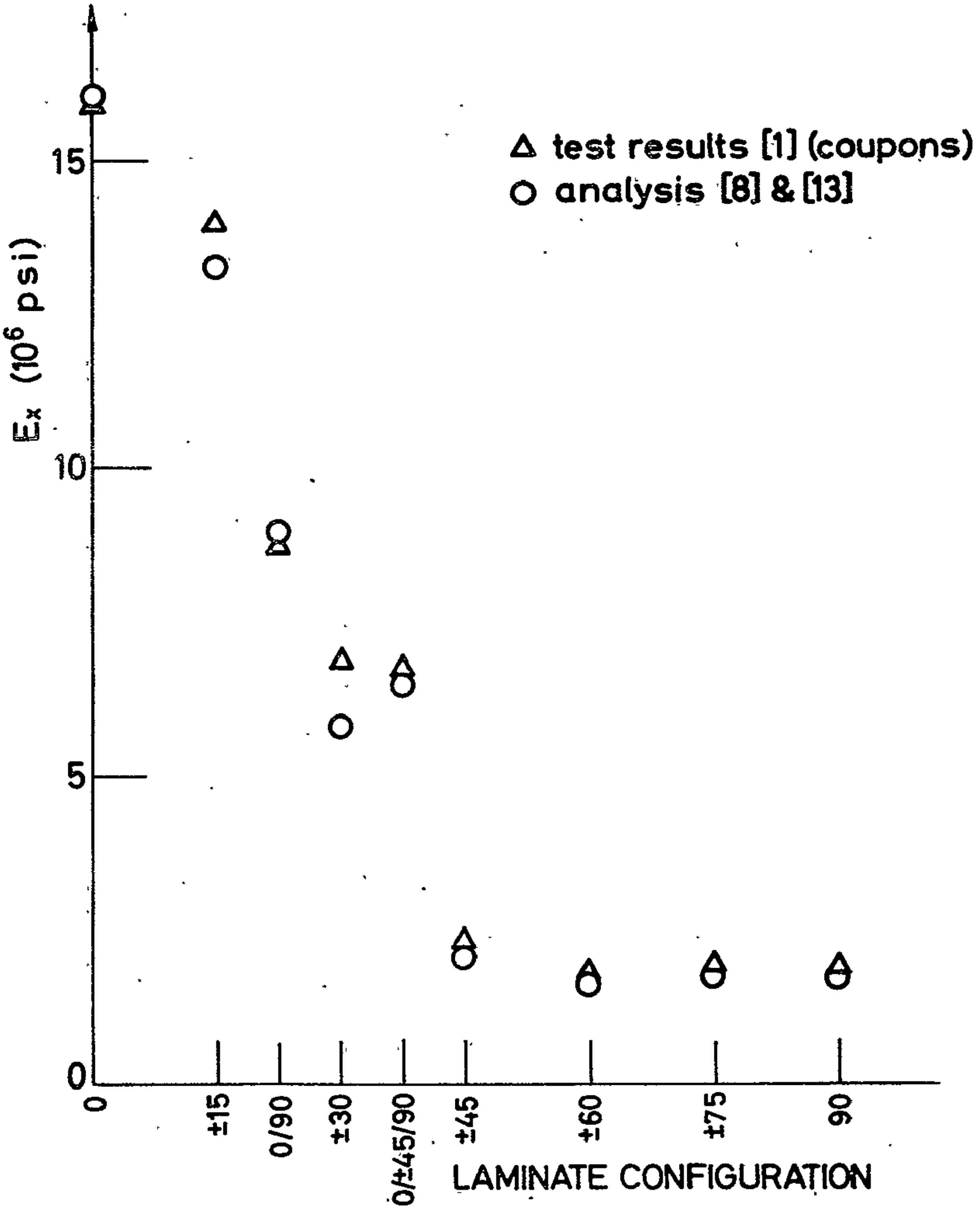

FIG. 1A YOUNG'S MODULUS OF 3M SP-286T3 GRAPHITE EPOXY LAMINATES AS A "FUNCTION" OF LAMINATE CONFIGURATION

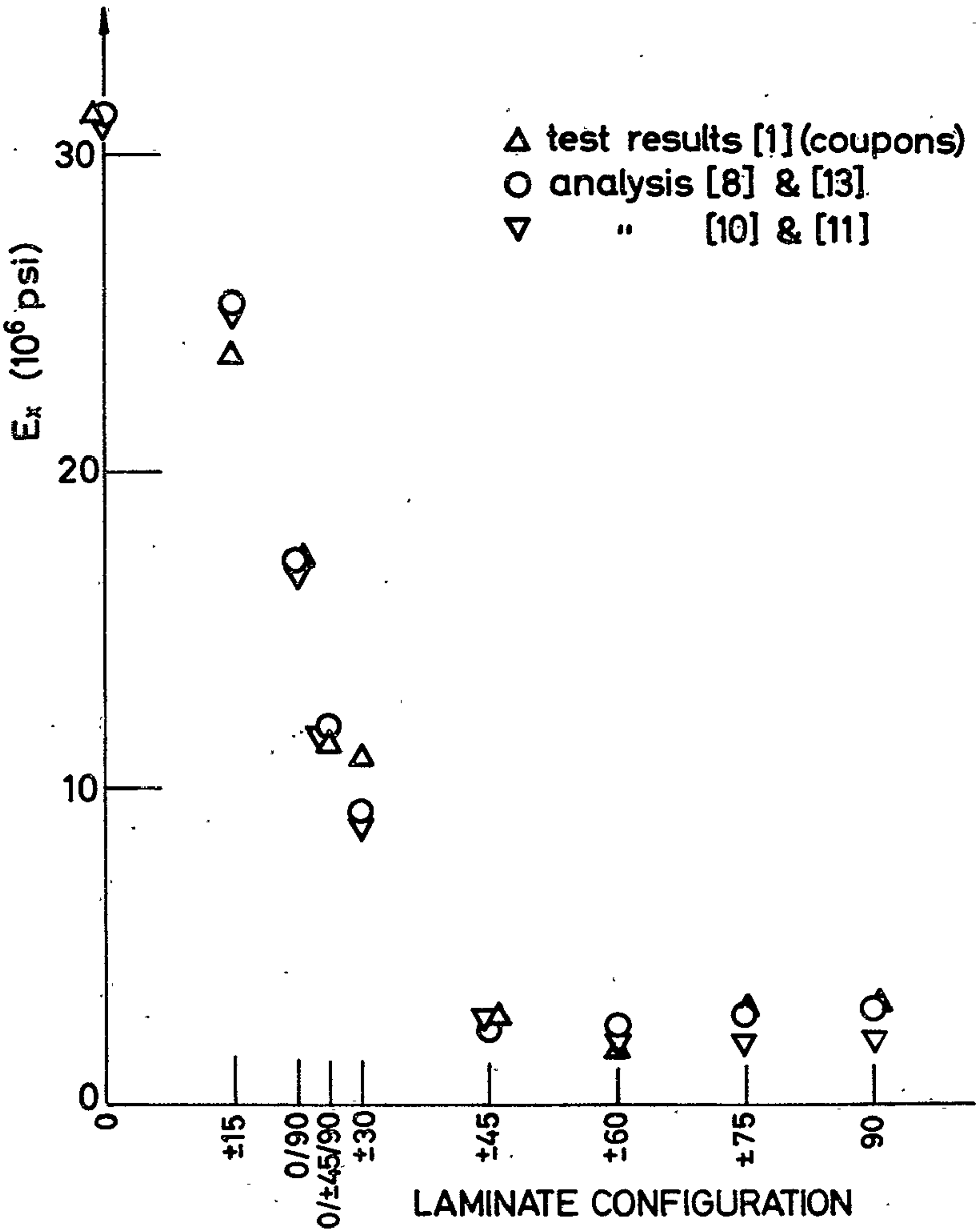

FIG. 1B YOUNG'S MODULUS OF AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES AS A "FUNCTION" OF LAMINATE CONFIGURATION

