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FATIGUE CRACK PROPAGATION RATES IN WOVEN AND NON-WOVEN FIBERGLASS LAMINATES

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ABSTRACT

The characteristics of fatigue crack propagation are described for fiberglass laminates containing woven fabric, woven roving, chopped fiber mat, and unidirectional ply reinforcement. The mode of crack propagation is shown to be a stepwise, ligament by ligament advance of the crack front. The rate of crack propagation is predicted to vary exponentially with the stress intensity factor by an approximate theory based on the fracture toughness, unnotched fatigue life curve, and microstructural characteristics. Good agreement is demonstrated between theory and experiment for each material. The crack growth rate data are normalized to a single relationship for all woven reinforcements, and to a second relationship for non-woven reinforcements.

Key Words: fatigue, fatigue crack growth rate, fiber reinforced plastics.

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INTRODUCTION

The rate of fatigue crack growth in metals has been the topic of numerous studies which have, in most cases, established a linear relationship between the rate of crack growth, dc/dN, and some power of the range of the stress intensity factor, K_I [1]. A recent study of fatigue crack propagation in a 0°/90° crossplied glass/epoxy laminate [2] indicates an exponential relationship between dc/dN and K_I which can be predicted by an approximate theory. The present paper describes the development of an improved test specimen for measuring fatigue crack growth in certain composites and compares theoretical and experimental crack growth rates for several important classes of fiberglass laminates typical of marine applications.

THEORY

The mode of fatigue crack propagation in crosspied 0°/90° glass/epoxy has been described previously [2] as a series of ligament failures. As dipcted in Figure 1, the crack tip in the 0° plies (plies having fibers perpendicular to the crack) remains stationary in a given position for a number of cycles of stress until a ligament of material fails, whereupon the crack extends by one ligament width, d, and the process is repeated. Thus, the main crack extends in a stepwise fashion and the crack growth rate is taken as the ligament width divided by the number of cycles necessary to fail the ligament. For purposes of discussion, crack extension is defined as extension of the main crack in its original direction as distinct from extension of the subcrack parallel to the fibers.

The rate of crack growth may be predicted by an approximate theory which assumes that the ligament of material at the crack tip fails according to the fatigue life curve of an unnotched strip of material, but at the local crack tip stress level [2]. If the stress vs. log cycles to failure (S-N) curve for the material can be approximated as linear over the stress domain of interest, then the fatigue life of the ligament will be given by

$$\log N = \frac{\sigma_f - \sigma_\ell}{S} \tag{1}$$

where σ_f is the ultimate tensile strength at the appropriate strain rate, σ_ℓ is the local stress in the ligament, and S is the slope of the S-N curve. The value of σ_ℓ is determined by assuming a linear increase in local stress with K_I up to the critical stress intensity factor, K_Q, at which point σ_ℓ must equal σ_f, so that

$$\sigma_\ell = \sigma_f \left(\frac{K_I}{K_Q}\right) \tag{2}$$

Substituting (2) into (1), the crack growth rate for a ligament width d will be

$$\frac{dc}{dN} = d/\exp\left[2.3\ \frac{\sigma_f}{S}\ (1 - K_I/K_Q)\right] \tag{3}$$

Although Equation (3) neglects cumulative damage effects for ligaments ahead of the crack tip, Ref. [2] has indicated that for ligament widths of 0.25 mm. and greater, such effects are negligible because of the high stress gradients in the crack tip region.

MATERIALS AND TEST METHODS

The four types of E-glass reinforcement used in the study are described in Figure 2 and Table 1; in each case the fibers were supplied with a polyester compatible finish by the manufacturer (Uniglass Ind.). The matrix used in all cases was Laminac 4155 (American Cyanamid Co.) with 0.5% MEK peroxide. Laminates were fabricated by hand lay-up followed by compression molding at 0.35 MN/m^2 and room temperature for one day, then postcure at 100°C for two hours.

Test specimens were machined to the sizes indicated in Figures 4 and 6 using a diamond-edged wheel and TensilKut router; the initial crack was cut with a 0.63 mm. thick diamond-edged wheel. Unnotched tension specimens for woven roving laminates were machined to a larger size, 3.8 cm. wide in the gage section, due to the increased material hetrogeneity. Ultimate strength and K_Q values were obtained at the displacement rates indicated in Table 1 using an Instron universal or Model 1251 machine; because of the strain rate dependence of strength and toughness [3], tests were conducted at a similar strain rate to that used in the fatigue tests. Fatigue crack growth data were obtained on an Instron Model 1211 dynamic cycler at constant load amplitude with an approximately sinusoidal load vs. time variation at a frequency of 4-7 Hz. All fatigue loading was approximately 0-tension, with a minimum load of 0.5 MN to avoid gripping problems. Tests were conducted in an uncontrolled laboratory environment using wedge-action grips for unnotched specimens and pin loading for crack growth specimens. A replication factor of four was used in all monotonic tests.

The value of stress intensity factor was determined from the relationship [4]

$$K_I = \frac{3.46\,P\,(\frac{C}{H} + 0.7)}{BH^{1/2}} \tag{4}$$

where P is the applied force in MN and B is the thickness (B,C, and H are in meters). This relationship was derived for isotropic constants and is in slight error when applied to anisotropic materials, but has been found to give invariant toughness results for various crack lengths in laminates similar to those used in this study [5]. In all cases the crack was propagated parallel to the warp direction of fabric reinforced samples to reduce instances of deviation of the crack from the intended direction of propagation.

