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On Poisson's Ratio for Metal Matrix Composite Laminates

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ON POISSON'S RATIO FOR METAL MATRIX COMPOSITE LAMINATES*

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ABSTRACT

The definition of Poisson's ratio for nonlinear behavior of metal matrix composite laminates is discussed and experimental results for tensile and compressive loading of five different boron-aluminum laminates are presented. It is shown that there may be considerable difference in the value of Poisson's ratio as defined by a total strain or an incremental strain definition. It is argued that the incremental definition is more appropriate for nonlinear material behavior. Results from a [0] laminate indicate that the incremental definition provides a precursor to failure which is not evident if the total strain definition is used.

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INTRODUCTION

Strictly speaking, Poisson's ratio is defined only for linear material behavior. However, it is also rather common practice to refer to the negative ratio of lateral strain to axial strain as Poisson's ratio when a material exhibits nonlinear behavior. This practice is adopted in this paper.

Poisson's ratio can be a very important material property for accurate stress analysis when dissimilar materials are under consideration. Composite laminates are a special class of dissimilar materials in that the material properties of each layer are a function of the fiber orientation of that layer. If a finite width composite laminate is loaded in one direction only, the mismatch of Poisson's ratios between layers gives rise to an internal (away from the edges) biaxial stress state and large interlaminar stresses in a boundary layer region along the free edges. The magnitude of the stresses in individual layers is, of course, a function of all mechanical properties. However, the triaxial stress state in the boundary layer is always present whenever there is a mismatch of Poisson's ratios between layers. This can be seen clearly by consideration of a $[0/90]_s$ laminate in which the interlaminar stresses are the direct result of the mismatch of Poisson's ratios between laminae. For more general laminates, a mismatch of the coefficients of mutual influence [1] will also give rise to a triaxial stress state in the boundary layer region of a composite laminate under axial load.

Both linear and nonlinear numerical analyses [2] of the free edge problem have shown that the interlaminar stresses in the boundary layer region may be quite large; further, delamination failures have been observed in the laboratory [3]. Thus, accurate prediction of the interlaminar stresses is vital for failure analysis of composite laminates with free edges. Such analyses can only be as reliable as the material properties used in the analysis.

Linear elastic stress analyses are properly performed using a constant value for Poisson's ratio. However, and unfortunately, Poisson's ratio is often assumed to be a constant for nonlinear analyses. This is undoubtedly due to the lack of available experimental results for the variation of Poisson's ratio during nonlinear material behvaior. The present study was motivated by a need for input properties for an incremental nonlinear finite element analysis of composite materials.

The paper discusses the proper definition of Poisson's ratio during nonlinear material behavior and presents a comparison of experimental results using two different definitions. The experimental results were obtained from both tension and compression tests on five different boron-aluminum laminates. It is shown that Poisson's ratio may vary considerably over the entire range of loading and that the values depend upon the definition used.

POISSON'S RATIO

A review of the literature in the field of solid mechanics indicates that relatively little attention has been given to the variation of Poisson's ratio during nonlinear material behavior. This is undoubtedly due to the fact that Poisson's ratio of traditional structural materials varies over a limited range from 0.2 to 0.5. In contrast to this limited range, composite laminates are known to exhibit values ranging from essentially zero to greater than 1.0 (experimental values greater than 3.0 are presented in this paper).

The classical definition of Poisson's ratio is that it is the negative ratio of the total lateral strain to the total axial strain. Thus, for a uniaxial loading σ_x, the classical Poisson's ratio, ν_{xy}, is given by

$$\nu_{xy} = - \frac{\varepsilon_y}{\varepsilon_x} \qquad (1)$$

where ε_x and ε_y are total strains. A more accurate definition of the instantaneous Poisson's ratio would be the negative ratio of the instantaneous change in lateral strain $d\varepsilon_y$ associated with the instantaneous change in axial strain $d\varepsilon_x$; thus

$$\nu_{xy} = \frac{-d\varepsilon_y}{d\varepsilon_x} \qquad (2)$$

For incremental analyses Equ. (2) can be modified to the form

$$\nu_{xy} = \frac{-\Delta\varepsilon_y}{\Delta\varepsilon_x} \qquad (3)$$

The definition (2) corresponds to the instantaneous Poisson's ratio whereas equation (1) represents an averaging over the entire range of loading. Both definitions are identical for linear material behavior. As will be shown by the experimental results, significant differences may exist between the definitions for nonlinear behavior of metal matrix composites. The incremental definition (3) is, of course, more appropriate than the classical definition (1) for use in incremental numerical procedures.

For linear material behavior it can be shown [1] that the Poisson's ratios and elastic moduli of an orthotropic material must satisfy the relationship

$$\frac{E_1}{E_2} = \frac{\nu_{12}}{\nu_{21}} \tag{4}$$

where the subscripts (1) and (2) refer to the fiber direction and perpendicular to the fiber, respectively, and ν_{ij} corresponds to the lateral strain in the j direction associated with an applied strain in the i direction. In addition, a laminated composite must satisfy the relationship

$$\frac{E_x}{E_y} = \frac{\nu_{xy}}{\nu_{yx}} \tag{5}$$

Equations (4) and (5) are used in linear analysis in order to reduce the number of problem parameters. It is natural then to determine the applicability of such equations for nonlinear analyses. This question will be addressed in the results section of this paper.

EXPERIMENTAL PROGRAM

Specimens

Tension and compression specimens for this study were fabricated from commercially supplied boron-aluminum. This material system combined 5.6 mil boron fibers and 6061 aluminum matrix. Laminates of the following orientations were tested in both tension and compression: $[0_8]$*, $[90_8]$, $[0/(90)_2/0]_s$, $[(\pm 30)_2]_s$, $[+45/(-45)_2/+45]_s$+.