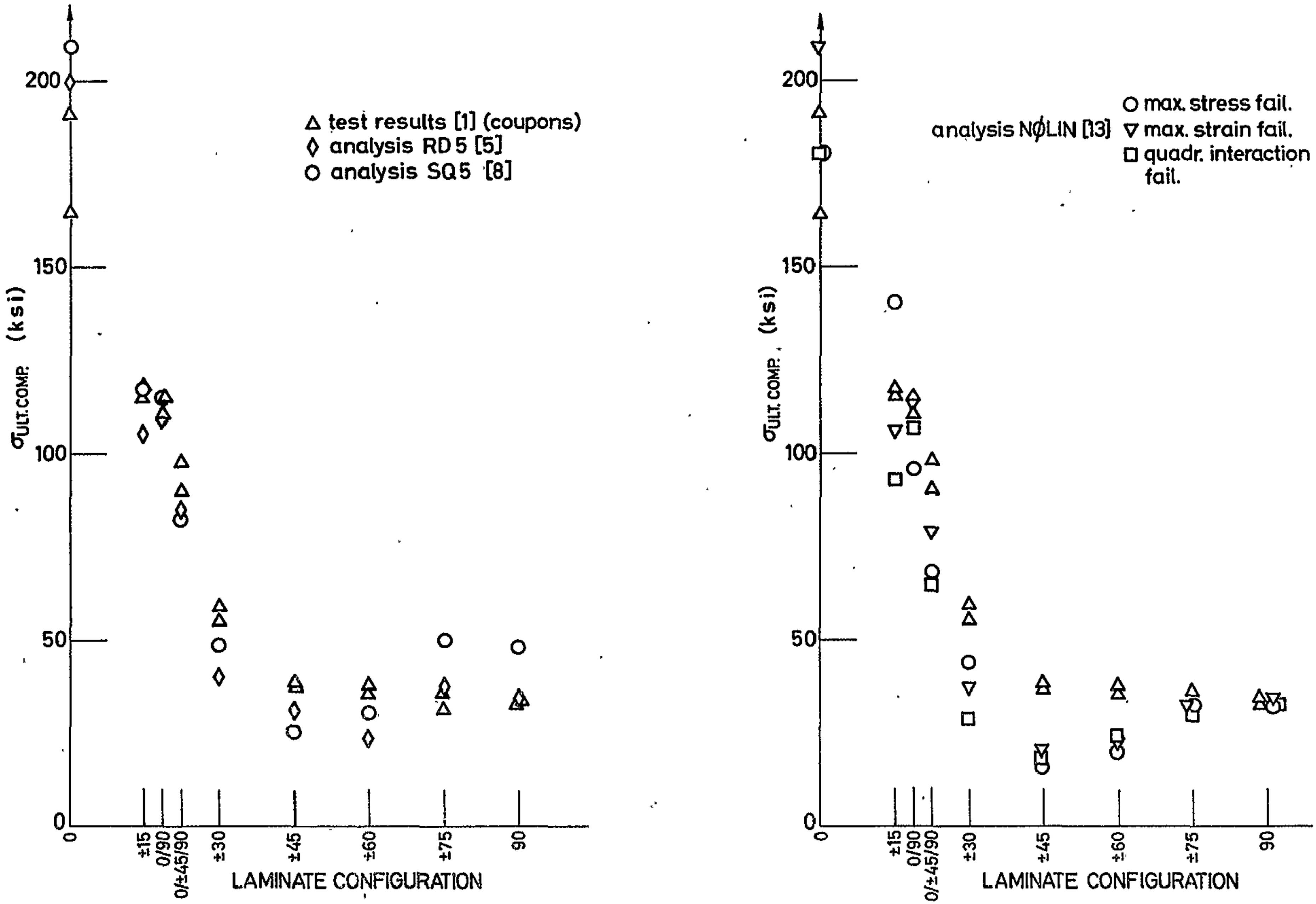

FIG. 2A ULTIMATE STRESS OF 3M SP 286T3 GRAPHITE EPOXY LAMINATES AS A "FUNCTION" OF LAMINATE CONFIGURATION

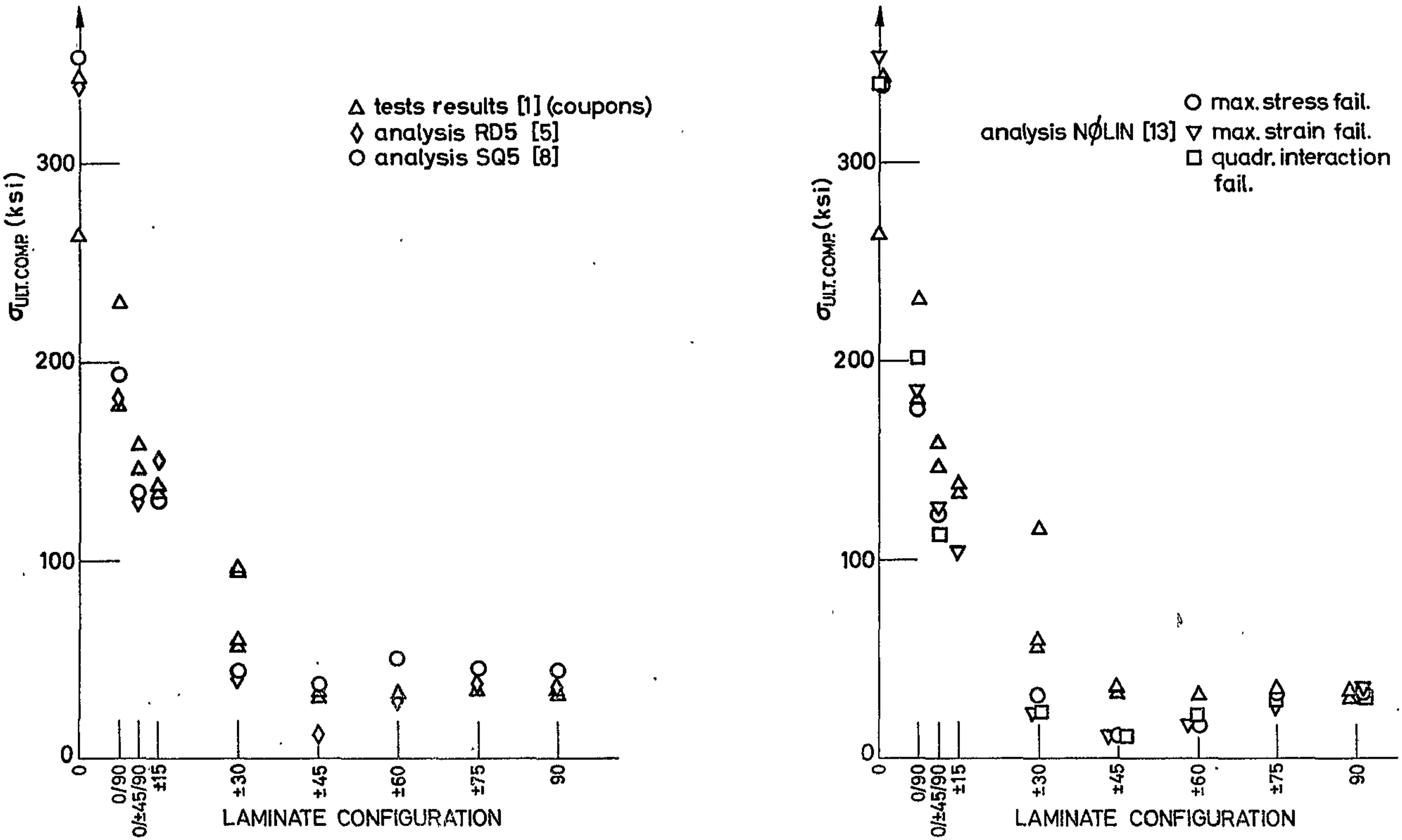

FIG. 2B ULTIMATE STRESS OF AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES AS A "FUNCTION" OF LAMINATE CONFIGURATION

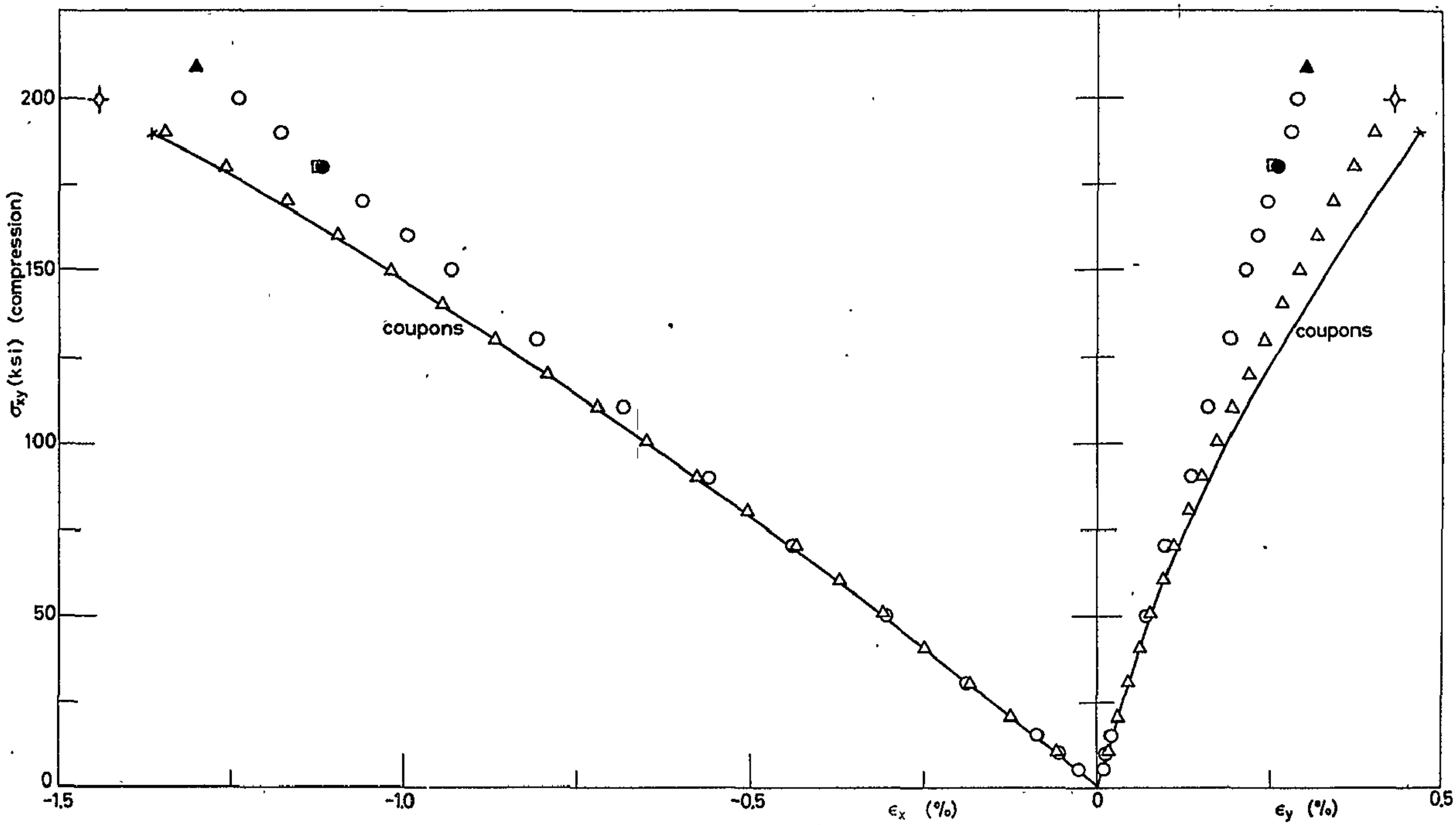

FIG. 3 COMPRESSION RESPONSE OF 0° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

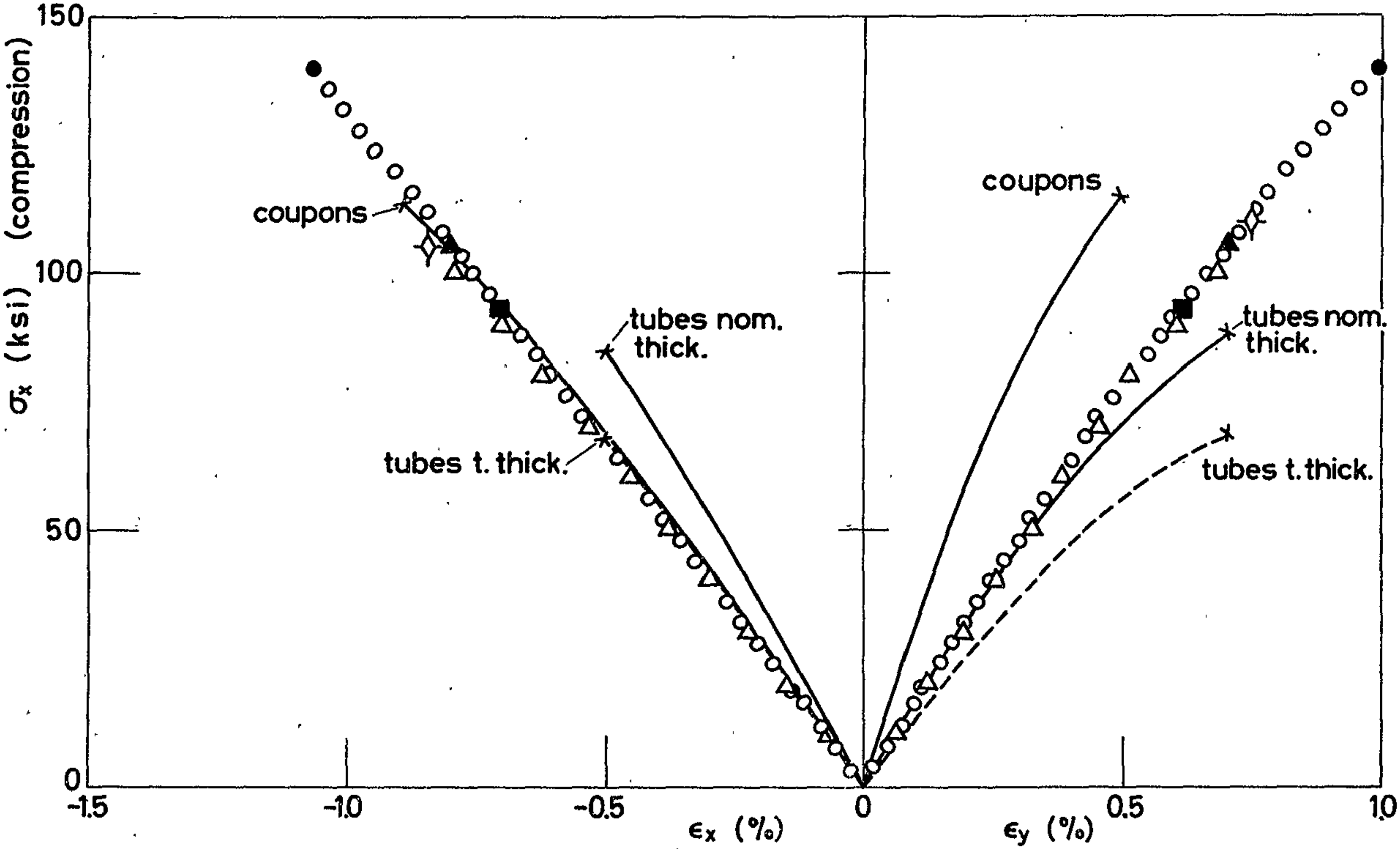

FIG. 4 COMPRESSION RESPONSE OF ±15° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