RESULTS AND DISCUSSION

The ligament by ligament nature of crack propagation was observed for all materials tested in this study. The ligament width, d, was clearly evident from polished cross-sections for the woven reinforcements as shown in Figure 3; the ligament width for the random chopped mat laminates was less definite, and an approximate value was determined from crack length vs. time curves.

Figure 4 indicates that the S-N curves for unnotched samples were typically linear down to some low stress level, where a knee in the curve was evident for woven fabrics. The approximately linear portions of the S-N curves in Figures 4 and 5 were fit by a least squares program to obtain values for σ_f and S to be used in the dc/dN prediction for each material. The relatively steep S-N curves for the woven materials apparently result from the development of cracks at the crossover points of the weave [6]; such cracks are clearly observable (see Figure 9), and are quickly followed by failure in the case of the unnotched samples. Table 1 gives the experimentally determined values for d, σ_f, S, and K_Q to be used as material properties in Equation (3).

Figures 6 and 7 indicate approximate agreement between experimental and predicted crack growth data for all four materials. Figure 8 indicates that all data along with previous data for glass/epoxy [2] can be normalized to fall along one of two lines when plotted K_I/K_Q vs. log (dc/dN)/d. All of the woven reinforcement data fall along a line given by Equation (3) with $\sigma_f/S = 6$, while data from the non-woven materials fall along a line given by $\sigma_f/S = 10$. The scale for $(K_I)_{max}$ in Figures 6 and 7 was expanded because of the steepness of the curves; in conventional metals technology dc/dN varies with K_I to some power, typically in the range of 3-6 [1], while the results in Figures 6 and 7 indicate approximate exponents between 9 for the woven roving and 13 for the chopped fiber mat if the data are approximated by a straight line.

Several problems were encountered in the development of the fatigue crack growth test. The cleavage-type sample without side-grooving is useful only for materials in which the crack has a strong tendency to propagate down the length of the specimen; if the woven roving, for example, were oriented with the warp direction perpendicular to the specimen length, the crack would still propagate parallel to the warp, perpendicular to the desired direction. Heating of the crack growth specimens at high frequencies was also a problem. Although preliminary tests did not indicate a significant dependence of dc/dN on frequency below 10 Hz, some specimens, particularly the woven roving, became warm to the touch near the crack tip; however, the heating problem was not studied in detail. Difficulty was also encountered in measuring the crack length because of the stepwise nature of the crack growth and the extensive damage region associated with the crack tip. The lack of any fatigue striations typical of homogeneous materials [1] made it necessary to estimate the position of the crack tip on the specimen surface by optical inspection at low magnification.

The reduction of the test data by classical fracture mechanics techniques may have introduced some inaccuracy. Although fundamental aspects of the applicability of classical fracture mechanics to similar materials have been questioned in the past [3], recent unpublished analytical modeling of subcracking of the type shown in Figure 1 indicates that the $r^{-1/2}$ stress singularity is maintained for inplane stresses outside of a very local region at the immediate crack tip. Other studies [3,7] have suggested that a crack length correction factor should be applied to account for subcracking at the crack tip, but results for the cleavage-type sample with its longer crack length suggest that such a correction factor is unnecessary [5]. The use of an isotropic K-calibration introduces some error which will vary with the degree of anisotropy [5] as discussed previously, and the combined effects of microcracking for significant distances away from the crack tip and near the loading points, evident in Figure 3, and the effects of time on the modulus in regions of high stress may further alter the K-calibration. Another possible complication is the use of specimens of different thickness for the unnotched and crack growth tests; however, previous results have indicated no significant effect of laminate thickness on K_Q over a broad range for similar materials [3].

The results in Figures 5-8 provide convincing evidence that the fatigue crack growth rate for these specific materials and testing conditions can be deduced from the fracture toughness and S-N parameters combined with microstructural observations. The underlying mechanisms which lead to the fatigue failure are contained in the S-N curve, and the results suggest that no additional mechanisms are introduced by the sharp crack. Other investigators have associated the fatigue failure of unnotched material with the extension of microcracks [8] and the formation of cracks at the weave crossover points [6]. The absence of macroscopic heating in the unnotched specimens suggests that fatigue failure may result from local stress concentrations in the vicinity of microcracks or the abrasion of the exposed fibers as the microcracks open and close in fatigue; the latter explanation appears to be particularly likely in the case of the woven fabric where the crack formed at the weave crossovers is relatively large and significant friction is to be expected during cycling.

Analytical procedures are not yet available for the prediction of the ligament size, but it is observed to be approximately 0.025 to 0.050 cm. in all cases except for the random chopped mat. The apparent ligament size for the random chopped mat samples appears to be more a function of statistical point to point variations in fiber content and orientation rather than any fundamental mechanism which may be operable in the other cases.

CONCLUSIONS

It appears that the relationship between the fatigue crack growth rate and the stress intensity factor can be predicted by Equation (3) for a variety of fiberglass laminates using the S-N curve as a material property, for the simple case of pulsating opening mode loading. The crack growth rate curves can be normalized to a single relationship for all woven reinforcements tested, and to a second relationship for non-woven reinforcements.