The tension specimens were flat coupons nominally 10" (25.4 cm) in length and 0.75" (1.9 cm) in width. Tapered fiberglass end tabs, 2.5" (6.3 cm) long, were bonded to each end of the specimen resulting in a 5" (12.7 cm) test section. The compression specimens were sandwich beams which measured approximately 22" (55.9 cm) in length, 1.0" (2.5 cm) in width, and 1.5" (3.8 cm) between the flanges. The beams were loaded in four-point bending and had a 4" (10.2 cm) test section in the upper composite flange. The bottom flange was titanium. Typical specimens are shown in Fig. 1.

Test Procedure

All specimens were loaded using a 120 kip (26.98 kN) capacity Baldwin testing machine with a constant load rate to failure. Tension tests were performed using ASTM standard D 3039-76 [4]. Foil-type strain gages mounted on either side of the tensile coupon measured the strains. These data were recorded digitally with a multi-channel data acquisition system. The tests of $[0_8]$, $[90_8]$, and $[0/(90)_2/0]_s$ fiber orientations had stacked longitudinal and transverse strain

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*$[0_8]$ laminates were tested in tension; $[0_4]$ laminates were tested in compression.

+Actual lay-up in tension, $[+45/(-45)_2/(+55)_2/(-45)_2/+55]$.

gages. The $[(\pm 30)_2]_s$ and $[+45/(-45)_2/+45]_s$ configurations had stacked strain rosettes oriented at 0°, 45°, and 90° to the longitudinal axis of the specimen.

The compressive load was applied to the test section by four-point bending [5]. Strains were measured using foil-type strain gages mounted on the composite flange and recorded using the previously mentioned data acquisition system. Similar to the tension tests, the $[0_4]$, $[90_8]$ and $[0/(90)_2/0]_s$ specimens had stacked longitudinal and transverse strain gages; the $[(\pm 30)_2]_s$ and $[+45/(-45)_2/+45]_s$ fiber orientations had stacked strain rosettes oriented at 0°, 45°, and 90° to the longitudinal axis of the beam.

A minimum of two tests were conducted for each type of specimen.

RESULTS AND DISCUSSION

Typical results showing the variation of Poisson's ratio with applied strain for both the classical definition (Eqn. 1) and the incremental definition (Eqn. 3) are presented in Figs. 2 - 6. Results from both tension and compression tests are presented along with the associated stress-strain diagrams.

The results from a [0] laminate are shown in Fig. 2. The tensile loading results appear to exhibit only small differences between the two definitions. In both cases Poisson's ratio, ν_{12}, attains a constant maximum value over the strain range 0.4% - 0.7% with the incremental value being slightly higher (0.28 compared to 0.26). However, the incremental definition attains its constant maximum value at a considerably lower strain (0.15%) and also indicates a rather sudden decrease in Poisson's ratio at a strain of approximately 0.7%. This sudden decrease occurs just prior to laminate failure and is believed to be due to localized failures such as matrix cracking and fiber-matrix debonding which results in relaxation of internal stress. The sudden decrease in Poisson's ratio exhibited by the incremental definition serves as a precursor to laminate failure. Such a precursor is obviously not evident with the classical definition of Poisson's ratio or from the stress-strain diagram. Thus, the proper definition of Poisson's ratio can have important implications in experimental work as well as numerical investigations. The fact that the stress-strain diagram does not exhibit a decrease in modulus prior to laminate failure is an indication that the sudden decrease in the incremental Poisson's ratio is due to matrix cracking and fiber-matrix debonding and not fiber breakage. If there were significant fiber breakage the stress-strain diagram would exhibit a decrease in modulus for this [0] laminate.

The compression results indicate a significant difference in magnitude of Poisson's ratio depending upon the definition. However, both definitions exhibit similar trends with the value increasing continuously over the range of available data. These compression results are somewhat questionable since they were obtained from a sandwich beam specimen with an aluminum honeycomb core. The core may restrict the free lateral strain of the specimen, and hence the measured value may not be purely material behavior, but may also include the influence of the structural constraint of the sandwich beam. Considerable differences in compressive modulus results from sandwich beams and compression coupons have been reported previously [5]. The compression results are not complete because they could not be obtained over the complete range of compressive material behavior. The specimens usually failed due to stress concentrations at the point of load application or debonding from the honeycomb core, and not because the ultimate compressive stress of the material had been attained.

The results for a [90] laminate (Fig. 3) indicate a behavior which is entirely different from that of the [0] laminate. The Poisson's ratio, ν_{21}, decreases continuously with increasing strain for both definitions and both types of loading. The incremental definition actually indicates negative values at larger strains for both types of loading. A negative Poisson's ratio during tensile loading corresponds to a positive increment of lateral strain during an increment of axial strain. As in the case of the sudden decrease in Poisson's ratio, ν_{12}, such behavior can possibly be explained by relaxation of internal stresses as local matrix cracking and fiber-matrix debonding occurs. Relaxation of internal stresses allows the material to unload and thus causes a change in the sign of the increment of lateral strain. However, unlike the [0] laminate, this appears to be a gradual process in the [90] laminate.

Equation (4) which relates moduli and Poisson's ratios in the material principal directions may be written in the form

$$\frac{E_1}{\nu_{12}} = \frac{E_2}{\nu_{21}} \tag{6}$$

The results in Fig. 2 indicate that E_1 and ν_{12} are constant over almost the entire strain range; the ratio E_1/ν_{12} is then also a constant over the same range. As indicated in the figure the range of constant values is larger for the incremental definition of Poisson's ratio. These results indicate that the ratio E_2/ν_{21} must also be constant over the entire range of loading if (6) is to be always satisfied. The results in Fig. 3 do indicate the proper trends for this to be true since both E_2 and ν_{12} decrease with increasing strain. However, actual calculations indicated that equation (6) is not satisfied for nonlinear behavior. It is obvious from the figures that E_1/ν_{12} is always positive, but that E_2/ν_{21} becomes negative for the incremental definition. Since Equ. (4) is not satisfied in the nonlinear range, neither is Equ. (5).