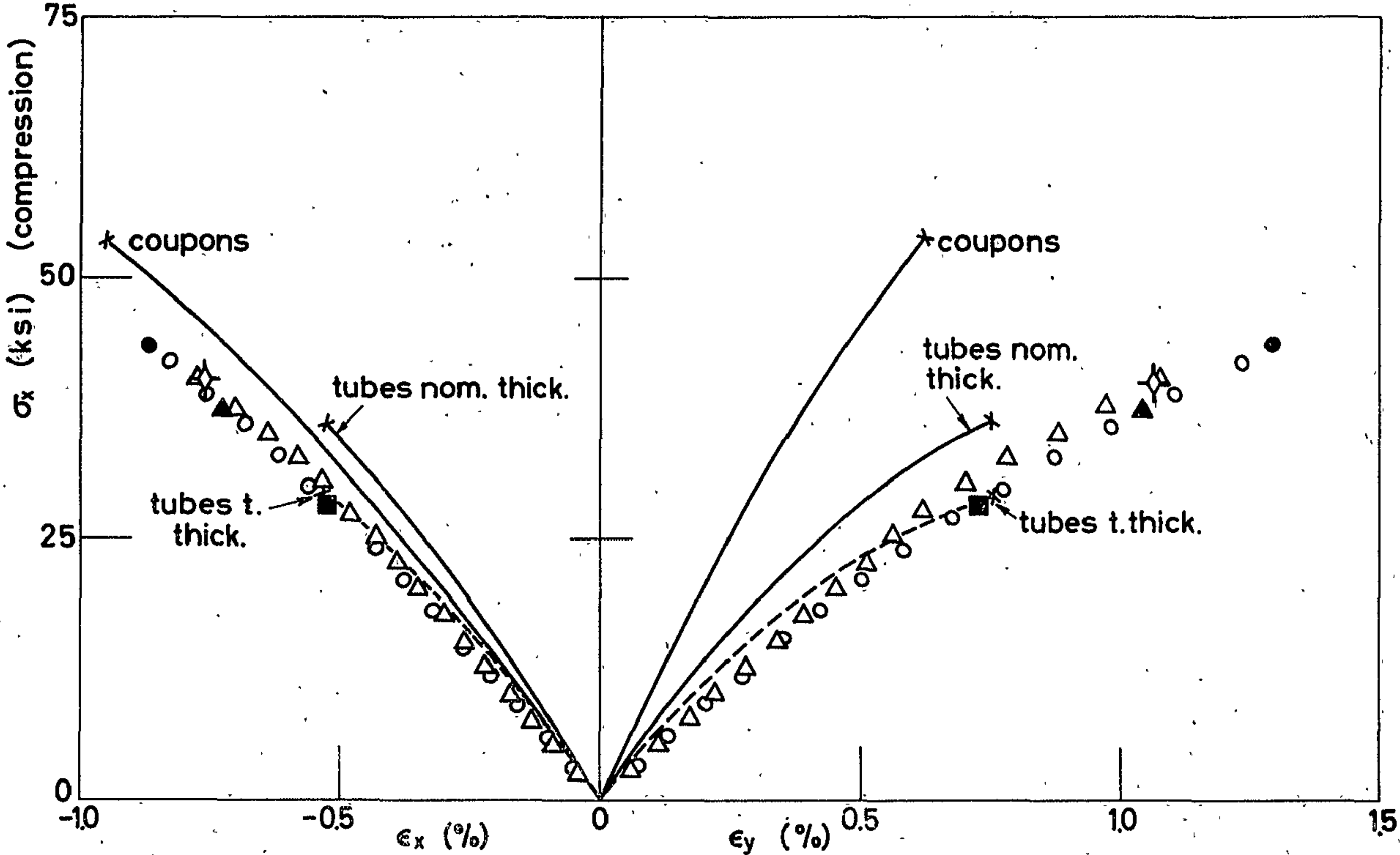

FIG. 5 COMPRESSION RESPONSE OF ±30° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

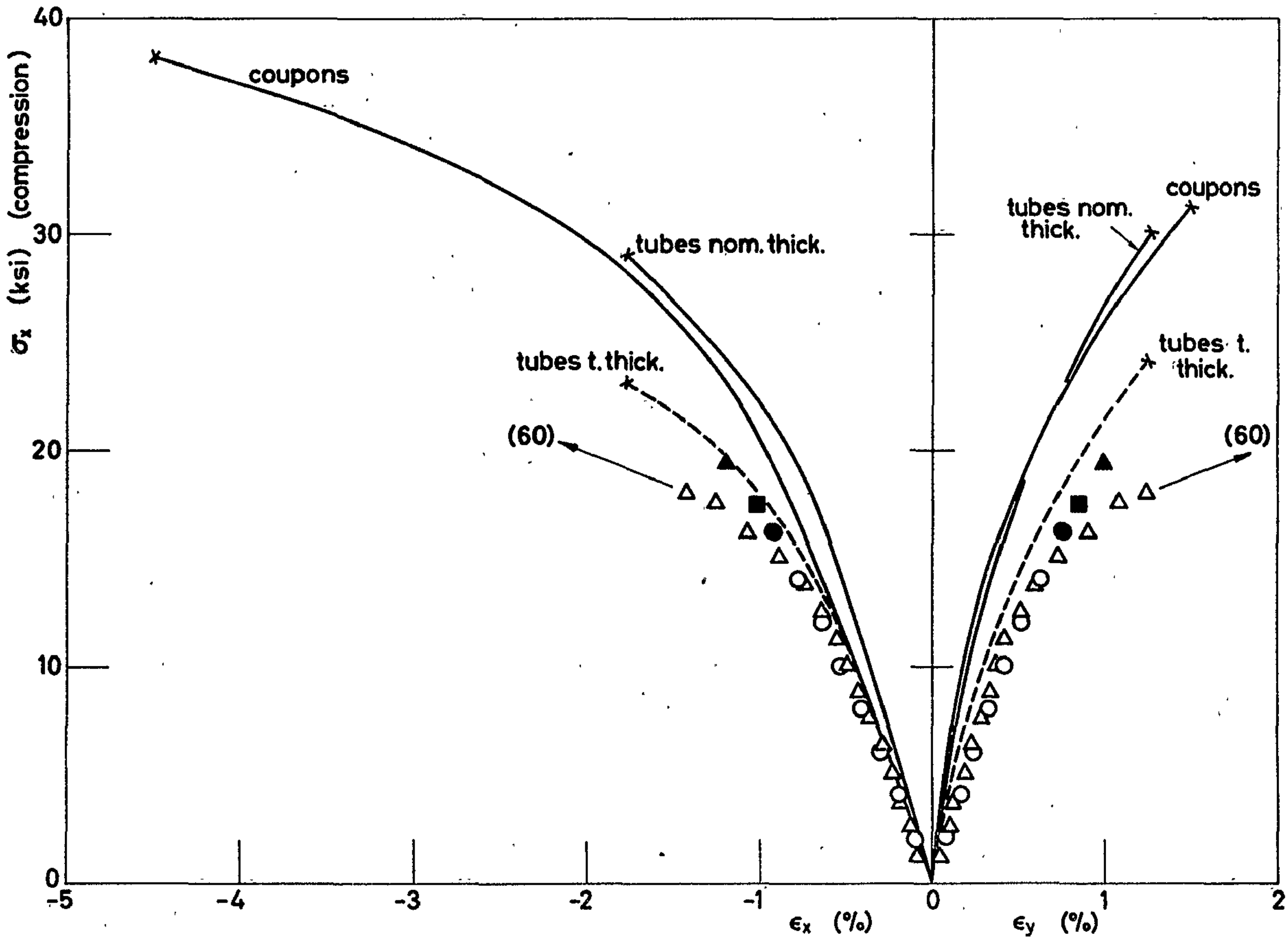

FIG. 6 COMPRESSION RESPONSE OF ±45° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

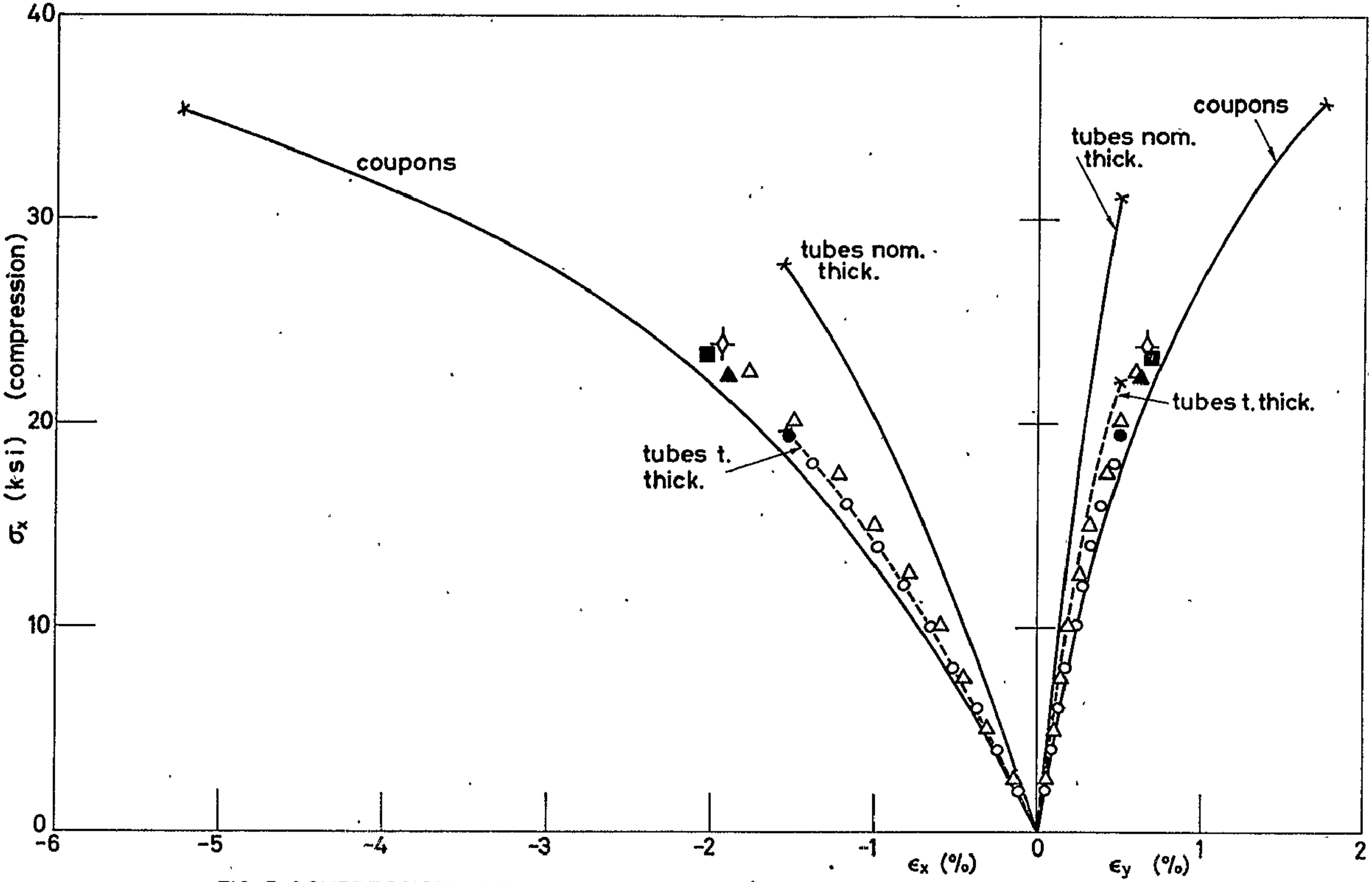

FIG. 7 COMPRESSION RESPONSE OF ±60° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