ACKNOWLEDGEMENTS

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TABLE 1 - PHYSICAL AND MECHANICAL PROPERTIES[a]

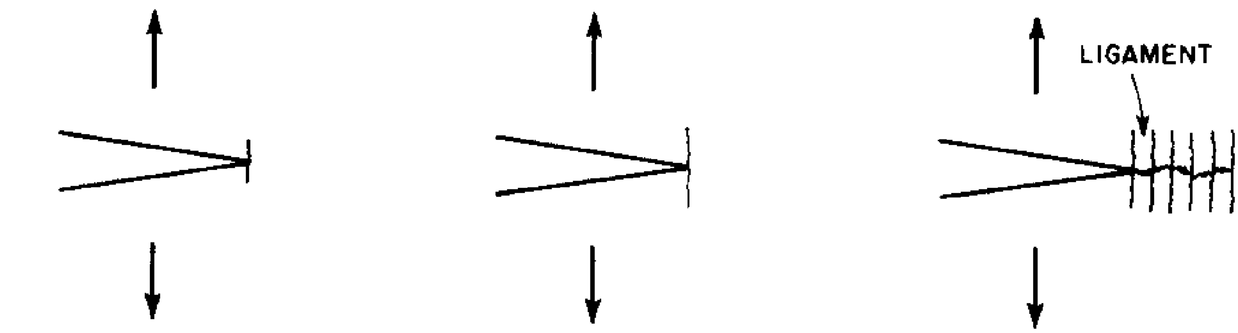
		Woven			Non-Woven	
Reinforcement (E-glass)		Fabric Style 181	Fabric Style 1800	Woven Roving Style 61	Chopped Fiber Mat	90/0/90/0/90 Crossplied[c]
Matrix		polyester	polyester	polyester	polyester	epoxy
Yarn Count Yarns/cm	Warp	22.5	6.3	1.6[b]	--	--
	Fill	21.3	5.5	1.6	--	--
Fabric Weave		satin	plain	plain	--	--
Fabric Weight (Kg/m^2)		0.303	0.329	0.611	0.458	--
No. Plies/Thickness (cm)	Specimen Unnotched	10/0.254	9/0.254	5/0.229	5/0.303	5/0.127
	Specimen Crack Growth	36/0.915	33/0.915	20/0.915	15/0.915	5/0.127
Fiber Volume Fraction		0.47	0.47	0.52	0.29	0.50
Ultimate Tensile Strength, σ_f (MN/m^2)[d]		429	339	450	134	418
Slope of S-N Curve, S[(MN/m^2)/decade]		70.8	58.0	71.9	12.9	42.5
K_Q ($MN/m^{3/2}$)[d]		32.3	26.7	45.4	14.0	26.4
Ligament Width, d (cm)		0.05	0.05	0.05	0.32	0.025

a - Fabric description is from manufacturer's data, thickness, fiber volume fraction and mechanical properties are average values, and ligament width is estimated as described in the text.

b - Although yarn count is balanced, the amount of fiber is approximately in the ratio of 5:8 in the fill:warp directions.

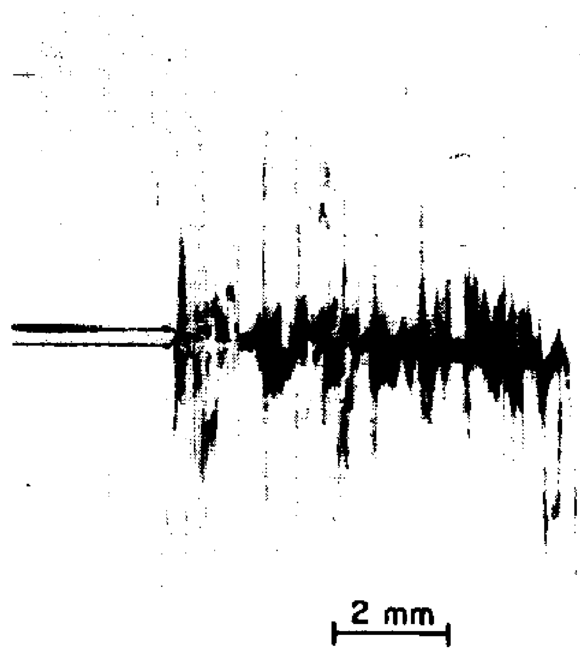
c - Scotchply Type 1002 unidirectional ply, 3M Co.

d - Monotonic tests were conducted at a displacement rate of 0.85 cm/s.



After first cycle After many cycles Stationary crack after 5 ligament failures

(a)
Schematic



(b)
Photograph of fatigue crack propagating from notch at left

FIGURE 1.
FATIGUE CRACK PROPAGATING IN 0° PLY OF
[90/0/90/0/90] GLASS/EPOXY LAMINATE.

