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EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF THE DUCTILE FRACTURE OF POLYMERS

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by

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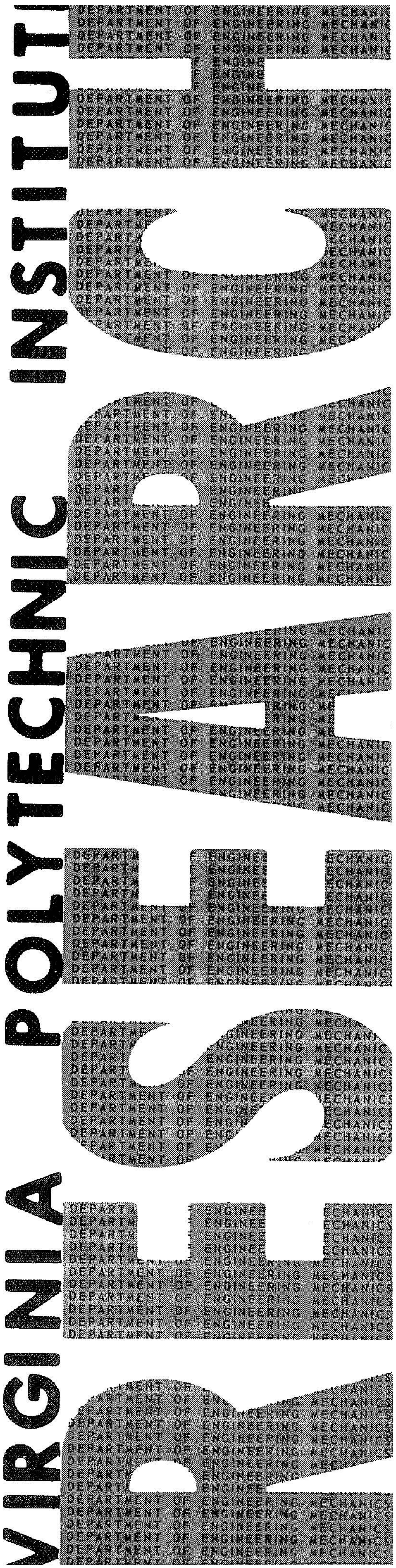

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INTRODUCTION

The objectives of the current research program sponsored under NASA grant NGR-47-004-051 was to study the ductile fracture of polymers both analytically and experimentally. The reason for the study, of course, was to gain some insight into the ductile behavior of polymers, or more paticularly, the ductile failure and/or fracture of polymers. Very little information about ductile fracture of polymers exists in the literature in contrast to the relatively large body of information that exists for the brittle fracture of polymers. [1]

Polycarbonate (lexan) was selected for this study because of its unique ductility properties and because its stress-strain behavior is very similar to that of mild-low carbon steel. Other reasons for its selection were its high birefrigence, and because some information about its properties exist in the literature [2,3,4,5] thus providing a basis of comparison.

The experimental aspects of the program represent a logical extension to this authors earlier work on the ductile fracture of polycarbonate [4]. In this work it was shown that the Dugdale theory of ductile fracture could be applied to polycarbonate [4]. Measurement of plastic zone sizes and crack opening displacements compared favorably with Dugdale's theory for the case of a tensile strip with a central crack loaded under plane stress (mode I) conditions.

The various experimental phases to be investigated in the current program include:

1. The measurement of the plastic zone size and strain energy release rates as a function of thickness, strain rate and temperature.

2. Making microscopic photoelastic photographs of the yield zone and concurrent measurement of thickness changes in the yield zone.

3. Measuring the size and shape of the plastic zone when the axis of the crack is rotated with respect to the axes of orthotropy.

4. Careful measurement of orthotropic properties.

Progress in items two and four are now nearly complete and will be reported briefly in the subsequent section. Results on items one, three, and four are anticipated in the near future.

The analytical phase of the program, which consists of incorporating thickness changes into the derivation of strain energy release rates and the extension of Dugdale's solution for ductile fracture to include general anisotropy, are currently under way with the latter nearing completion. These aspects will only be reported briefly here with a more detailed reporting to be made at a later date.