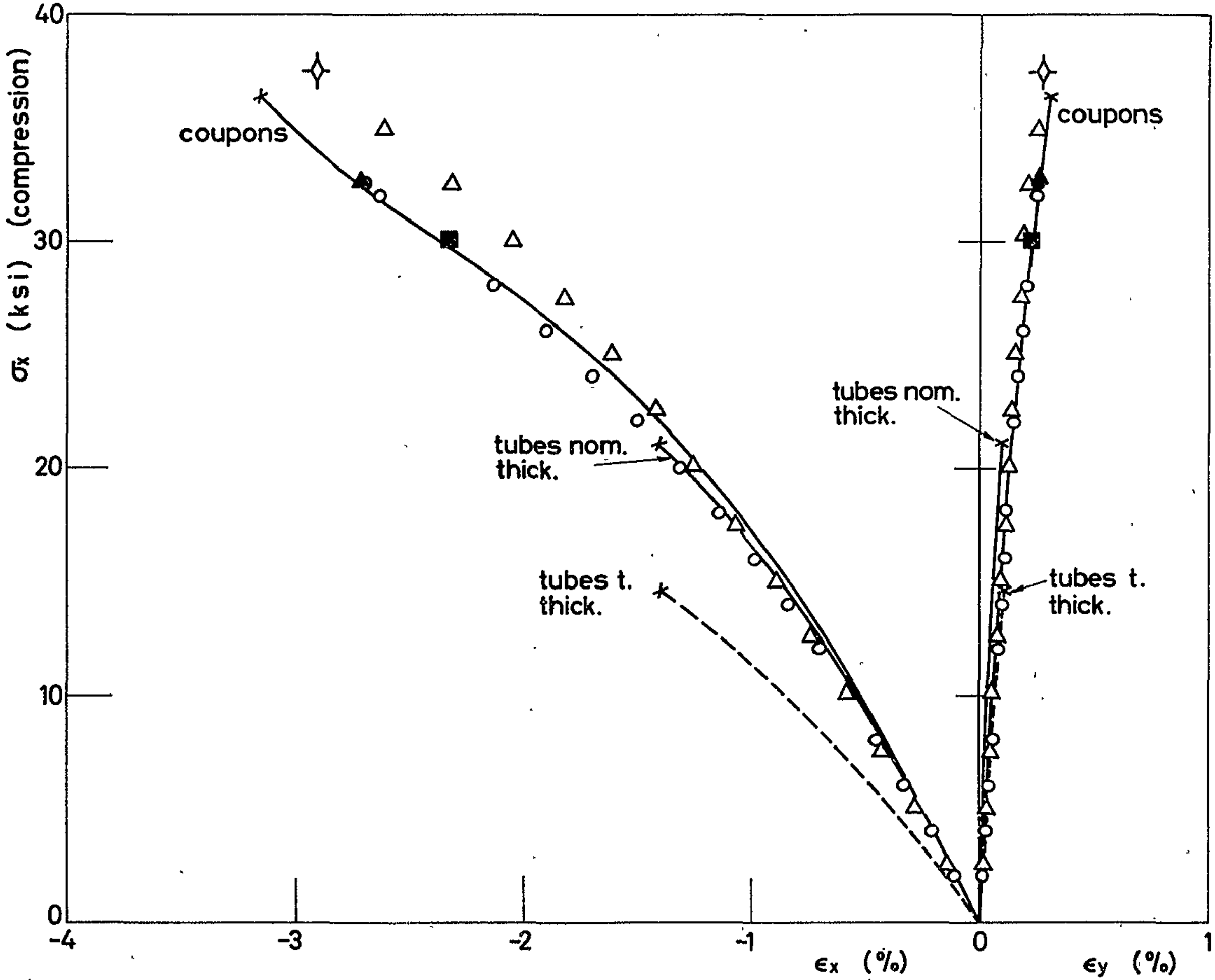

FIG. 8 COMPRESSION RESPONSE OF ±75° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

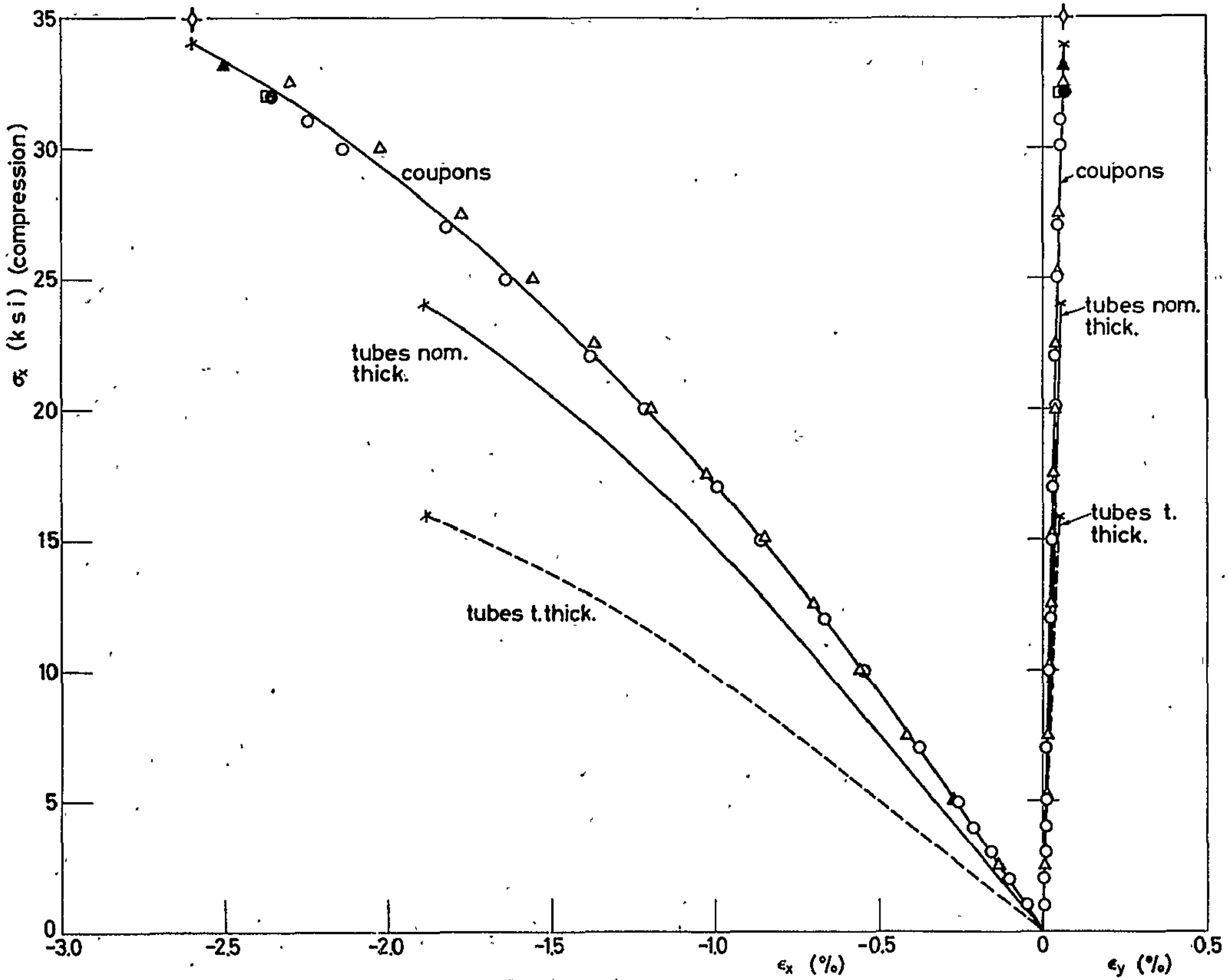

FIG. 9 COMPRESSION RESPONSE OF 90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

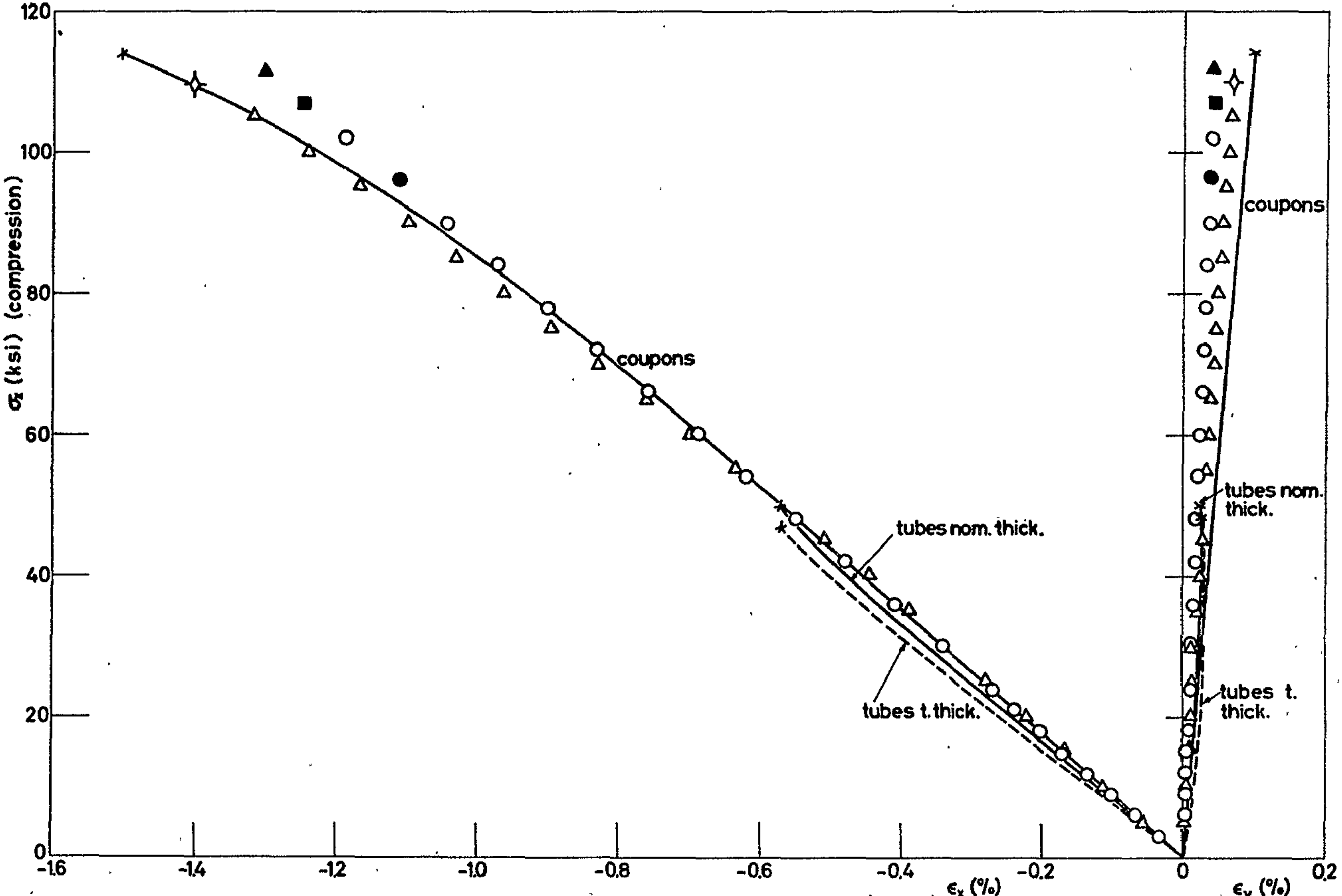

FIG. 10 COMPRESSION RESPONSE OF 0/90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