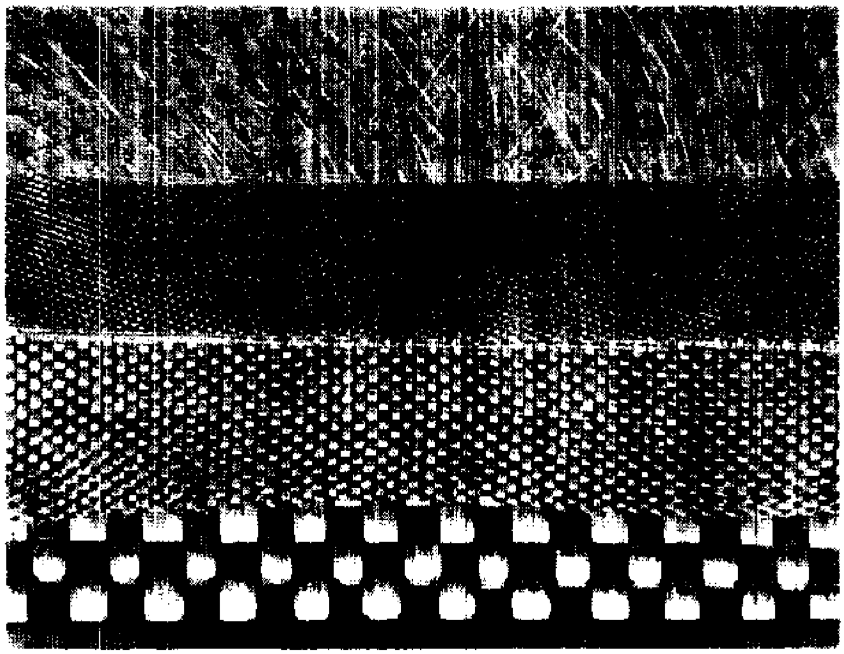
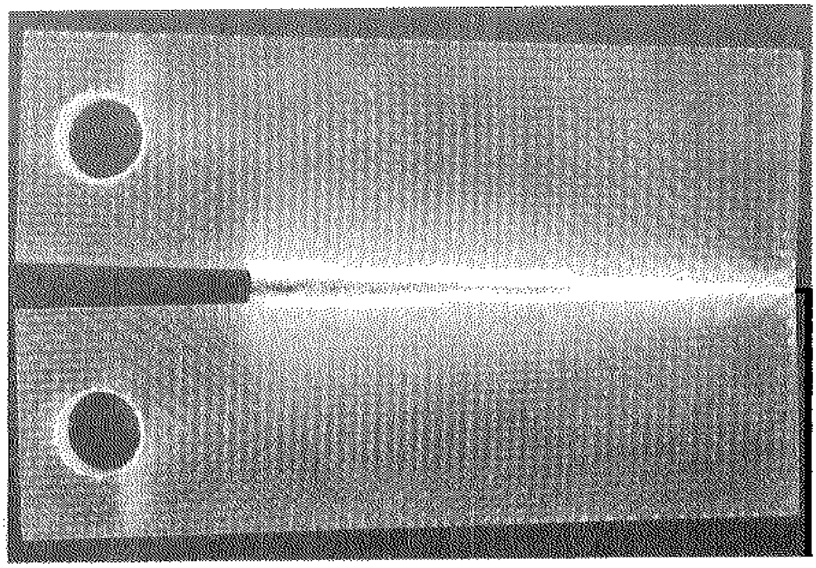
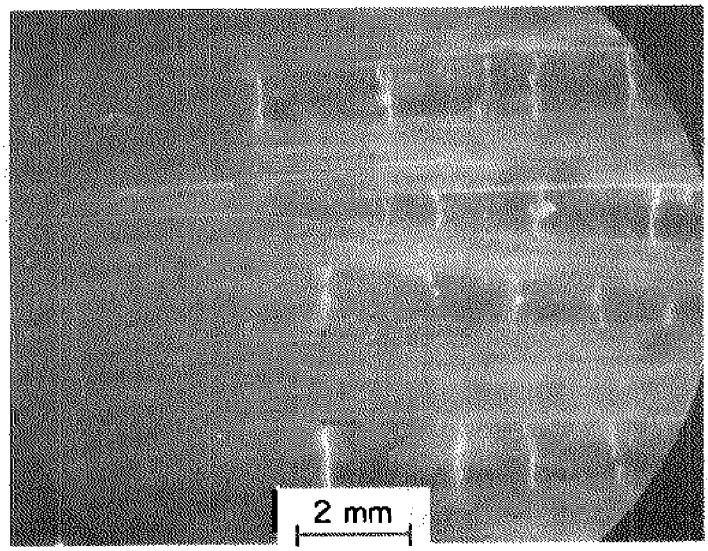


FIGURE 2.

TYPES OF E-GLASS FIBER REINFORCEMENT (TOP TO BOTTOM: RANDOM CHOPPED FIBER MAT, STYLES 181 AND 1800 WOVEN FABRIC, AND STYLE 61 WOVEN ROVING WITH CENTIMETER SCALE).



(a)
Fractured specimen, style 1800 fabric



NOTCH ——→|←CRACK GROWTH→

(b)
Cross-section of woven roving specimen taken parallel to the main crack plane, showing sub-critical splits.

FIGURE 3.

FRACTURED SPECIMEN AND CROSS-SECTION THROUGH LIGAMENTS.