Results for the bi-directional $[0/90_2/0]_s$ laminate are shown in Fig. 4. The tensile results indicate similar trends for both definitions with the Poisson's ratio decreasing rather rapidly at low strain levels and then leveling off to an almost constant small value for larger strains. As indicated by the data points in Fig. 4, the incremental results for this laminate were uncharacteristically erratic, but on the average followed the same trend as did the results using the total strain definition. The reason for the erratic behavior of this particular laminate is not obvious. A continuum would not exhibit such behavior unless local failure mechanisms were occuring in a somewhat random fashion. The erratic results could be due to limited accuracy in the measurement of small strains.

Comparison of the results for tension and compression shown in Fig. 4 indicates that the variation of Poisson's ratio is definitely a function of the type of loading. For compressive loading both definitions indicate an initial rise in Poisson's ratio followed by a general decrease with the value remaining positive for the entire range of available data. All limitations of the sandwich beam which were discussed previously apply to this laminate as well as all others to be discussed. However, the influence of the core will vary from laminate to laminate depending upon the mismatch of mechanical properties between the laminate specimen and the core.

The remaining figures show results for a $[\pm 45]_s$ and a $[\pm 30]_s$ laminate. The results for the $[\pm 45]_s$ laminate are quite consistent for both definitions and both types of loading. For tensile loading Poisson's ratio exhibits an initial rise followed by a slowly increasing value with the incremental definition maintaining a higher value throughout the entire loading history. The difference between the two definitions remains essentially constant. The initial Poisson's ratios are in the neighborhood of 0.5 and the final values are in the neighborhood of 1.0 which is the value predicted by lamination theory.

The results for compressive loading exhibit a different trend in that the initial values are approximately 1.0 and then gradually decrease to, and remain at, a value of 0.9 over most of the loading history. The incremental definition predicts a slightly higher value throughout the entire range of loading for both tensile and compressive loading.

It should be noted that Eqn. (5) would be satisfied identically over the entire range of loading for both the $[0/90_2/0]_s$ and the $[\pm 45]_s$ laminates. This is due to the fact that it is always true that $E_x = E_y$ and $\nu_{xy} = \nu_{yx}$ for these laminates because of the particular fiber orientations involved.

The results for the $[\pm 30]_s$ laminate shown in Fig. 6 are perhaps the most interesting of those presented in this paper. Poisson's ratio is initially a small value (0.3 - 0.4), but exhibits a continuous increase with increasing strain with the values prior to failure being approximately 2.5 for the incremental definition and 1.7 for the total strain definition. The tensile results exhibit some erratic behavior and the compressive results exhibit a rather sudden decrease in value just prior to failure. There is a significant different in the values obtained from the two definitions.

CONCLUSIONS

Experimental results have been presented showing that the value of Poisson's ratio over the entire nonlinear range of tensile and compressive loading of boron-aluminum composite laminates may vary considerably depending upon the definition of Poisson's ratio. It has been argued that a differential (or incremental) definition is more appropriate for nonlinear material behavior. It has also been shown that the incremental definition provides a precursor to failure of a [0] laminate which is not evident when a total strain definition is used.