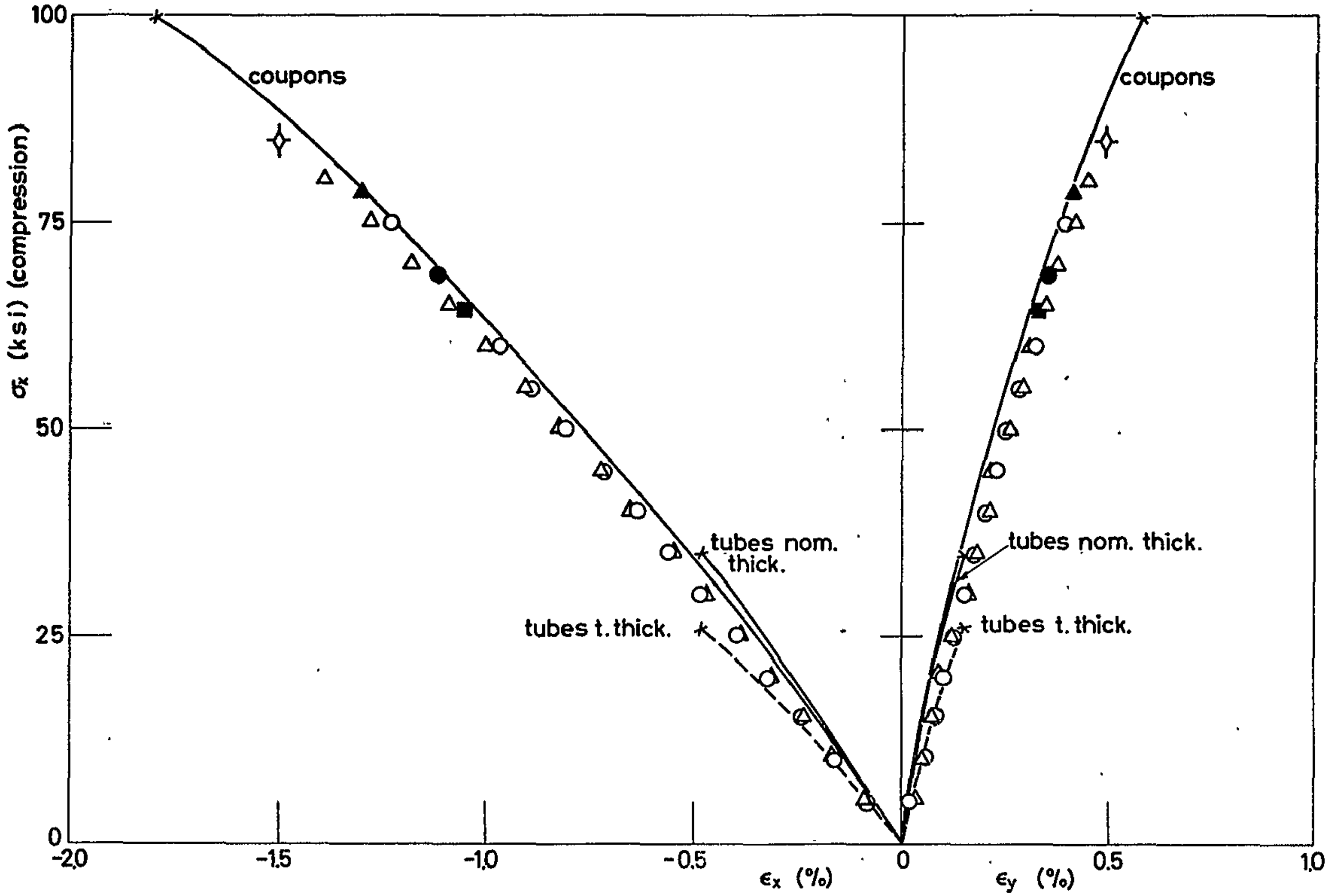

FIG. 11 COMPRESSION RESPONSE OF 0/±45/90° 3M SP-286T3 GRAPHITE-EPOXY LAMINATES

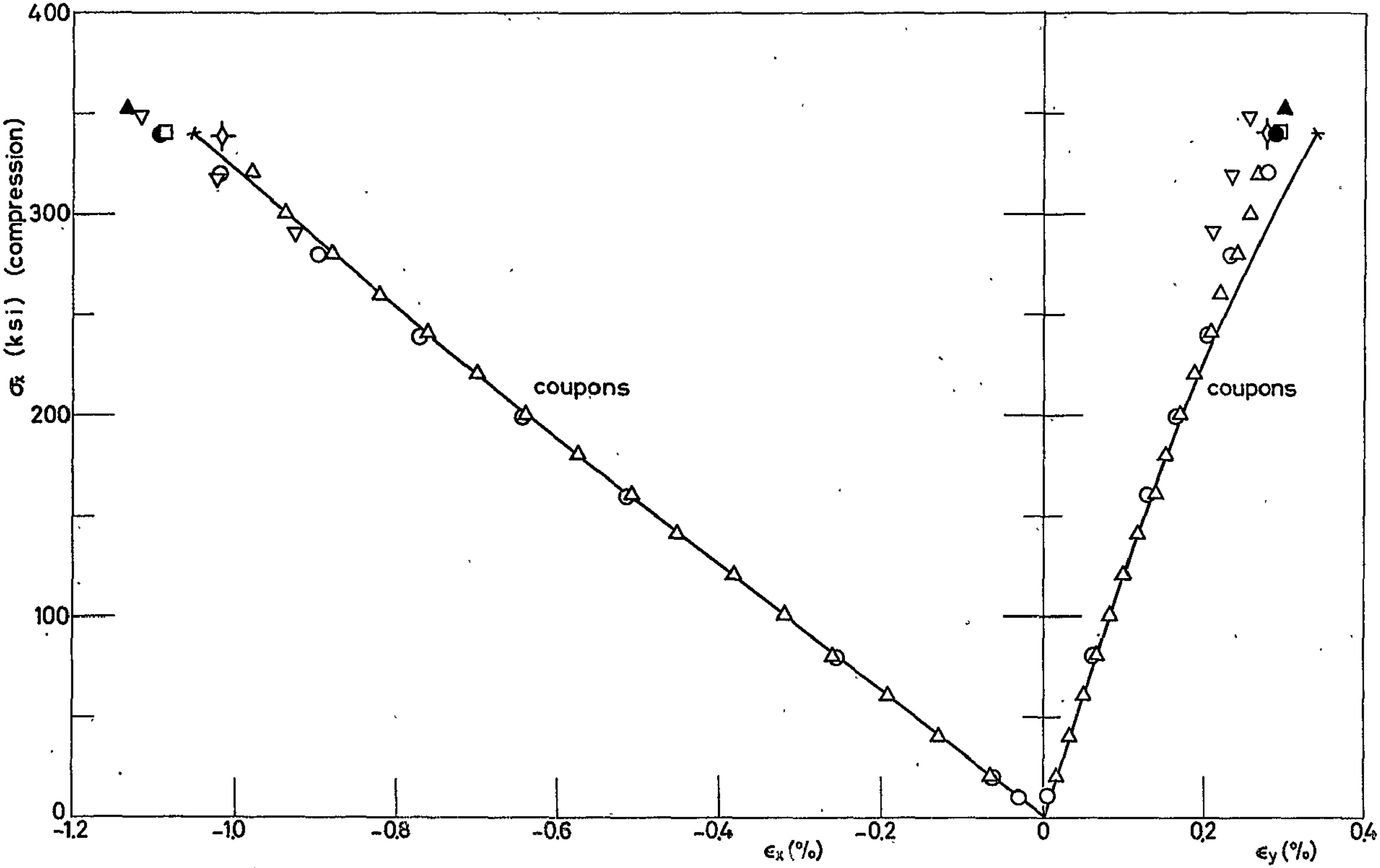

FIG. 12 COMPRESSION RESPONSE OF 0° AVCO 5505 / 5.6 MIL. DIA. BORON-EPOXY LAMINATES

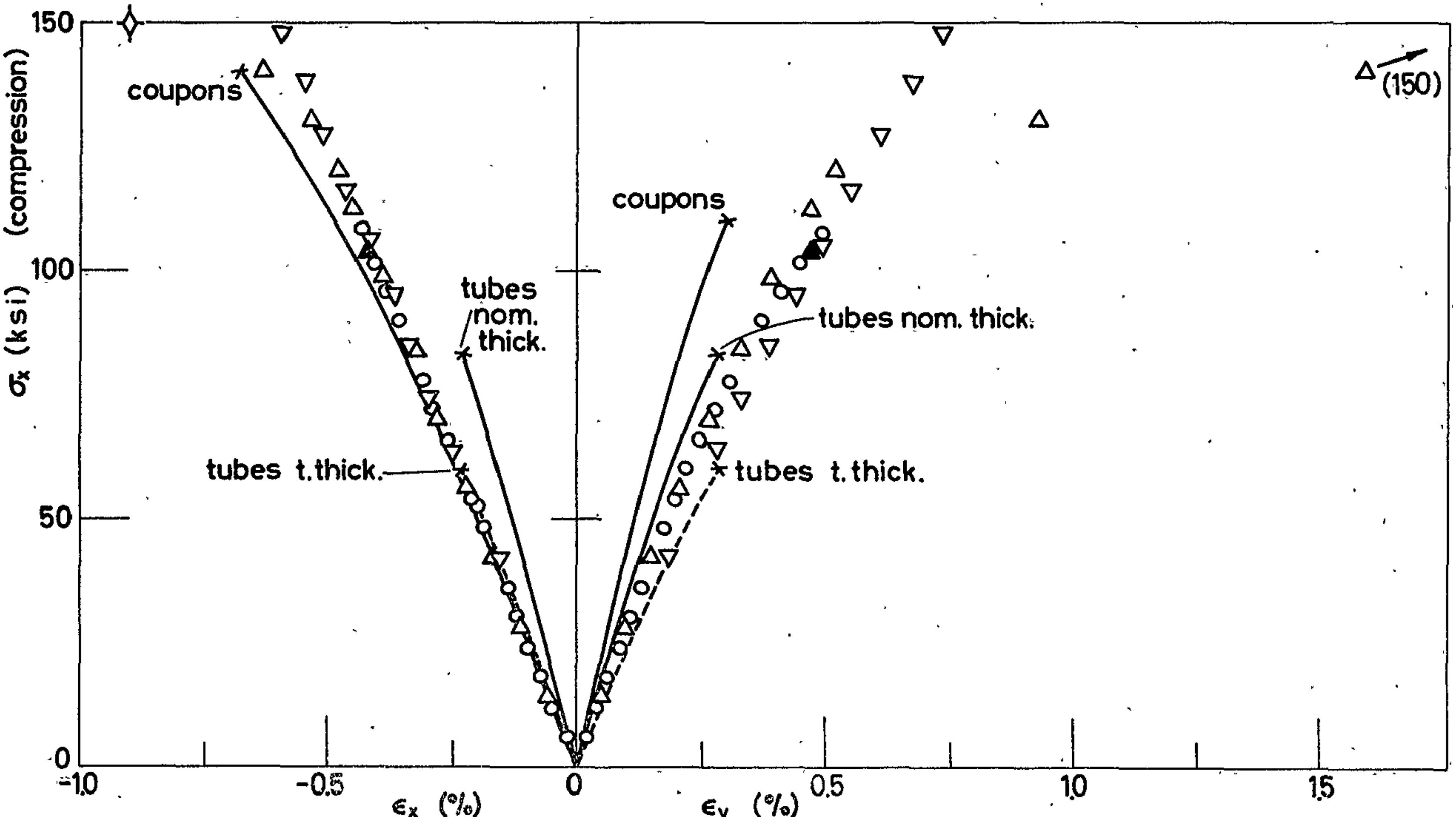

FIG. 13 COMPRESSION RESPONSE OF ±15° AVCO 5505 BORON-EPOXY LAMINATES

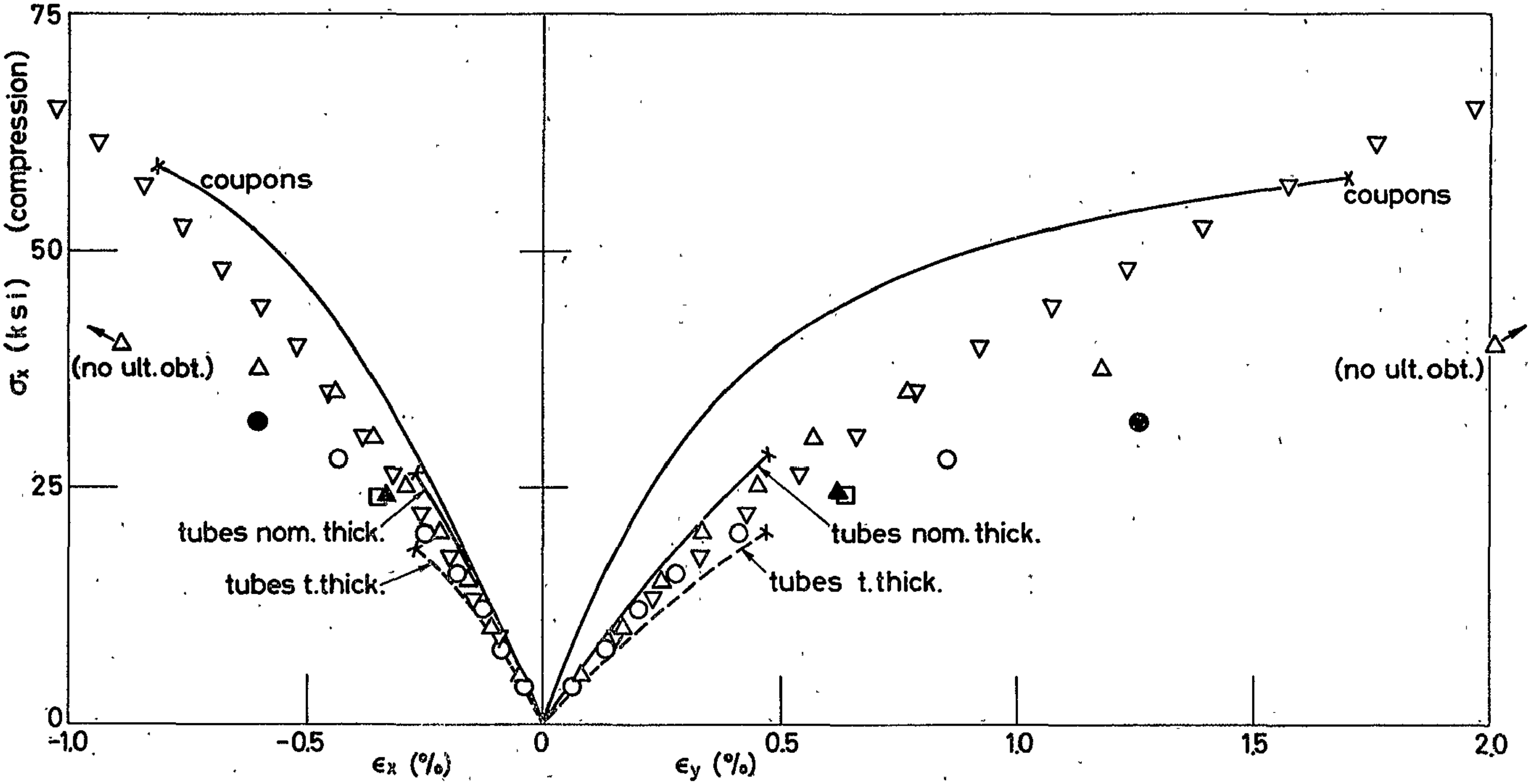

FIG. 14 A COMPRESSION RESPONSE OF ±30° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES (BATCH I)