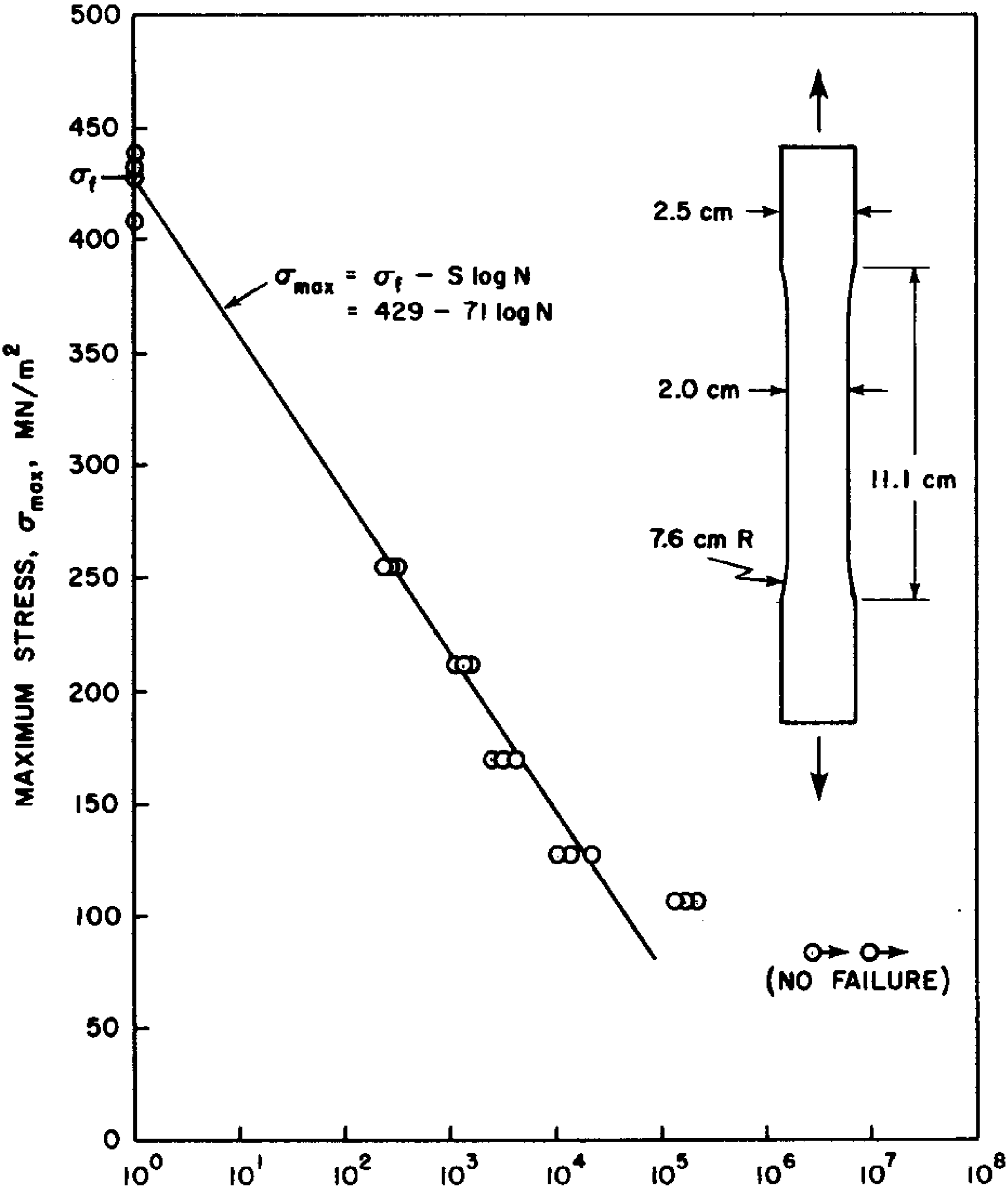


FIGURE 4.

UNNOTCHED STRESS vs. FATIGUE LIFE FOR STYLE 181 WOVEN FABRIC/POLYESTER MATRIX.

