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EFFECT OF WATER ON THE CRACK PROPAGATION RATE IN FIBERGLASS LAMINATES UNDER STATIC AND DYNAMIC LOADING

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TABLE OF CONTENTS

ABSTRACT

The rate of stable crack propagation in fiberglass laminates has been investigated under static and dynamic loading conditions in wet and dry environments. Crack propagation rates were measured as a function of the stress intensity factor over several decades in each case, and total specimen lifetimes were also recorded. The dynamic crack growth data were in good agreement with predictions based on a simple theoretical model, but no accurate prediction of the static results was possible. The effect of water in each case was to increase the crack growth rate for dynamic (cyclic) loading, but to decrease the rate for static loading.

INTRODUCTION

The tendency to fail in a notch-sensitive, brittle fracture mode is characteristic of a variety of fiberglass laminates, including those based on chopped strand mat, woven fabric, woven roving, and 0°/90° cross-ply [1-3]. These laminates are also known to be sensitive to static fatigue [4] as well as dynamic (cyclic) fatigue [5], both of which are considerably more severe in the presence of a water environment [6]. The application of fiberglass, particularly in the marine and transportation industries, is likely to lead to combinations of these geometric/loading/environmental factors as cracks slowly propagate under the influence of a particular load history, to eventually cause failure of the structure. The lifetime of structures in such situations depends primarily upon the rate at which cracks extend prior to reaching a critical length necessary for catastrophic fracture.

The various fatigue and environmental effects of interest in this study occur in the localized context of a propagating crack tip, so that the mechanisms of crack extension and crack resistance are of primary importance. The resistance to crack extension may be described from either an energetic [7, 8] or stress intensity point of view; the latter approach will be taken in this paper. The crack resistance of multi-directional laminates is found to derive from the extension of a damage zone at the crack tip, which serves, in effect, to blunt the crack and relax the locally high stresses [9, 10]. The mechanisms of stress transfer and the effect of the damage zone in relaxing the stresses tending to break the fibers in a 0°/90° laminate have been demonstrated analytically [11]. The damage zone size is a function of the stress intensity factor, K_I, for notch-sensitive laminates, and larger crack-tip damage zones lead to

higher values of fracture toughness [9, 10, 12].

The tensile strength of fiberglass laminates is found to decrease with log time under stress in an approximately linear manner [4]. The origins of this effect have been related to stress-corrosion of the fibers and the time-dependent nature of the resin [13]. In addition to the cumulative effects of time under stress, the cycling of the stress with time has a separate and usually severe effect [14], which is associated with cumulative debonding and matrix cracking damage [15]. Comparisons of static and dynamic fatigue results under dry and wet conditions indicate that water immersion tends to reduce the strength and increase the rate of reduction of strength with time [4, 6, 13].

A limited amount of information is available on the effects of fatigue and environment on the fracture toughness of fiberglass. The fracture toughness of 0°/90° glass/epoxy and woven roving/mat reinforced polyester was found to decrease with decreasing strain rate and increasing temperature to a similar degree as did the strength [2]. Cyclic fatigue loading was found to increase the residual fracture toughness in some cases [9, 15] due to enlargement of the damage zone and associated blunting of the crack. However, continued cyclic loading resulted in extension of the crack and eventual failure, even at relatively low stress intensity levels [17, 18]. The rate of crack extension has been studied for a variety of fiberglass laminates, and good agreement has been demonstrated with a theory which predicts an exponential relationship between the cyclic crack growth rate and the stress intensity factor [17, 18], as will be described later.

The purpose of the present study was two-fold: 1) to investigate the previously unexplored topic of crack extension under sustained static load

conditions, and (2) to investigate the effects of water immersion on the rate of crack extension for both static and cyclic loading. The initial part of the study was concerned with the effects of seawater on the rate of crack extension under cyclic loading; a laminate composed of alternate layers of woven roving and chopped strand mat with a polyester matrix was chosen for this work. While satisfactory results were obtained with this material, the scatter in the results was greater than is commonly observed with more finely woven fabrics. The increased scatter became impractical in the second part of the study, which was concerned with crack extension under static loads. Crack extension under static loads is so sensitive to the test parameters that it was necessary to switch to a fine woven fabric laminate which displayed more consistent properties. At the same time, the water environment was switched to distilled water which has an almost identical effect on laminate mechanical properties [19]. To provide a consistent set of results and to confirm the findings of the first two parts of the study, a subsequent series of experiments was conducted on a crossplied glass/epoxy material with both static and dynamic tests in air and in distilled water.