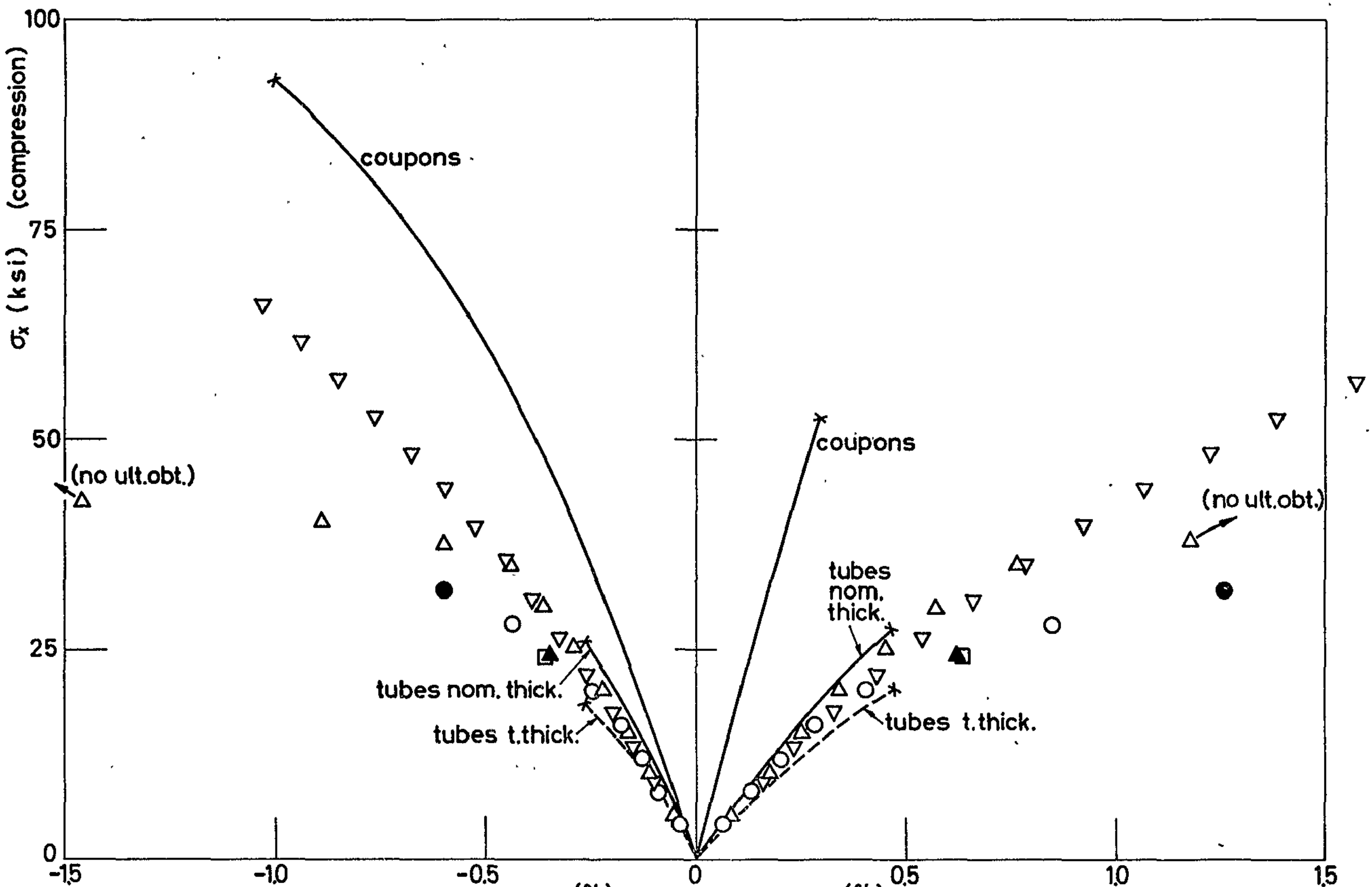

FIG. 14B COMPRESSION RESPONSE OF ±30° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES (BATCH II)

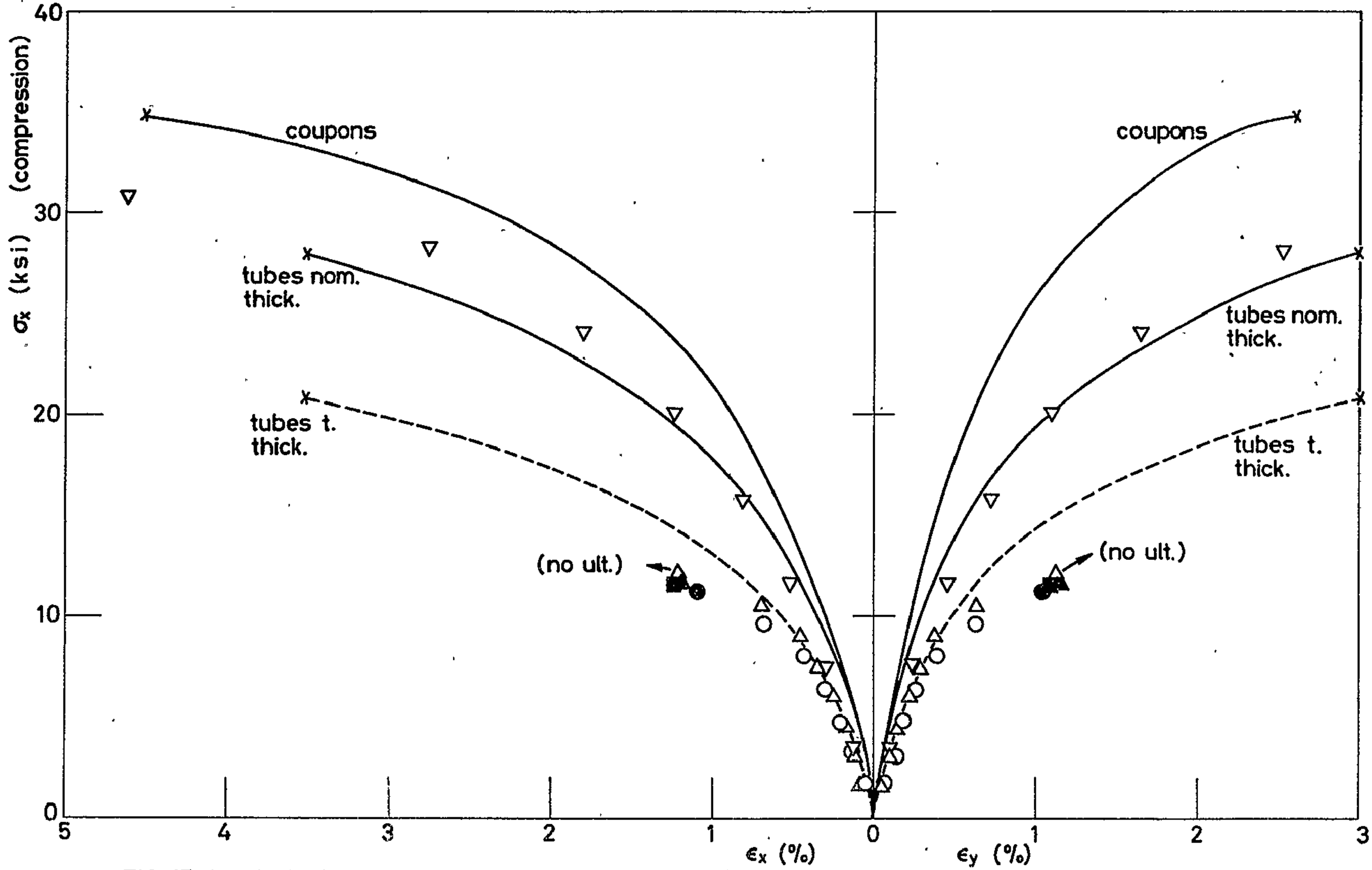

FIG. 15 COMPRESSION RESPONSE OF ±45° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES

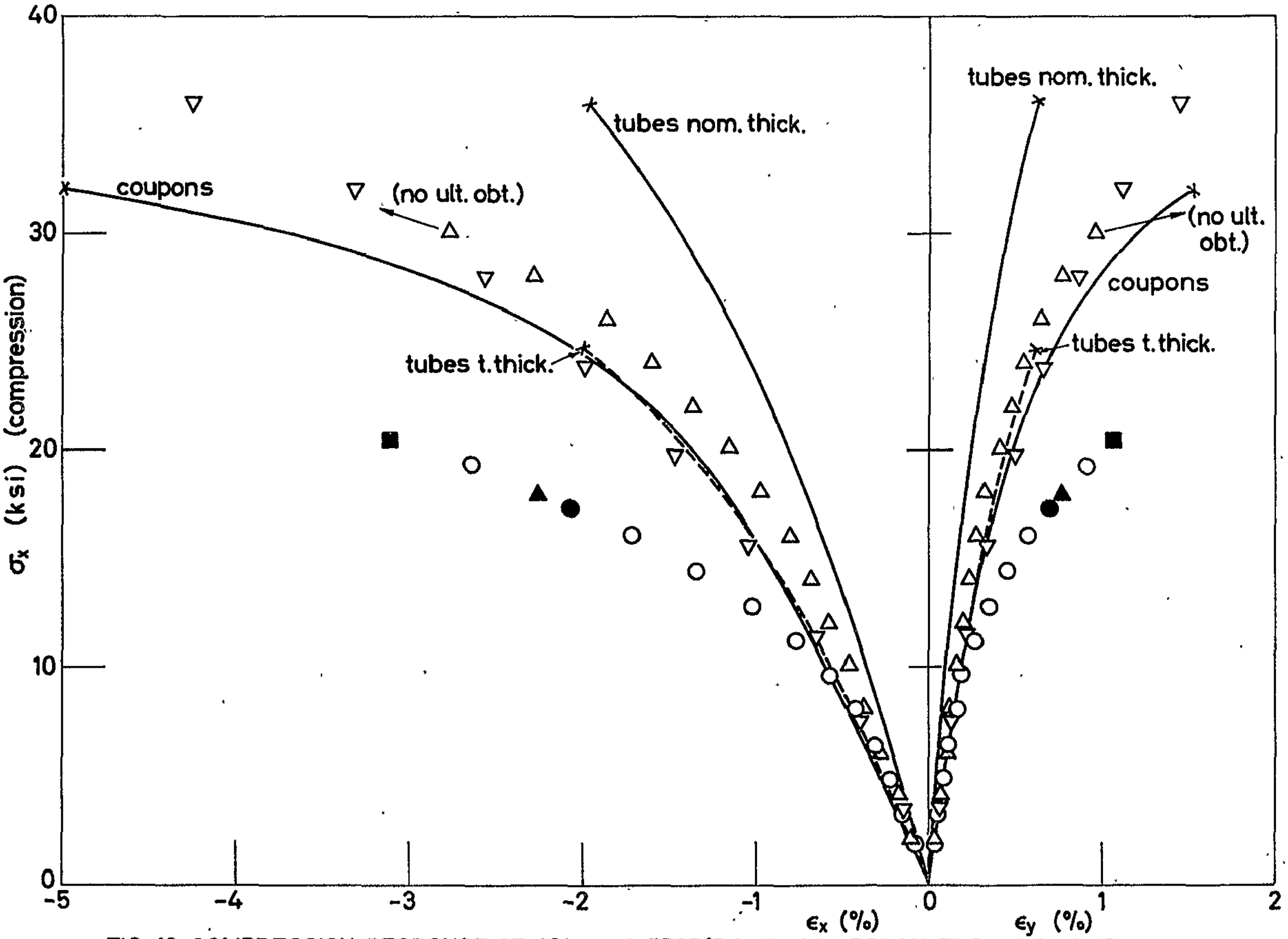

FIG. 16 COMPRESSION RESPONSE OF ±60° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES.