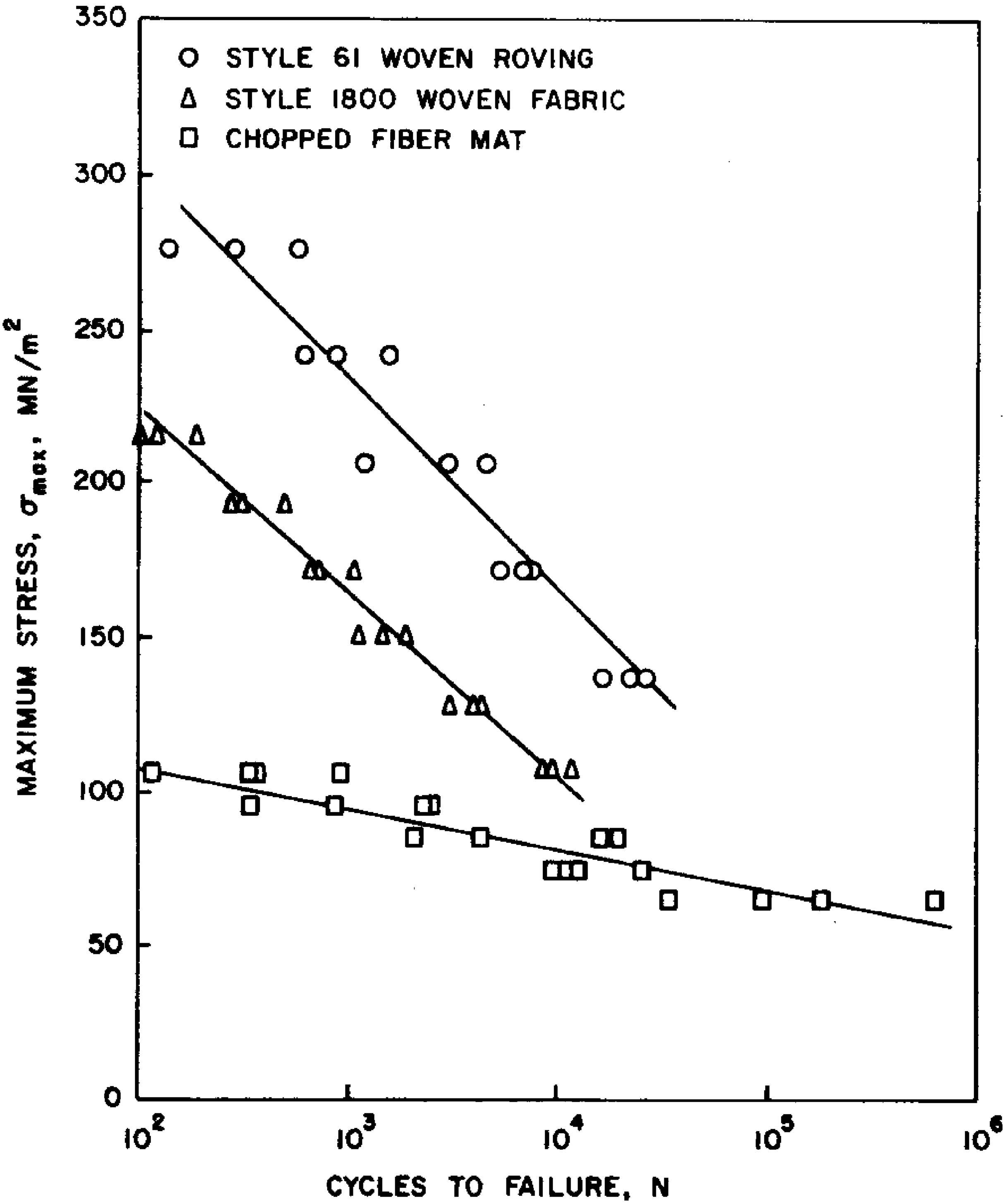


FIGURE 5.

UNNOTCHED STRESS vs. FATIGUE LIFE CURVES FOR VARIOUS REINFORCEMENTS/POLYESTER MATRIX.

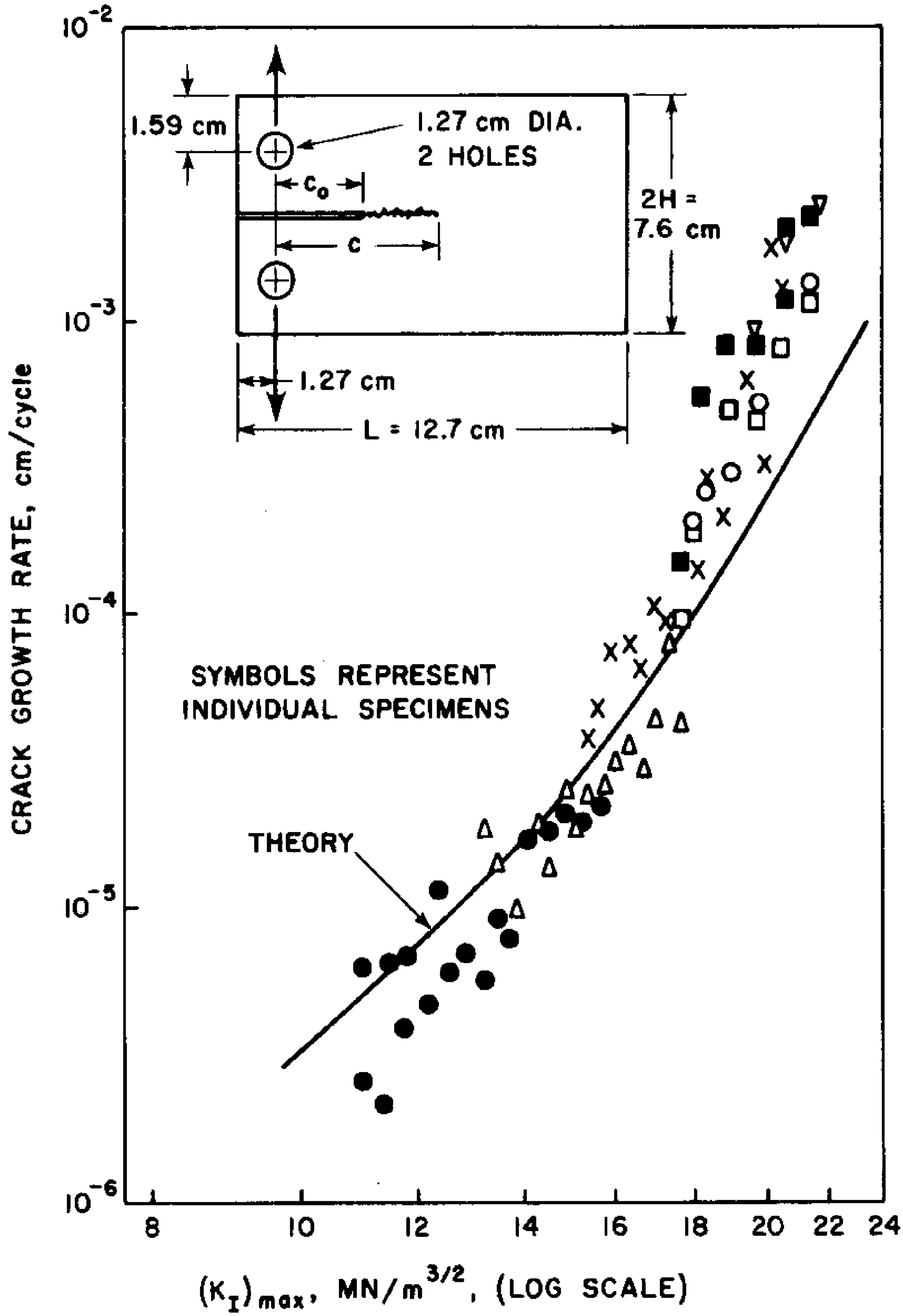


FIGURE 6.