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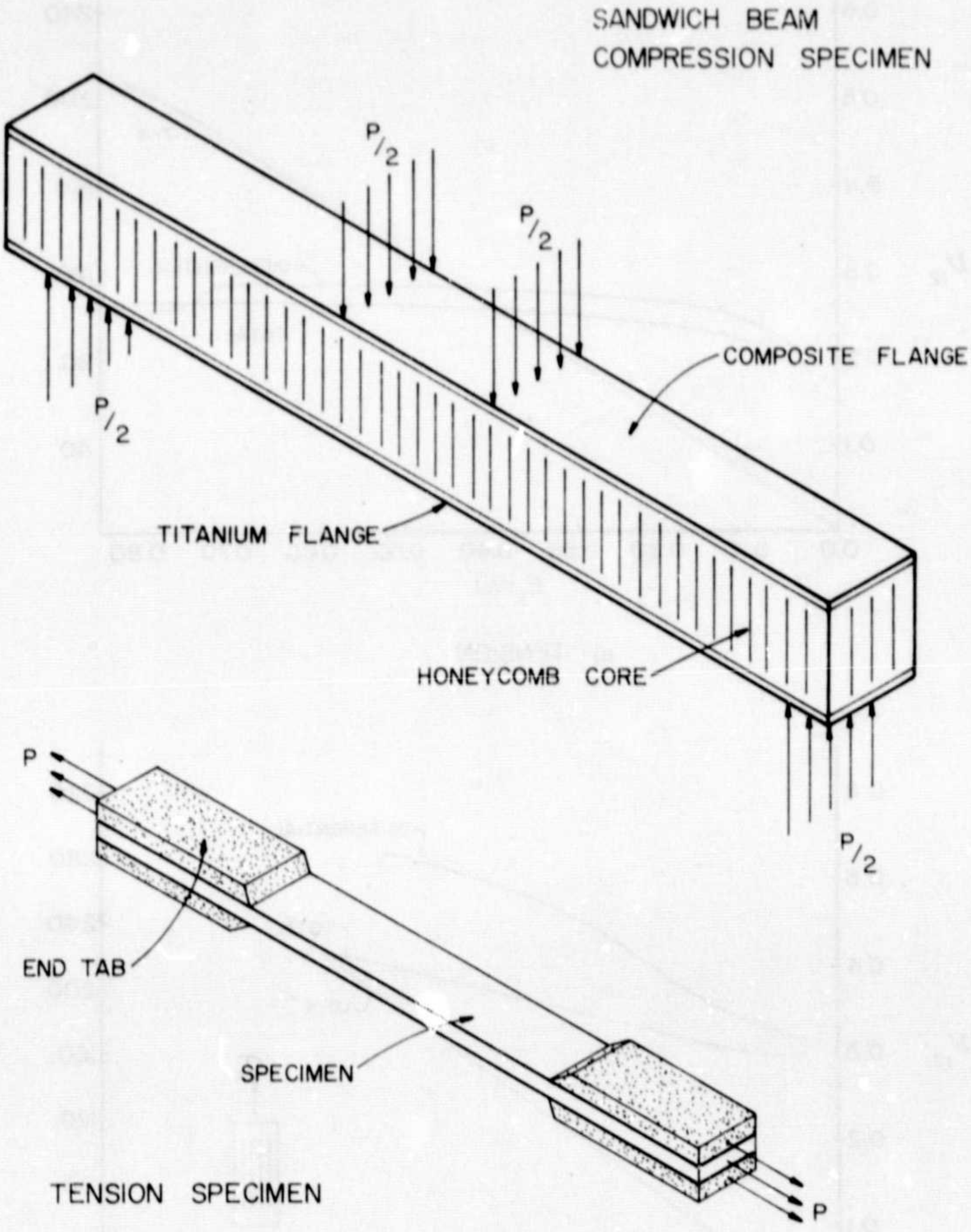
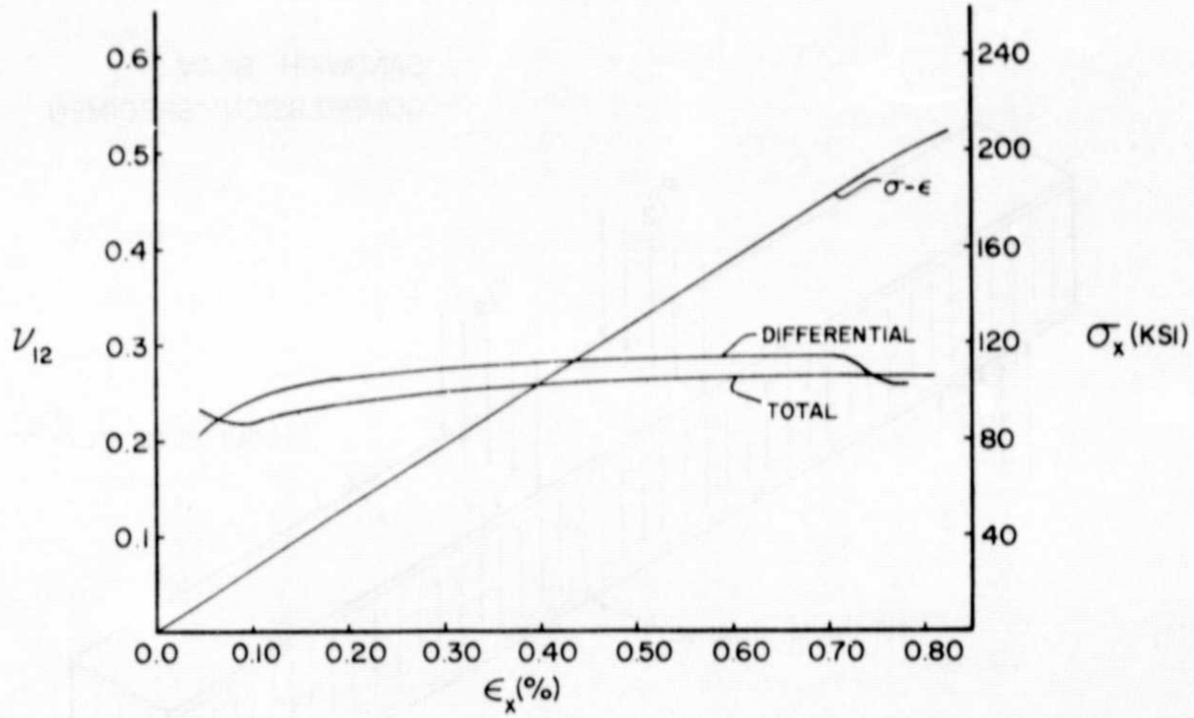
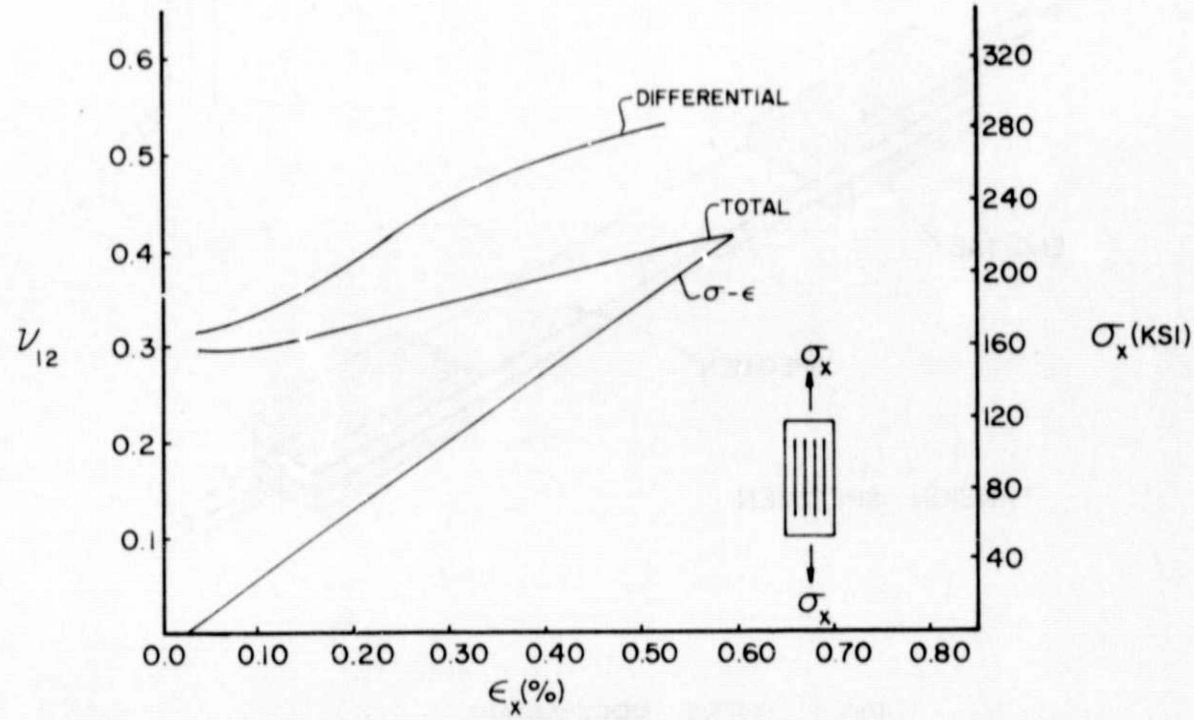