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EXPERIMENTAL METHODS

Materials

The materials used in this study were chosen to represent those laminates common to marine applications which have been demonstrated to fail in a notch-sensitive manner [2]. These include chopped strand mat, woven roving, and woven fabric reinforced polyester; additionally, laminates of 0°/90° unidirectional-ply glass/epoxy were used to confirm the trends observed for the other laminates. The following are the three types of laminates studied (all reinforcement was E-glass,supplied with a polyester-compatible finish for the chopped strand mat, woven roving, and woven fabric):

1. 181-style woven fabric (Uniglass Industries) with Laminac 4155 polyester matrix (American Cyanamid Co.). Laminates were compression molded, then postcured at 100°C for two hours.

2. Five plies of 1.5 oz. chopped strand mat alternated with four plies of style 779 woven roving (both from Stevens Fiberglass Co.) with Laminac 4155 polyester matrix (American Cyanamid Co.). Laminates were fabricated by hand layup, room temperature cure.

3. Scotchply Type 1003 unidirectional ply, epoxy matrix (3M Co.). Compression molded and cured at 350° F according to manufacturer's instructions, 44 alternating 0° (load direction) and 90° (crack direction) plies in the arrangement (90/90/0/90/90/0/.... /0/90/90/0/90/90).

Details of the thickness and fiber volume fraction are given for each case in Table 1.

Test Methods

The test specimens shown in Fig. 1 were machined from the laminates with a diamond-edged wheel and Tensilkut router. Notches were also cut with a diamond-edged wheel. With the exception of a few tests which will be noted individually, all tests were conducted on an Instron Model 1211 dynamic

cycler under load-control conditions. Water immersion was accomplished by surrounding the entire specimen and grip with a containment tank, which resulted in some contamination of the water by rust from the chrome-plated grips. This contamination was minimized by frequent water changes and silicone spray applied to the grips.

The unnotched specimen shapes given in Fig. 1 were determined by trial and error to provide the least reduction in strength due to stress concentrations at the shoulder, while avoiding failure in the grips. The wider specimen was used for the woven roving/mat laminates to offset the effect of increased heterogeneity.

The cleavage specimen used for all of the crack propagation studies has been investigated in detail previously [20]. Figures 2 and 3 indicate that the K-calibration used for the specimen results in a constant value of the fracture toughness, K_Q, for various crack lengths. These results were obtained on an Instron Universal testing machine at a displacement rate of 0.02 in./min. Figures 2 and 3 (taken from Ref. [20]) indicate that the test specimen may be used to impose a particular value of K_I on an opening-mode crack for crack growth studies; the damage zone associated with the crack tip clearly remains approximately constant in size as the crack extends. Thus, crack propagation may be studied over a distance of an inch or two under known K_I conditions and without significant specimen size effects. While the anisotropic elastic constants were considered in determining the K-calibration curve for the woven roving/mat laminates [20], the very similar isotropic K-calibration was used for the other laminates. The value of K_I in the latter case is given by [21]:

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

where P is the applied force, C is the crack length, B is the thickness, and H is the half-height of the specimen (1.5 in. in this case). Figures 4 and 5 indicate that crack propagation in the 181 fabric and scotchply laminates also occurred in the expected manner, with crack extension parallel to the original notch, and with a localized damage zone. The cleavage specimen geometry is effective only if the laminate is thick enough to avoid buckling and if the crack tends to propagate along the length direction.

In the course of the tests on the woven roving/mat and 181-style fabric laminates it was necessary to take frequent readings of the crack length. As the photographs in Figs. 3 and 4 suggest, it can be difficult to establish the precise crack tip location, particularly for the woven roving/mat laminates The methods used to determine the crack-tip position were visual observation followed by graphical smoothing of the data in the case of the 181-style laminates, and observation under cross polarized transmitted light of the woven roving/mat laminates. Only the total specimen lifetime was determined for the Scotchply laminates.