SUMMARY OF EXPERIMENTAL RESULTS

Orthotropic Properties

In both the work of Gurtman, et al, and Brill polycarbonate was assumed to be isotropic [2,3]. However, Brinson has indicated that the same material, as supplied by some manufactures, is slightly orthotropic and that the degree of orthotropy was approximately $E_y/E_x=1.1-1.2$ for the material used in reference [4]. Thus, initially, tests were conducted on remnants of the same batch as used in reference [4] to determine the degree of orthotropy. These tensile tests were performed with the aid of an MTS testing system operated at a constant elongation rate of .025in/min. Strains were measured with an optron optical tracking system. The results of seven separate stress-strain tests on three coupons taken parallel to the roll direction (strong direction) of the material and four coupons taken perpendicular to the roll direction (weak direction) are summarized below in TABLE I.

TABLE I
Principal Orthotropic Moduli of Polycarbonate

	$E_{\parallel}$ (Modulus in roll direction)	$E_{\perp}$ (Modulus transverse to roll direction)
	343,000 psi	277,000 psi
	352,000 psi	305,000 psi
	350,000 psi	280,000 psi
		309,000 psi
average	348,000 psi	293,000 psi

As can be seen the degree of orthotropy is $E_1/E_2=1.19$ and is close to the expected value.

In any linear elastic orthotropic analysis four material parameters must be measured in contrast to only two parameters which are needed in the linear elastic isotropic case. The simplest four to measure are E_1, E_2, μ_{12} and μ_{21}, where E_1 and E_2 are principal moduli of elasticity and μ_{12} and μ_{21} are the principal Poison's rates of a material (see reference [6]). Unfortunately, the test previously mentioned in obtaining the data in TABLE I exhausted the supply of material contained in that particular batch. Thus, more material was ordered and tested. Tensile tests were conducted on the new batch of material and no significant orthotropy was found. Apparently, in the three years between the purchase of the two separate batches of materials, the manufacturing process had changed in such a way that the roll direction of the material could not be discerned. At the present time tests are being conducted to assertain if it is possible to orient the molecular structure of the material by stretching at high temperatures. In this way it should be possible to manufacture the type and degree of orthotropy desired. This would be extremely advantageous inasmuch as it would permit anyone to independently manufacture or obtain a material with the same orthotropic properties thus allowing better comparison of data from a wide variety of sources.

Thickness Measurements in Yielded Regions

The original intent of the author was to measure thickness changes and isochromatic fringes orders in the Dugdale type yield zone which precedes a crack as outlined and suggested in reference [4]. It was hoped to make these measurements in situ. However, after several attempts it was realized that such measurements in situ represented a much too formidable task. Consequently, tensile specimens were stressed beyond the yield point until a finite yield zone was developed. Once the yield zone was fully developed across the width of the tensile specimen, all external load was removed. Permanent displacements, thickness changes and isochromatic fringes remained in the yield zone as shown in FIGURE I. Thickness changes and the isochromatic fringes orders were measured along ten vertical lines across the yield zone. A typical comparison of the results along one of these lines is shown in FIGURE 2.