FIG. I TEST SPECIMENS

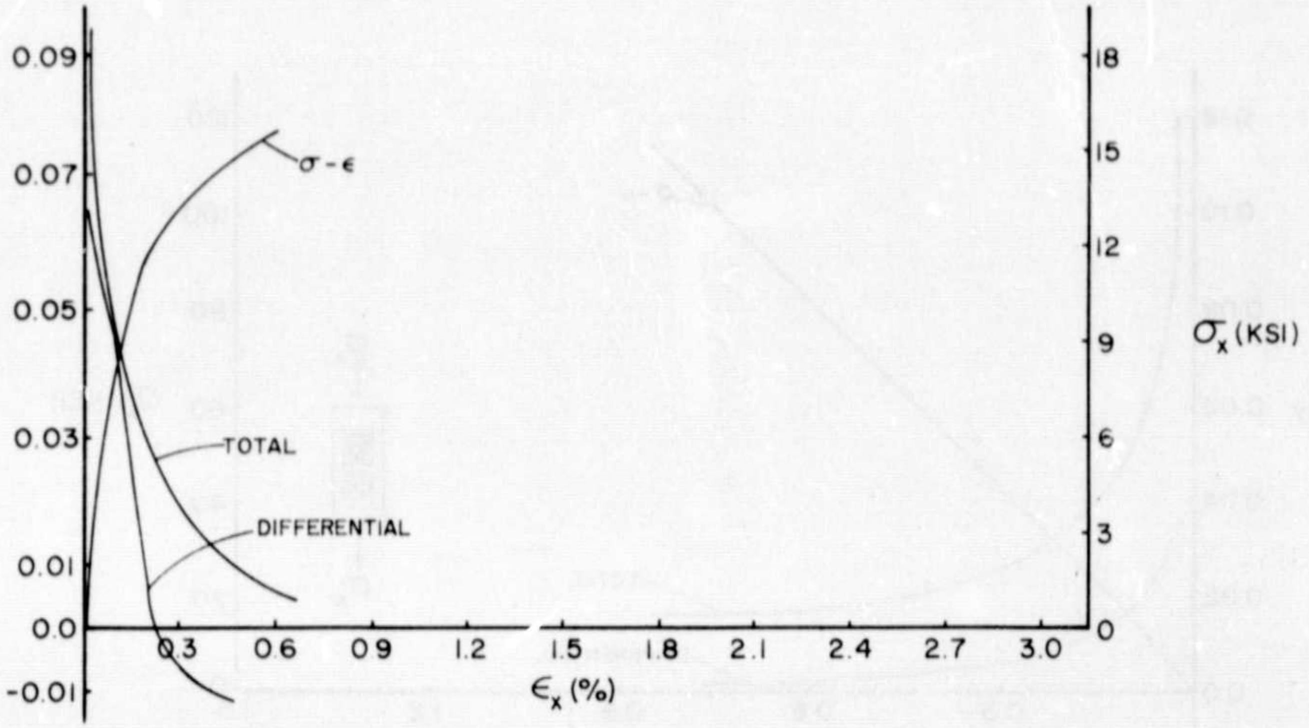


a) TENSION

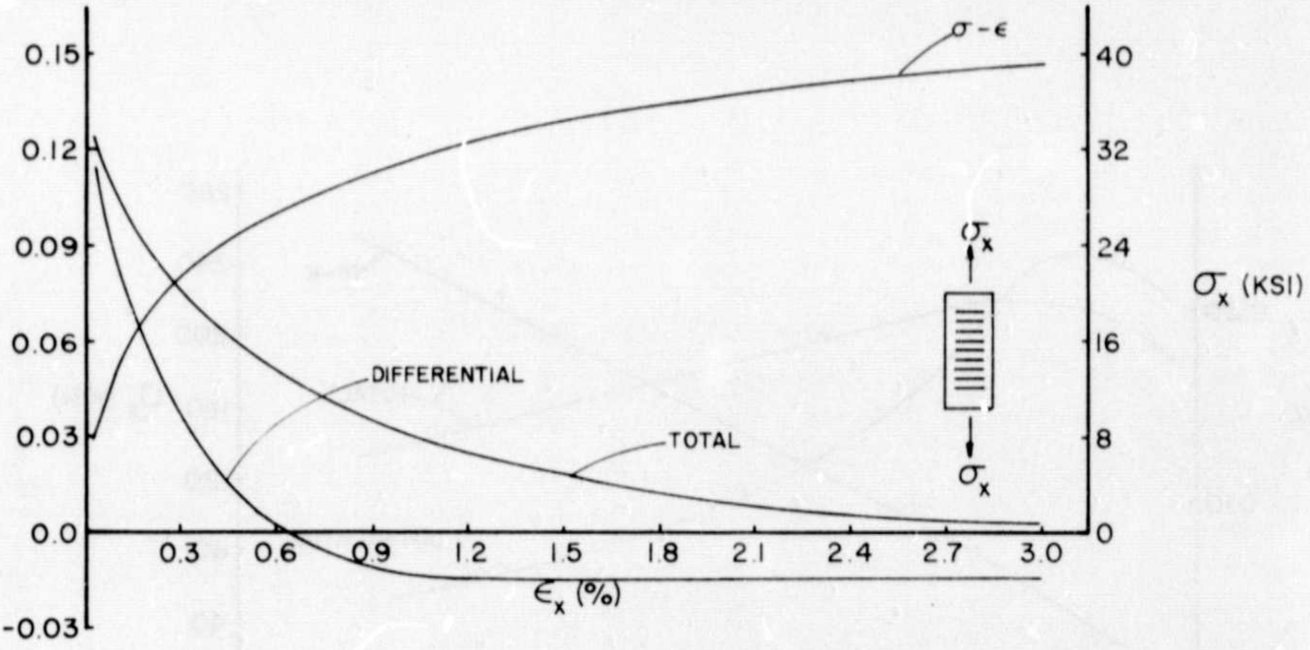


b) COMPRESSION

FIG. 2 POISSON'S RATIO ν_{12} FOR [0] Gr/E