THEORETICAL PREDICTION

A theory for the crack propagation rate under cyclic loading was presented in Refs [17] and [18]. The theory is based on a model of crack extension involving the ligament by ligament advance of the crack, with each ligament failing according to the S-N curve of the bulk material. Figure 6 indicates the mode of crack advance observed in the present study as well as in earlier studies [17, 18]: the crack remains stationary for a number of fatigue cycles until a ligament of material at the crack tip fails, then the crack advances to the next ligament. Only those fibers normal to the crack are considered in the model. Ligament widths observed for a variety of laminates range from 10^{-1} to 10^{-2} inches, so that a large number of individual fibers are contained in each ligament [18]. This mode of crack propagation is identical in appearance to that observed in monotonic fracture tests of 0°/90° laminates [1, 2].

For the simple, but commonly observed case where a substantial portion of the S-N curve for the unnotched material can be approximated by a linear relationship, the number of cycles to failure in the linear portion can be represented by

$$\log N = \frac{\sigma - \sigma_f}{S} \qquad (2)$$

where N is the number of cycles to failure, σ is the maximum applied stress, σ_f is the monotonic strength, and S is the slope of the S-N curve. Such a relationship has been found to give a good approximation to S-N data in 0-tension load cycling for chopped fiber mat, woven roving, woven fabric and 0°/90° unidirectional ply laminates [18] under conditions where σ_f is determined at the same strain rate as is used

in the fatigue tests and the specimen shape is similar to those in Fig. 1.

To apply the S-N relationship to the ligaments at the crack tip it is necessary to obtain an approximation to the local stress tending to fail the ligament. For this purpose, it is assumed that the local stress at the crack tip increases in proportion to K_I, reaching the local failure stress when K_I reaches K_Q, so that the stress on the ligament, σ_ℓ, is given by

$$\sigma_\ell = \sigma_f \left(\frac{K_I}{K_Q}\right) \tag{3}$$

This assumption is reasonable since fracture is observed to be synonymous with failure of the ligament at the crack tip in monotonic tests [1]. It may be questionable, hwoever, if the damage zone size varies significantly with the maximum value of K_I in the test.

Equating σ in Eq. (2) with σ_ℓ in Eq. (3) yields the prediction for the crack growth rate under 0-tension fatigue as

$$\frac{dc}{dN} = d/\exp\left[2.3\,\frac{\sigma_f}{S}\,(1-K_I/K_Q)\right] \tag{4}$$

where d is the experimentally measured ligament width. Since the parameters d, σ_f, S, and K_Q in Eq. (4) may be determined directly from the S-N curve, a fracture toughness test, and the observed ligament width, Eq. (4) provides a direct prediction of the crack growth rate, dc/dN, as a function of K_I. Although the prediction may be modified to account for cumulative damage effects on ligaments further away from the crack tip [17], these effects have not proven to be significant, and

Eq. (4) has been found to accurately predict the crack growth rate for a variety of laminates [18].

The applicability of the theory to laminates which fail by crack propagation involving fiber fracture appears to derive from the simple, stepwise, ligament by ligament advance of the crack. This contrasts with the mode of crack advance in metals, which usually involves an incremental extension of the crack with every cycle by a complex mechanism. Despite this difference, a similar model to the one described here has been reported to give encouraging crack growth rate predictions for some metals [22].

RESULTS

Dynamic Tests

The dynamic tests were initially run on the woven roving/mat laminates only. The loading consisted of a sinusoidal load-time curve between a maximum tensile load and a minimum load which was approximately 5% of the maximum; the frequency was 5-6 cycles per second in all cases. The environment was either ambient (approximately 75°F, 50-70% R.H.) or salt water immersion at room temperature. The salt water was a synthetic 3% NaCℓ solution. Specimens tested in the salt water environment were presoaked in salt water for ten days prior to the initiation of the test. Slight heating (warm to the touch) was observed for the dry environment crack growth tests, but the temperature effect was not investigated.