THEORETICAL vs. EXPERIMENTAL FATIGUE CRACK GROWTH RATES FOR STYLE 181 E-GLASS WOVEN FABRIC WITH POLYESTER MATRIX.

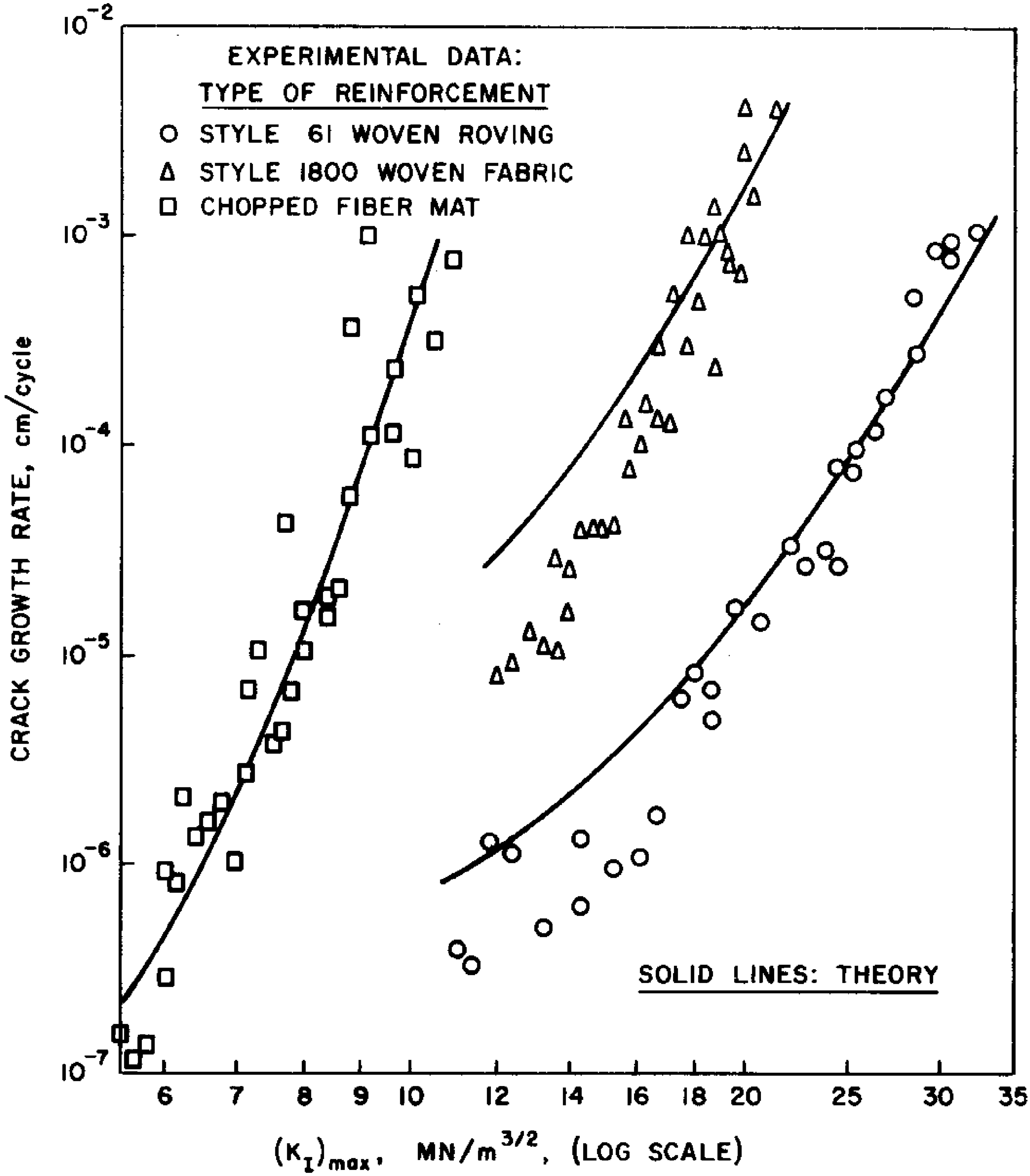


FIGURE 7.

THEORETICAL vs. EXPERIMENTAL FATIGUE CRACK GROWTH RATES FOR POLYESTER MATRIX WITH VARIOUS FORMS OF E-GLASS REINFORCEMENT.