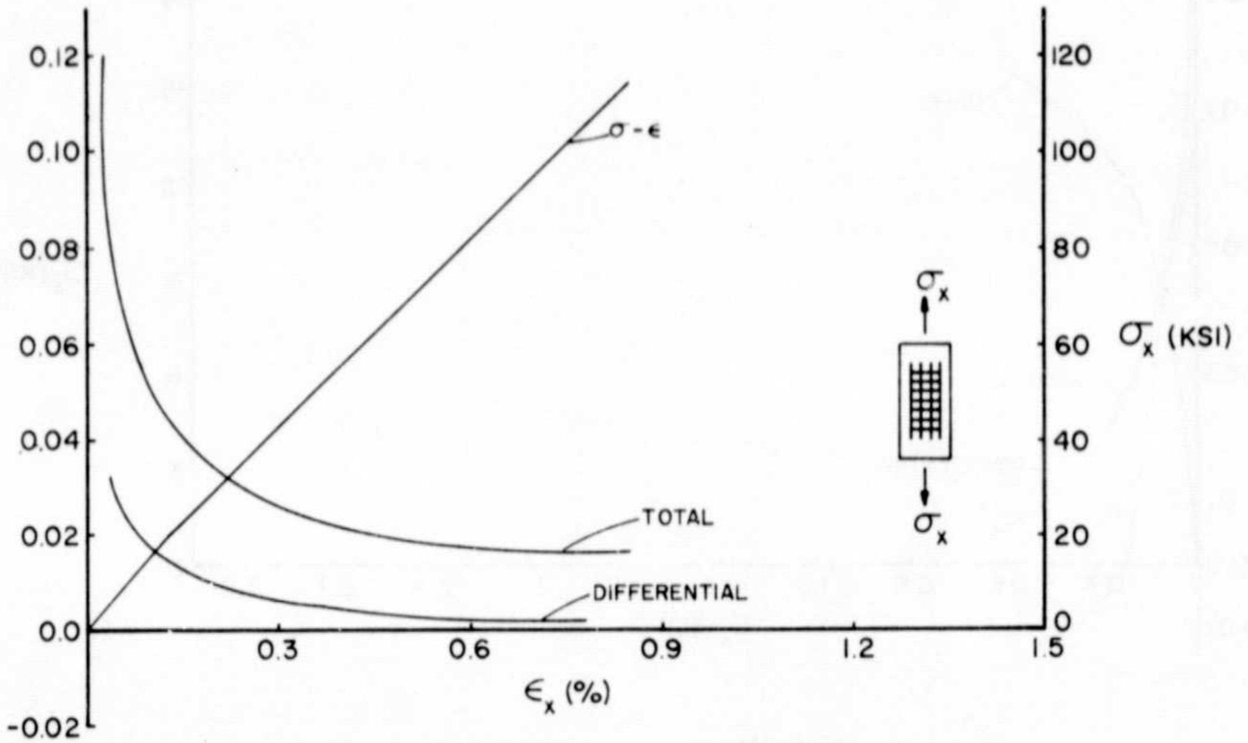


a) TENSION

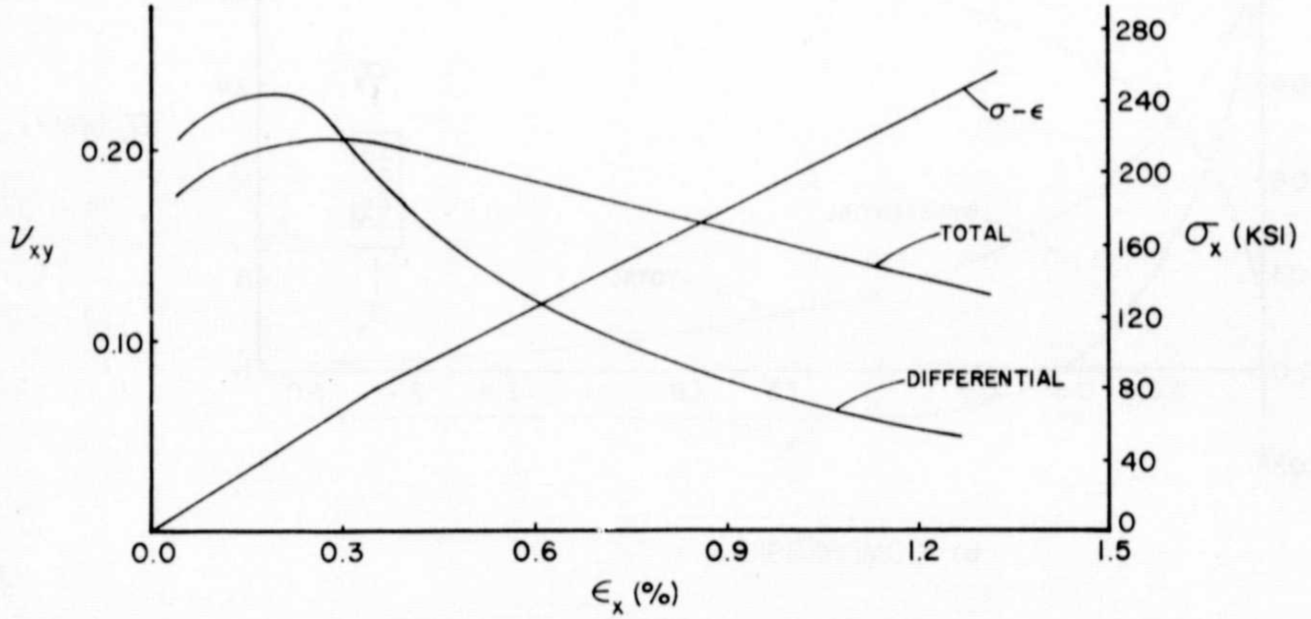


b) COMPRESSION

FIG. 3 POISSON'S RATIO ν_{21} FOR [0] Gr/E

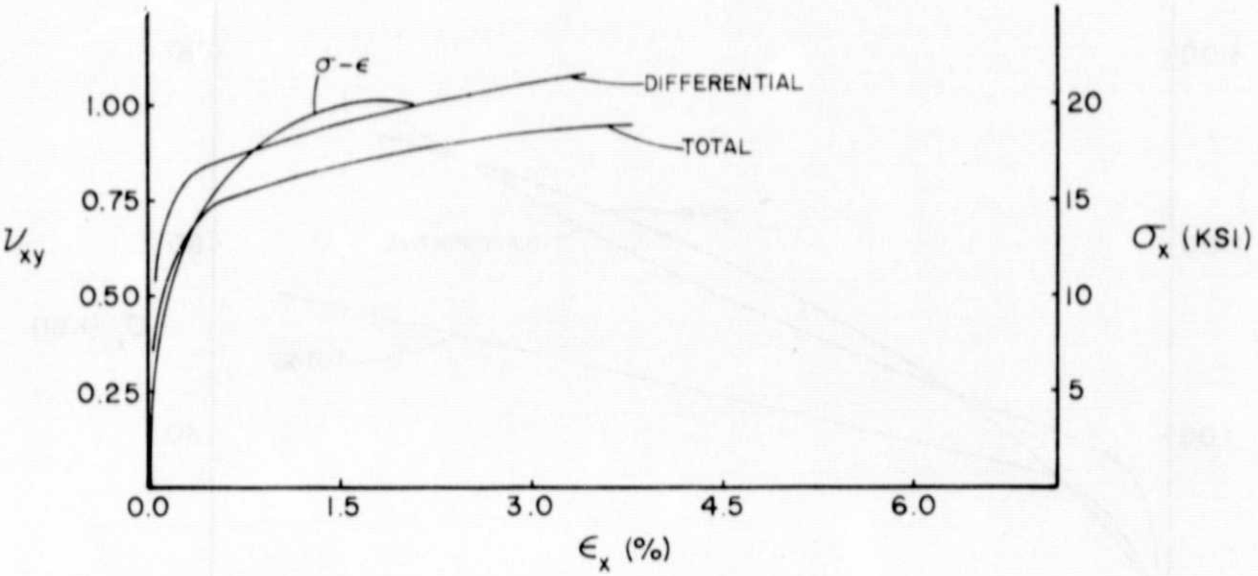