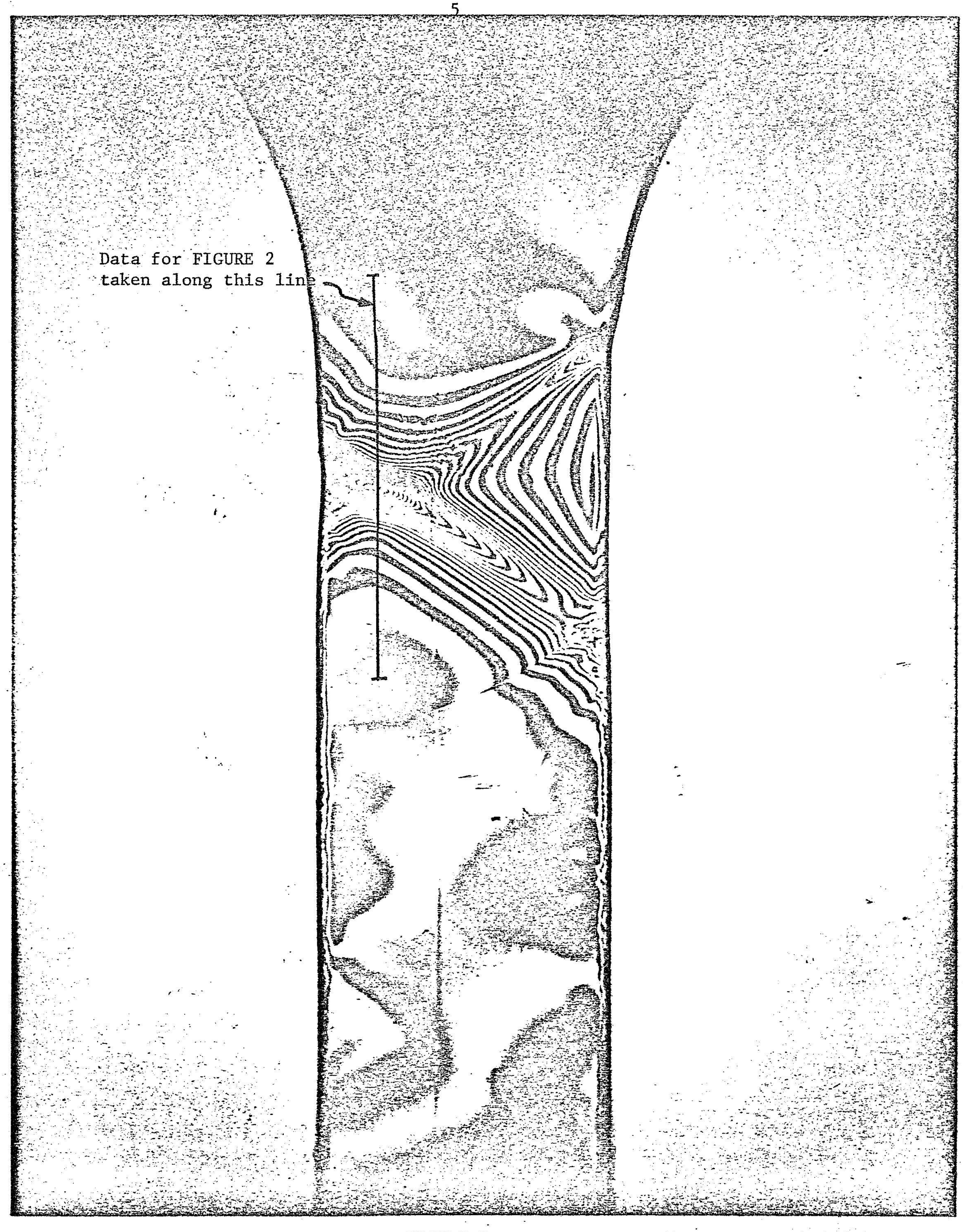

FIGURE 1
Isochromatic Photograph of Permanent Yield Zone in Polycarbonate

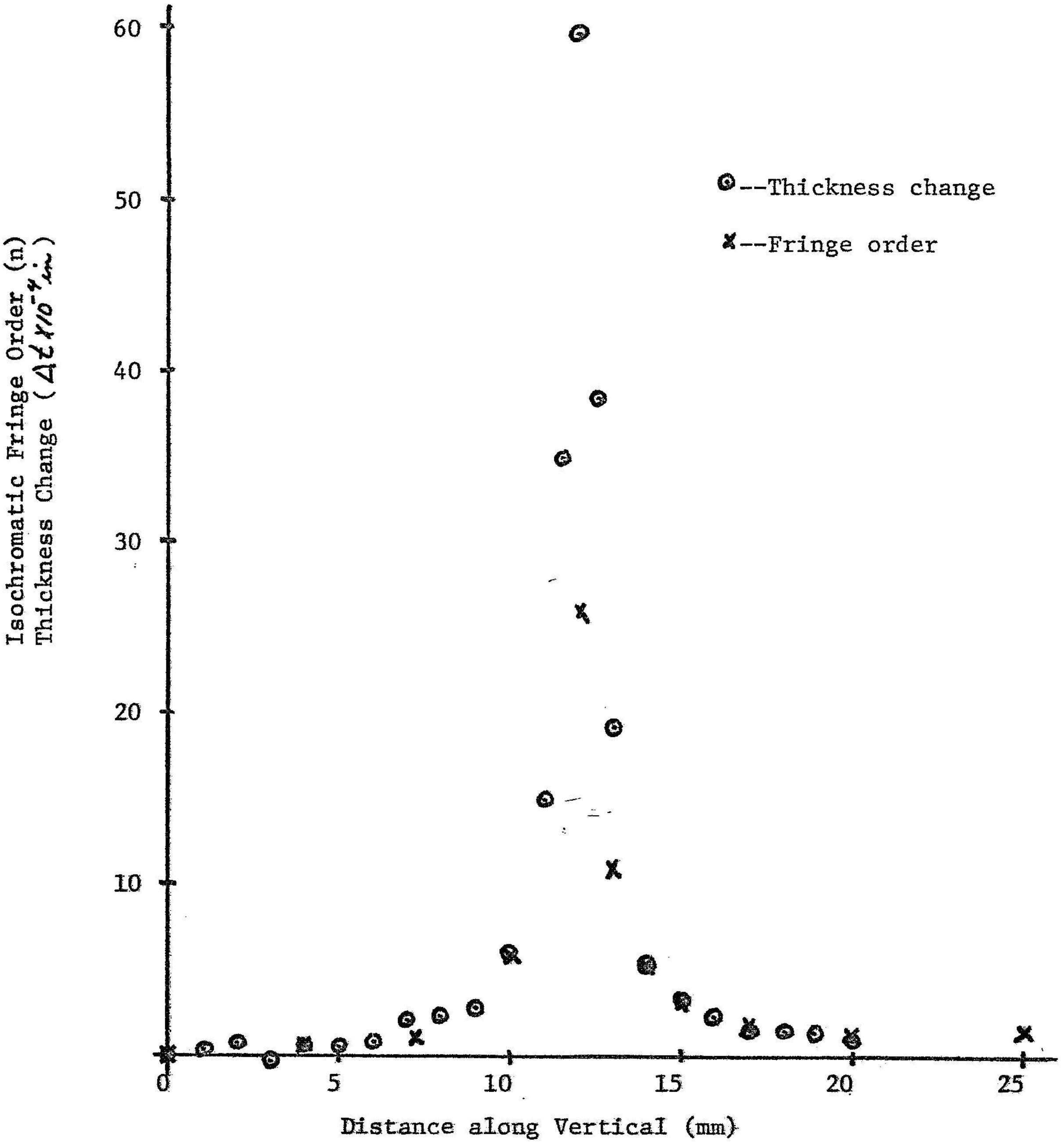

FIGURE 2

Variation of Thickness Change and Isochromatic Fringe Order Across Yield Zone as Indicated in FIGURE I.

Although qualitative agreement in all cases were excellent, quantitatively it was not possible to determine the exact relationship between thickness change and isochromatic fringe order in the plastic zone. Nevertheless, the author does feel that qualitatively, at least, the hypothesis on photoplasticity proposed in reference [4] is indeed correct. Holography has been used and is currently being used to get a second independent verification of the quatitative relationship between thickness change and isochromatics in the plastic zone. These results will be detailed in a later report.

Summary of Analytical Results

The stress functions, stresses, and displacements have been ascertained for the anisotropic Dugdale Model. As in the orthotropic case [7], it is possible to show that the results defer from the isotropic case only by a constant amount which depends on the anisotropic properties of the material. These results can be indicated mathematically,

$$f_a = (e_a)_k f_i \qquad (1)$$

where f_a and f_i refer to the anisotropic function and isotropic function respectively and $(e_a)_k$ refers to the anisotropic properties. For example, the stress along the line of the crack (y=0) is found to be

$$\sigma_{xx} = [\beta_1\beta_2 - \alpha_1\alpha_2] \frac{2Y}{\pi} \tan^{-1} \frac{\sin 2\vartheta_2}{X^2 - \cos 2\vartheta_2} \qquad (2)$$

where the term in brackets represents the anisotropic properties, the remaining terms represent the isotropic solution to the Dugdale Model, Y is the yield stress of the material, and $\vartheta_2 = \cos^{-1} \ell/a$ with ℓ being the half crack length and a being the sum of half length of the crack and plastic zone length. This result specialized to the orthotropic case is shown plotted in FIGURE 3.