Figures 7 and 8 give the S-N curves for unnotched specimens in dry and salt water environments. The data are easily approximated by a straight line over the range of cycles investigated. The lifetimes of the dry samples are generally longer than those for the samples in salt water, but little difference is observed at lower stress levels. Table 2 gives the values for the slopes of the S-N curves (S) and the monotonic strengths (σ_f). The monotonic strengths determined by extrapolation of the S-N curves to one cycle are significantly lower than the ultimate strengths measured experimentally at the corresponding displacement rate of 60 in/min. Earlier results have shown that the S-N curve is approximately linear including the monotonic strength value for woven and unidirectional ply laminates [17, 18], so the present discrepancy is attributed to some shift in the failure mechanism between monotonic and cyclic tests which is peculiar to laminates containing both woven roving and chopped strand mat. In the prediction of

the cyclic crack growth rate, the extrapolated value of σ_f is used. Additional constants to be used in the theoretical prediction of Eq. (4) are K_Q measured at 30 in/min displacement rate and the ligament width, d, taken as an average value from the crack length vs. time data, both of which are also given in Table 2.

Figures 9 and 10 give the theoretical and experimental crack growth results for cyclic loading in dry and salt water environments. The notable features of the results are the good agreement between the theoretical and experimental values, the significant scatter in the data points, and the shift to more rapid crack growth in the salt water environment. The rate of crack extension in salt water averages approximately one half of a decade more rapid than in the dry environment at corresponding K_I values.

Static Tests

The substantial scatter in the cyclic data led to a switch to 181-style fabric reinforced polyester laminates for the static tests, due to the expectation of a greater sensitivity to K_I in the static case. The static tests were conducted by loading the specimen as rapidly as possible to a predetermined load, and then holding this load constant until failure occurred. The wet specimens were not preconditioned in water prior to testing in most cases, but the effect of preconditioning was investigated separately.

Figures 11 and 12 give the strength vs. time to fail data for the unnotched specimens in dry and distilled water environments. The data are reasonably approximated by a linear relationship, and the limited data for the wet environment indicates a much more rapid decrease in strength with time than for the dry environment.

Figure 13 indicates a typical crack length vs. time curve for the cleavage specimens. The discrete data points were approximated by a smooth curve, and the slope of the curve at each point was determined graphically to obtain a value for the crack growth rate, dc/dt. Figure 14 indicates that the log time to fail each ligament at the crack tip was a linear function of K_I ; the average ligament with, d, was approximately 0.02 in. The crack growth rate vs. K_I data are plotted in Figs. 15 and 16 for dry and wet environments. The more complete results for the dry environment clearly suggest a power law relationship between dc/dt and K_I as

$$dc/dt \propto K_I^n \tag{5}$$

where n is approximately 24 for the dry environment and 22 for the wet environment

Comparison of Figs. 15 and 16 indicates the surprising result that the crack grows approximately ten times faster in the dry environment than in the wet environment. This is also evident in the total lifetime data for the two environments given in Table 3: the lifetime of the wet samples is 20-40 times longer than that for dry samples.

As noted previously, the results for the static tests do not include a presoak prior to testing. Table 4 indicates that the effect of presoaking the samples for forty days prior to testing is not significant, with only a slight decrease in the lifetime of the presoaked cleavage samples.

Scotchply Static and Dynamic Tests

Results from the previous sections indicate that water tends to accelerate cracks under dynamic loading, but to declerate them under static

loading. However, this finding is complicated by differences in the style of reinforcement, presoak time, and water composition. To clarify the previous results, a set of tests were run on a different material, 0°/90° unidirectional-ply glass/epoxy (Scotchply), with a fixed presoak time (ten days) and a fixed water composition (distilled water). Static and dynamic tests under ambient and water immersion conditions were performed at identical values of maximum applied force; the testing details were unchanged from previous tests.

Rather than recording the rate of crack extension, only the time to complete failure was recorded. The failure time is synonymous with the time to extend the crack 3.5 inches, but the lifetime was consumed almost entirely in the first 0.5 inches of propagation since the constant applied load of 1740 lb. in all cases resulted in a rapidly increasing value of K_I as the crack extended (see Eq. 1). The specimen lifetime data are, in effect, an average of the crack growth rates at different K_I values as the crack extends under constant load.

Table 5 gives the results of the Scotchply tests. The specimen lifetime under dynamic loading was almost three times longer in the dry environment, while the wet environment gave a lifetime almost four times as long for static loading. Thus, the earlier finding is confirmed with a significantly different material under invariant conditions. Table 5 also indicates that the damage zone size is larger for the dynamic tests but is unaffected by the environmental conditions (see also Fig. 5).