a) TENSION

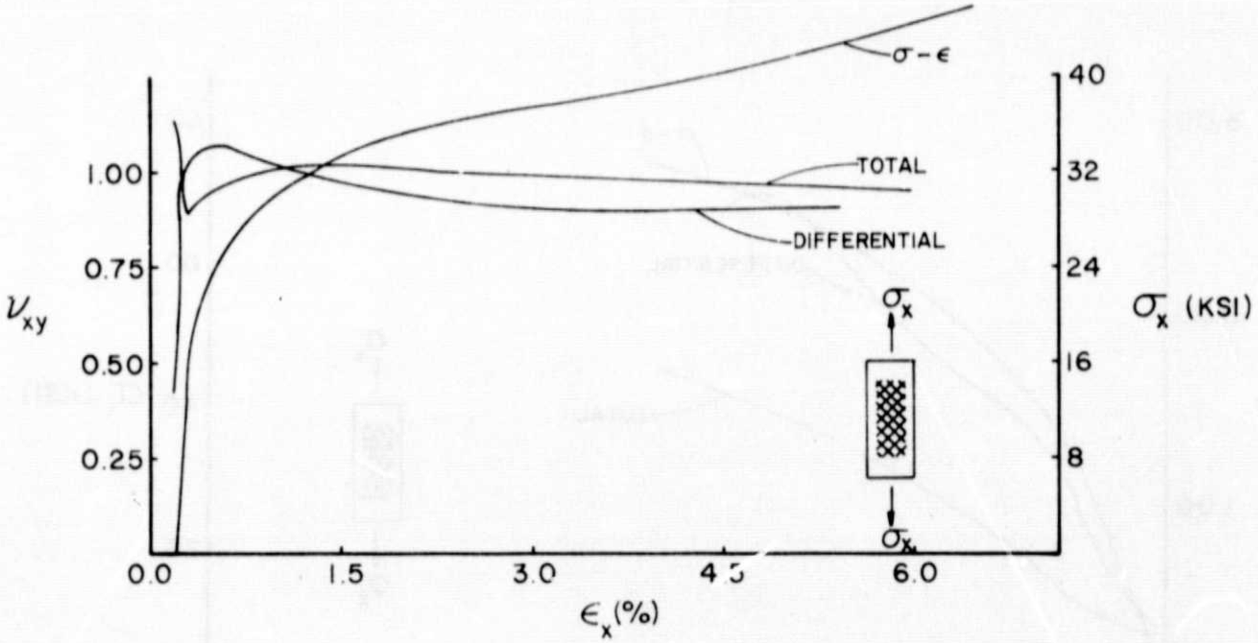


b) COMPRESSION

FIG. 4 POISSON'S RATIO ν_{xy} FOR $[0/90]_s$ Gr/E

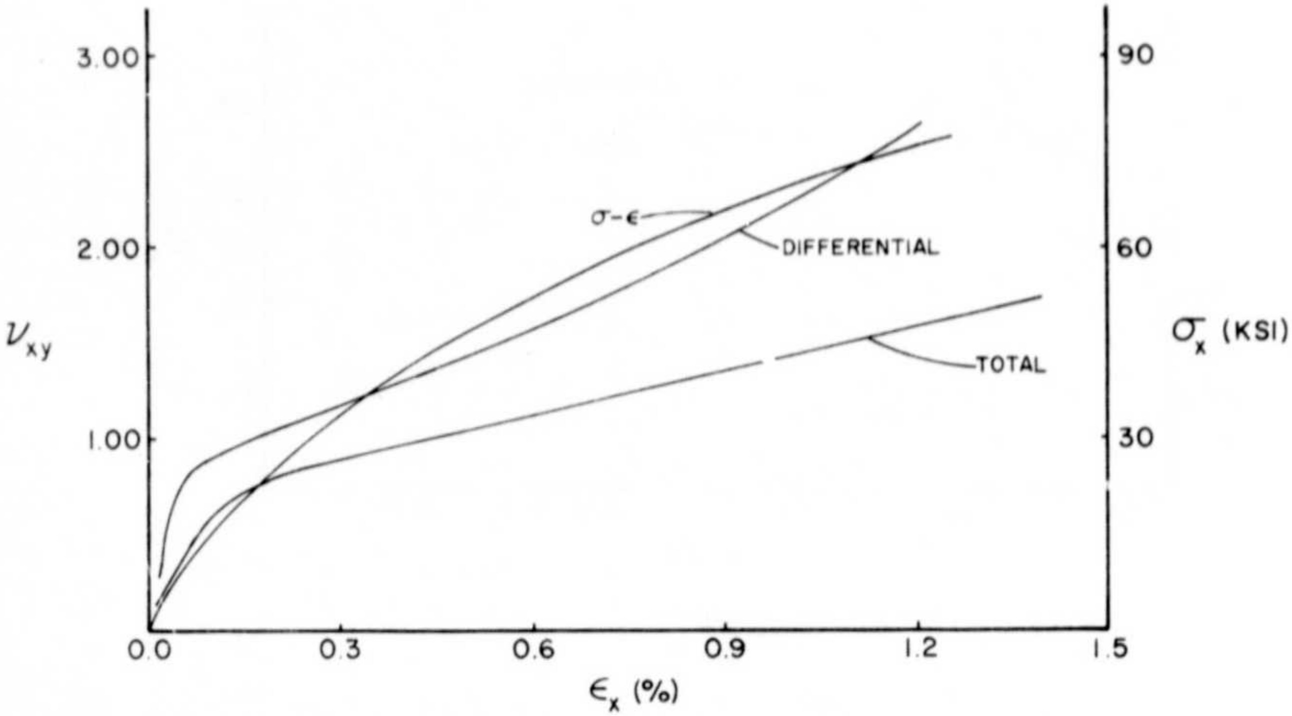


a) TENSION