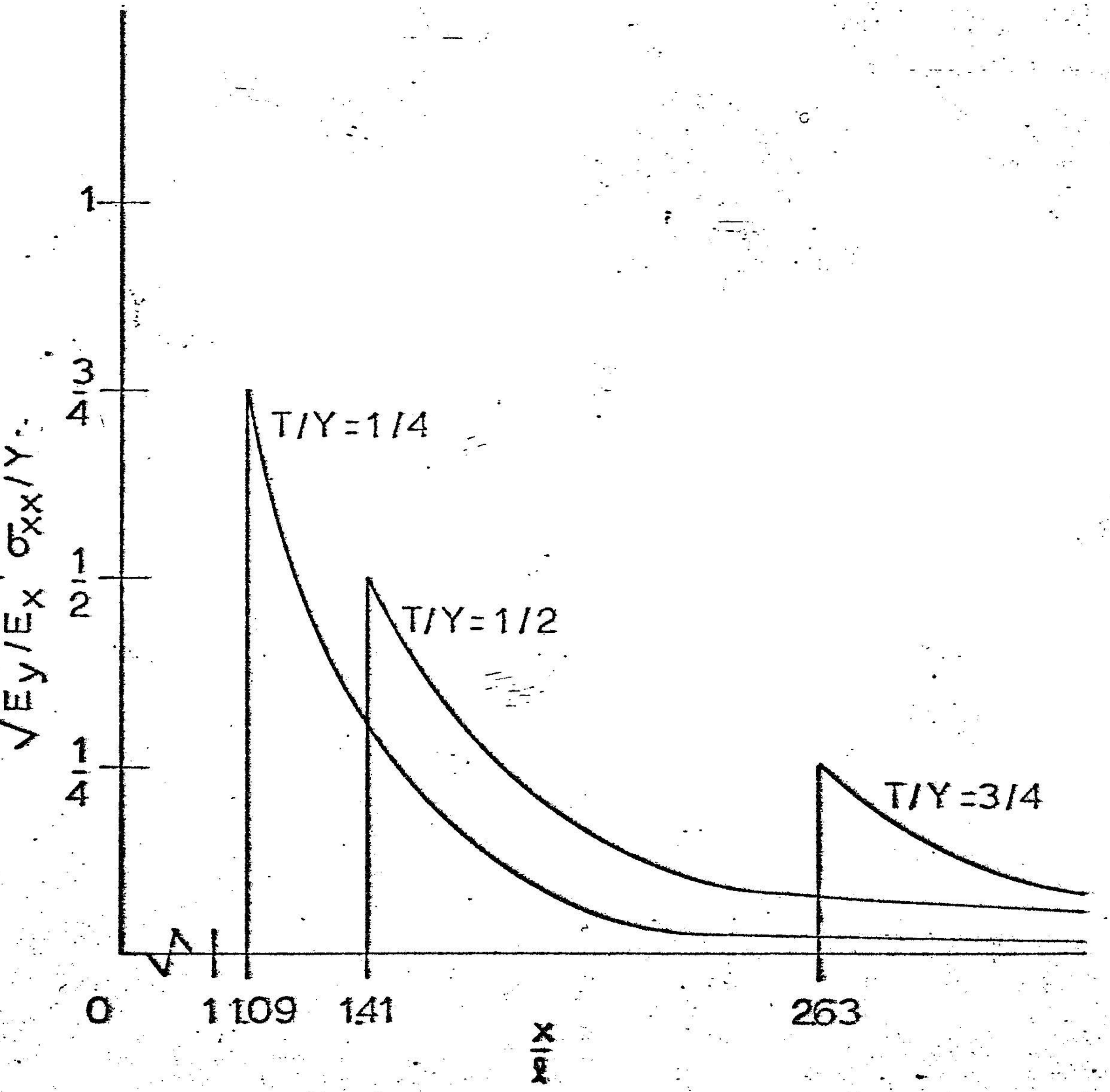

Figure 3

σ_{xx} STRESS ALONG x-AXIS FOR ORTHOTROPIC STATIC DUGDALE MODEL

More detailed results of this anisotropic solution will be reported at a later time.

CONCLUSIONS

The foregoing remarks represent a brief summary of the work to date on NASA Grant NGR-47-004-051 and are not meant to be inclusive or unclusive. Results of both the experimental and analytical phases are continuing. Portions of both are expected to be submitted for publication in technical journals shortly.

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