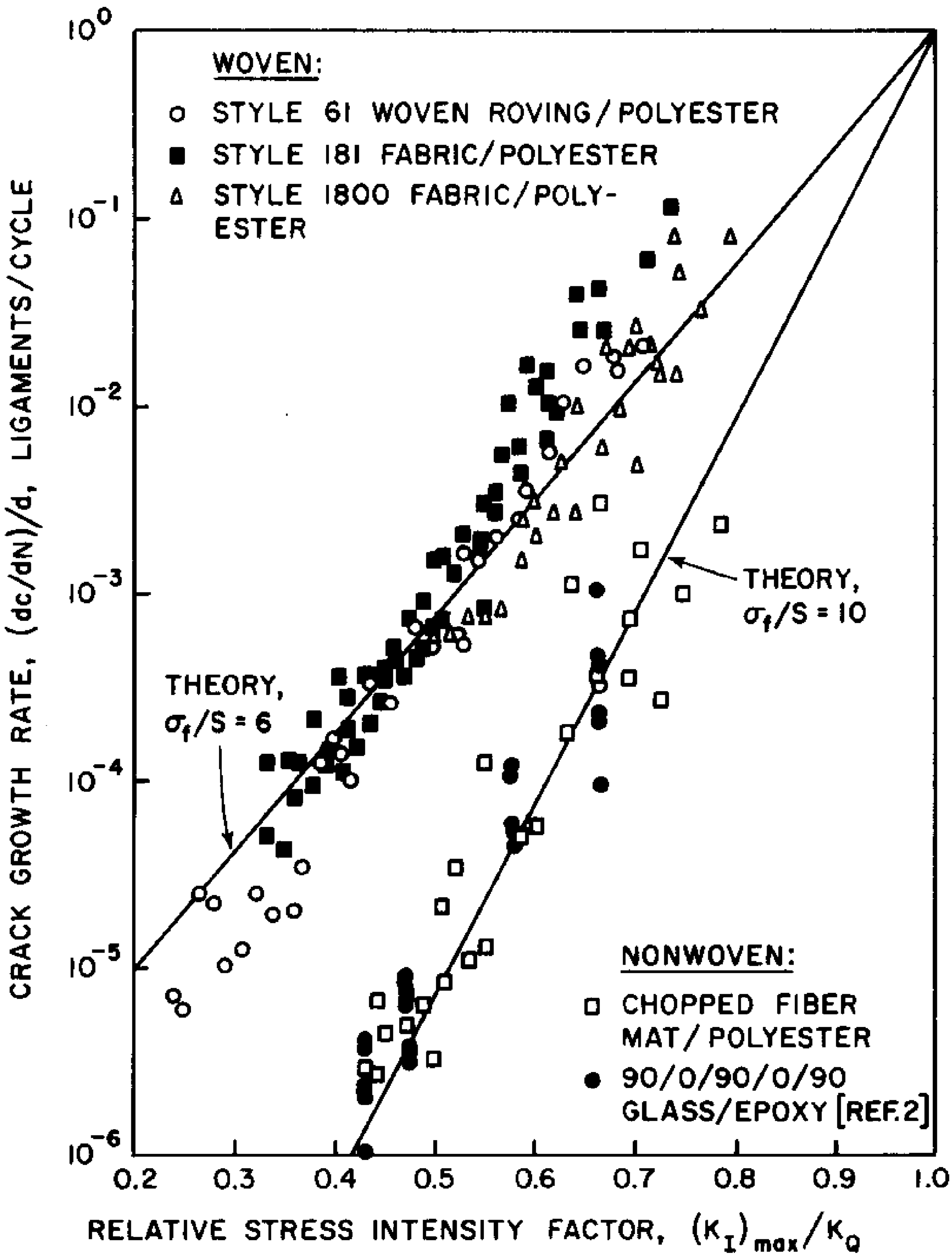


FIGURE 8.

NORMALIZED FATIGUE CRACK GROWTH RATE CURVES FOR FIVE MATERIALS.

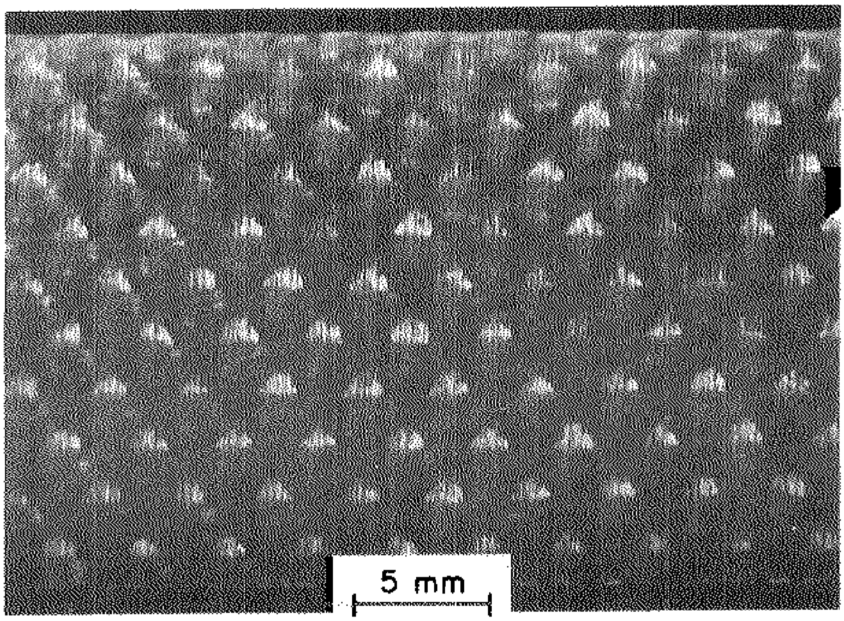


FIGURE 9.

FORMATION OF CRACKS AT WEAVE CROSS-OVER POINTS IN UNNOTCHED STYLE 1800 WOVEN FABRIC/POLYESTER SPECIMEN.