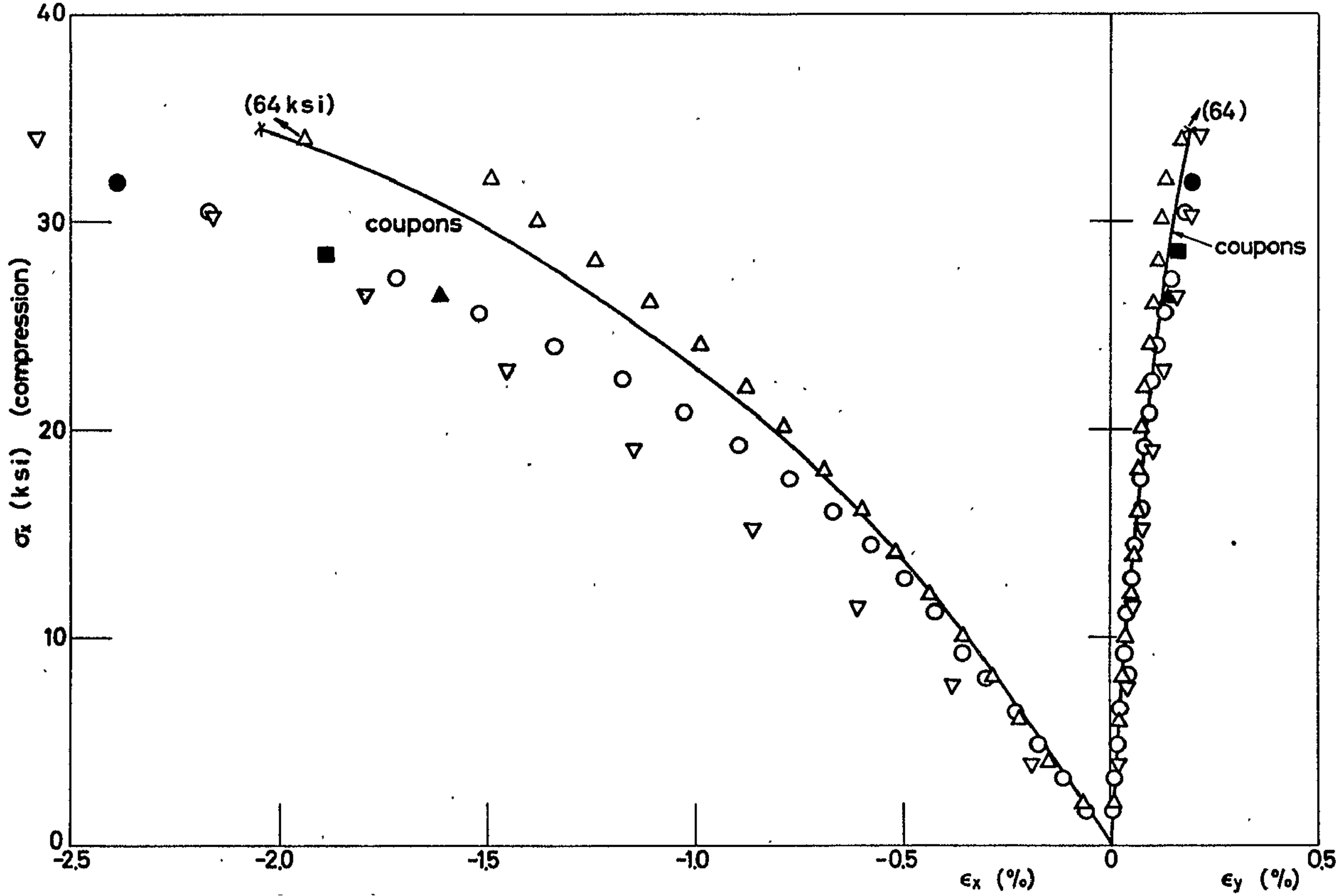

FIG. 17 COMPRESSION RESPONSE OF ±75° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES

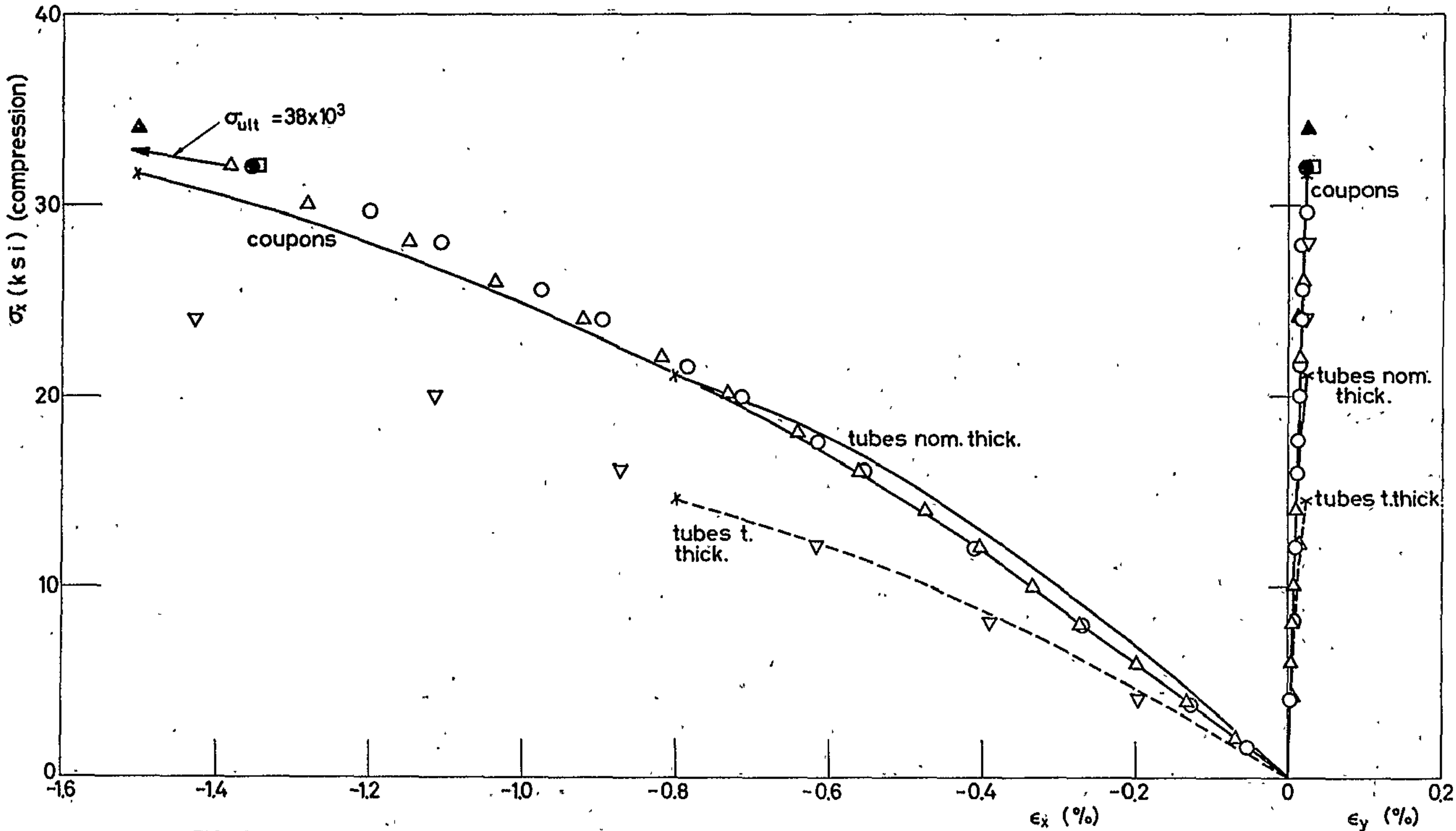

FIG. 18 COMPRESSION RESPONSE OF 90° AVCO 5505/5.6 MIL. DIA. BORON EPOXY LAMINATES

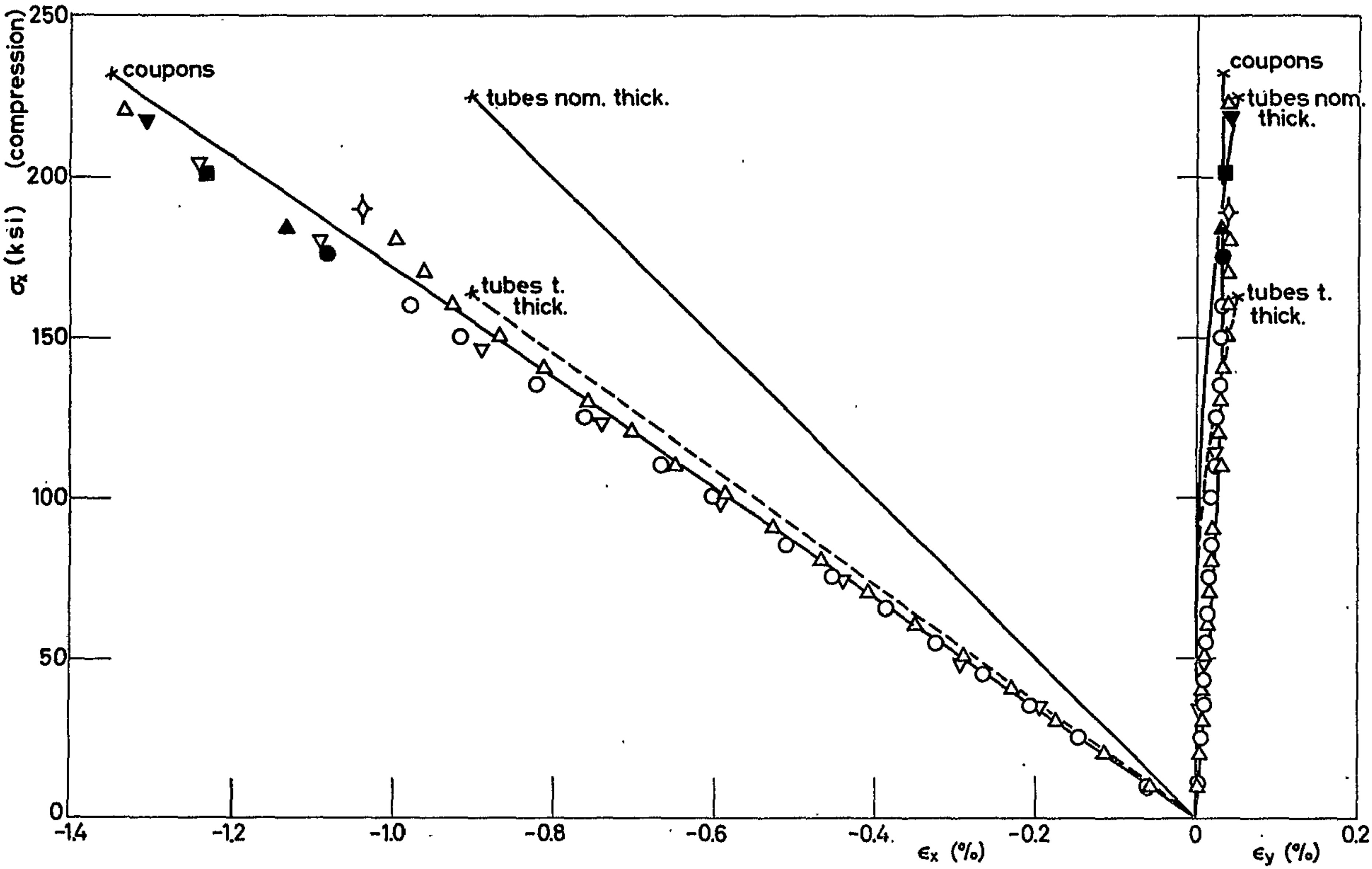

FIG. 19 COMPRESSION RESPONSE OF 0/90° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES

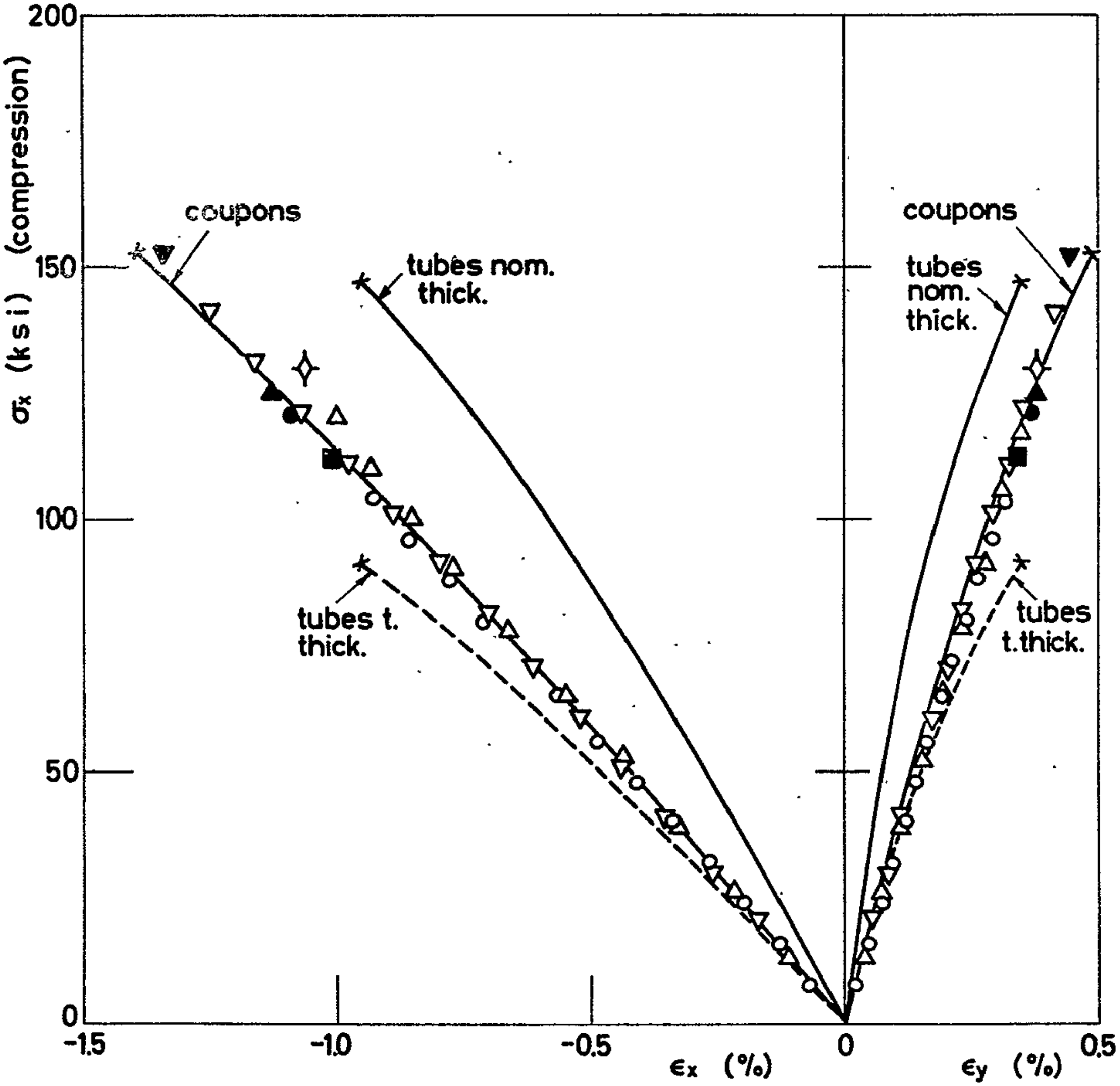

FIG. 20 COMPRESSION RESPONSE OF 0/±45/90° AVCO 5505/5.6 MIL. DIA. BORON-EPOXY LAMINATES

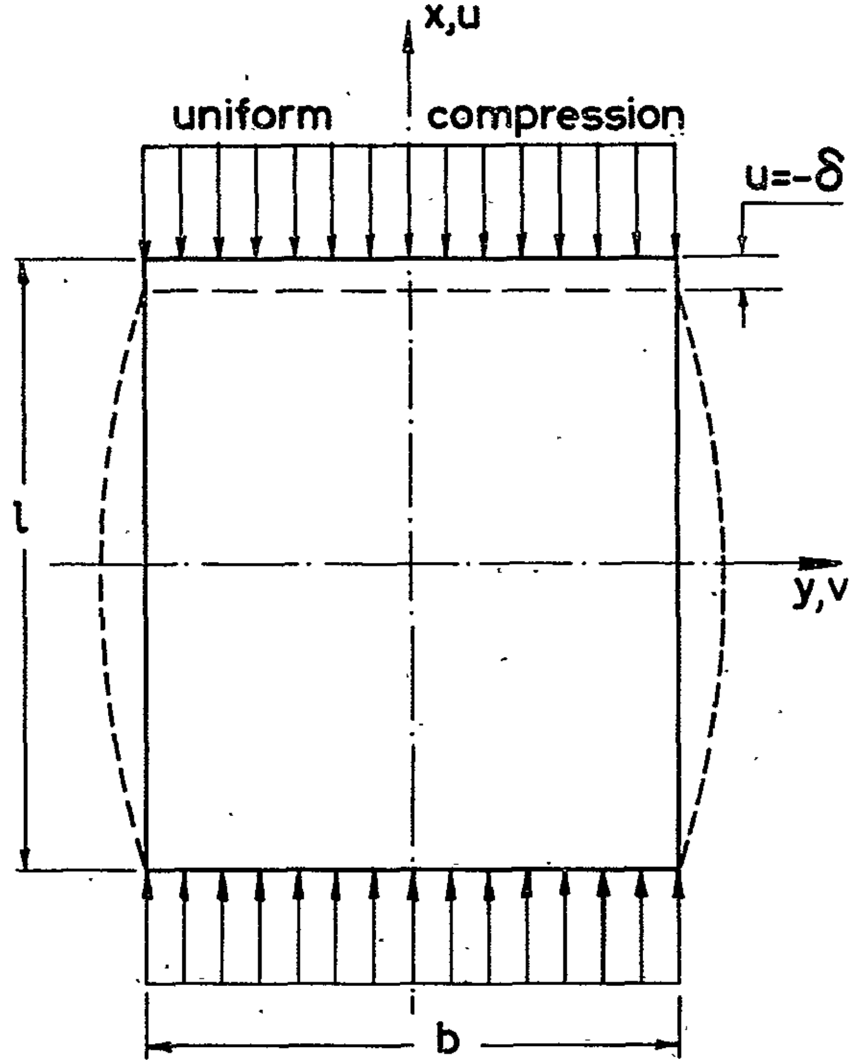

FIG. APB1 COUPON UNDER UNIFORM COMPRESSION

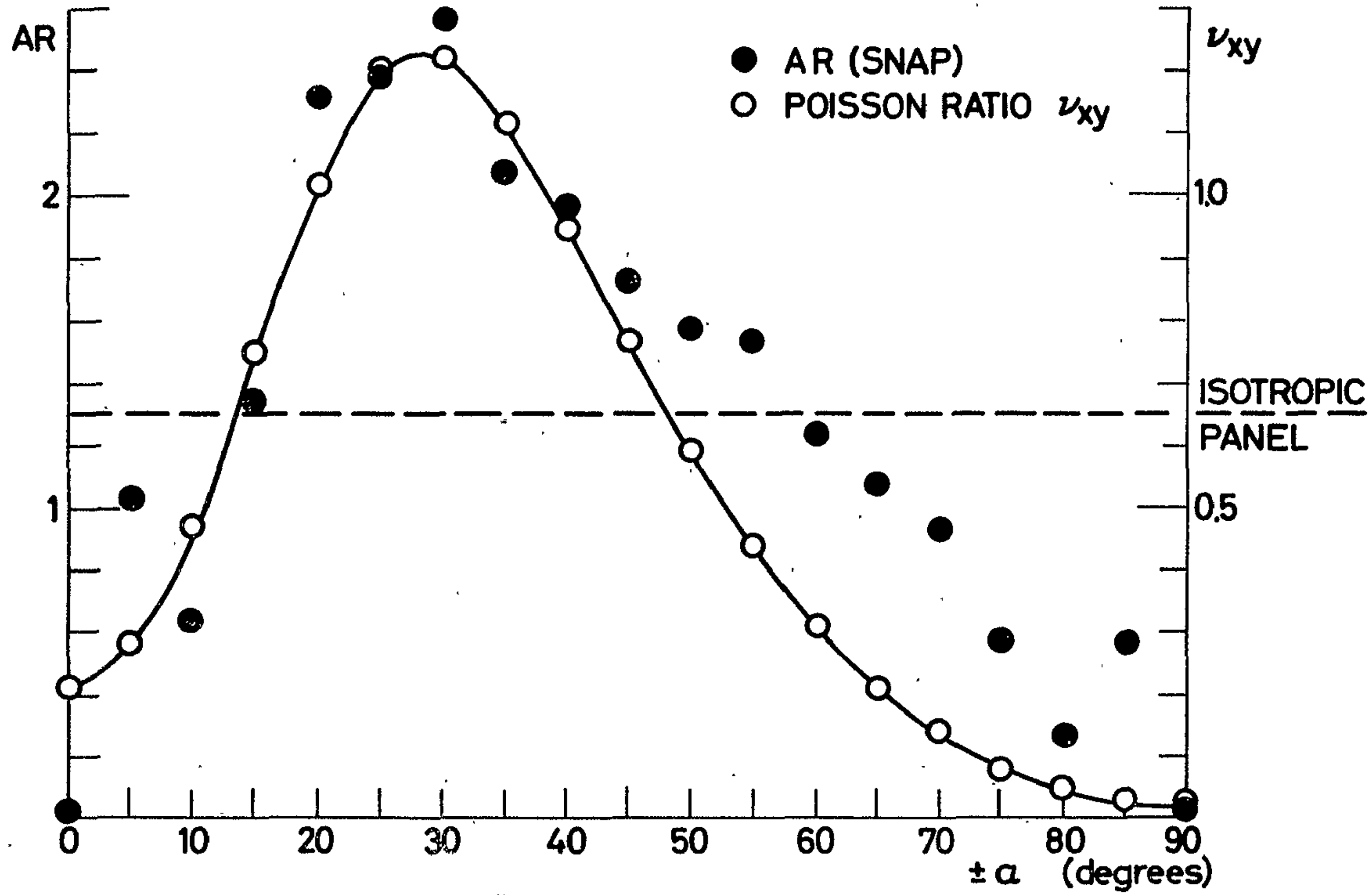

FIG. APB 2 MIN AR FOR "BEST" STRESS DISTRIBUTION ALONG THE CENTER LINE OF THE COUPON