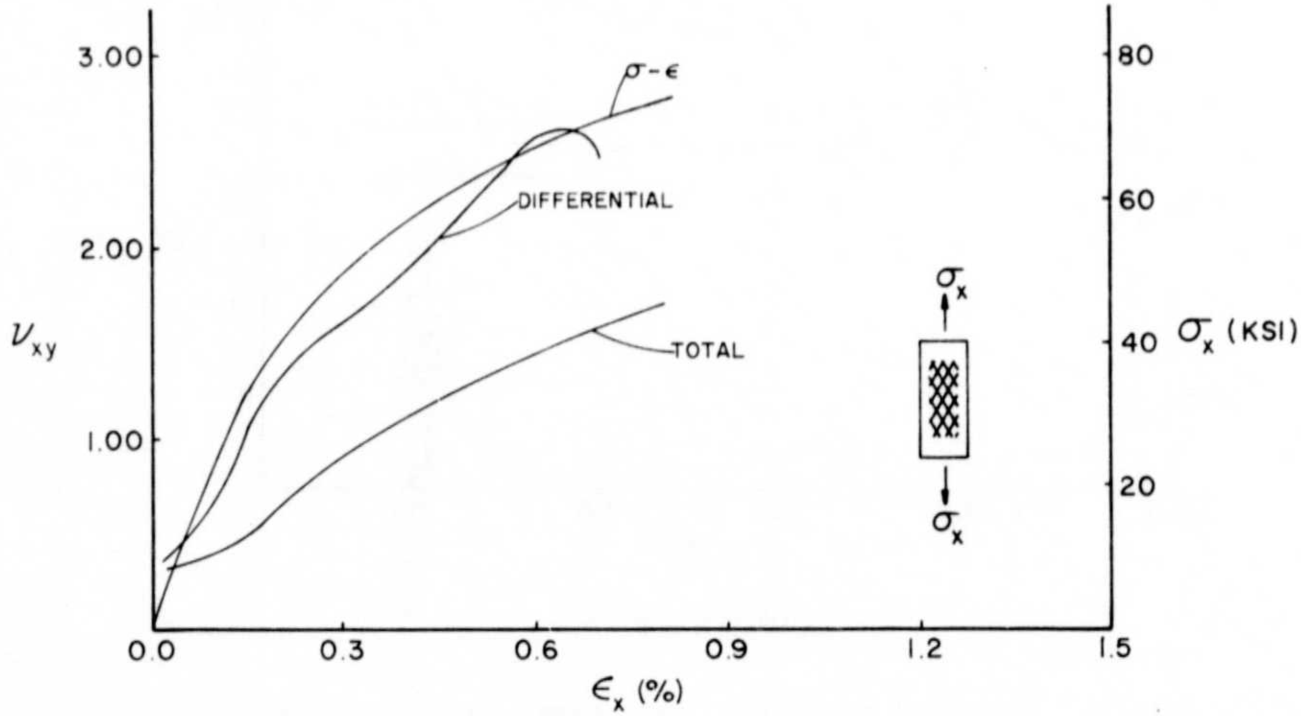


b) COMPRESSION

FIG.5 POISSON'S RATIO ν_{xy} FOR $[\pm 45]_s$ Gr/E



a) TENSION



b) COMPRESSION

FIG.6 POISSON'S RATIO ν_{xy} FOR $[\pm30]_s$ Gr/E