DISCUSSION

Applicability of Crack Growth Model

The simple theoretical model for crack extension described earlier rests on the assumption of a ligament of material at the crack tip which is subjected to fatigue at its local stress level. Failure of the ligament is assumed to occur under the same conditions as failure of an unnotched cupon of the same material, tested at the same stress level. Results from the dynamic tests confirm the applicability of this model for both wet and dry conditions; crack extension is observed to occur in a stepwise, ligament by ligament manner, and the theoretical crack extension rate prediction is shown to be in good agreement with the experimental data over a broad range of loads and crack growth rates. This agreemnt is anticipated from previous studies of a variety of similar materials [17, 18].

The dominant terms in the theoretical relationship given in Eq. (4) are K_I/K_Q and σ_f/S. The first term, K_I/K_Q, simply describes the loading on the specimen relative to its failure condition. The second term, σ_f/S, gives the fundamental fatigue characteristics of the material in tension. Previous studies [18] have shown this ratio to be approximately six for all woven fabric and woven roving laminates over a broad stress range, while the ratio is approximately ten for nonwoven reinforcements including chopped strand mat and Scotchply. The material employed in the dynamic study combines woven roving and chopped strand mat, and the resulting σ_f/S ratio is an intermediate 8.6-8.9 for wet and dry conditions. This intermediate value suggests that neither the woven roving nor the mat dominate the fatigue behavior, but that they both contribute substantially. This is consistent with earlier fracture studies which indicated that the woven roving/mat combinations showed considerably

different damage zone sizes and fracture behavior than did each material separately [2, 23].

The ligament by ligament advance of the crack was also observed for the static loading cases, and, as mentioned, previous dynamic studies have shown the applicability of Eq. (4) for both the 181-style fabric and Scotchply used in the static studies [17, 18]. The implication is that a relationship similar to Eq. (4) should be useful in predicting the static fatigue crack growth rate. Such a relationship for the static case may be derived by substituting σ_{f1} and K_{Q1}, the strength and fracture toughness at the reference failure time of one minute, for σ_f and K_Q in Eq. (4). This gives the relationship

$$\frac{dc}{dt} = d/\exp\left[2.3 \frac{\sigma_{f1}}{S} (1 - K_I/K_{Q1})\right] \tag{6}$$

where d and S are the appropriate values for the statically tested materials. The values of σ_{f1} and S are given in Figs. 11 and 12, and K_{Q1} may be taken from Fig. 14 as the value of K_I corresponding to a one minute failure time for the ligament. Unfortunately, when the correct constants are substituted into Eq. (6), poor agreement is found with the experimental data; in fact, the slope of the ligament strength-time data of Fig. 14 does not correspond to the slope of the unnotched specimen results in Fig. 11. In addition to this, Eq. (6) would predict a higher crack growth rate in water, while a slower rate is observed. It is apparent that this theoretical approach is not directly applicable to the static crack growth phenomenon despite the consistent mode of crack extension. No suitable modification or alternative has yet been discovered

Effects of Water Immersion

The finding that water immersion tends to decrease the crack growth rate under static loading conditions is contrary to expectations. The strength of unnotched cupons is generally decreased in the presence of water for both dynamic and static loading. Since crack extension clearly occurs in each case by the tensile failure of ligaments at the crack tip, water is expected to result in more rapid failure of the ligaments and a consequent higher crack growth rate. This expectation is realized in the dynamic case, where the crack growth rate is accurately predicted by the theory based on tensile cupon S-N data. However, the opposite trend is clearly and consistently observed for static loading.

There appear to be three general lines of explanation possible for this anomalous finding in the static case: (1) the actual stress at the crack tip is reduced by the presence of water for a given applied load, (2) the value of K_I given by Eq. (1) is decreased by the presence of water, or (3) the lifetime of the ligaments at the crack tip is increased in the presence of water despite the decreasing unnotched tensile cupon lifetime.

The first proposition would be convincing if water exposure was observed to increase the size of the crack tip damage zone, thus effectively increasing the bluntness of the crack. However, the data in Table 5 do not indicate such an effect, and the damage zone size is insensitive to water for both static and dynamic tests. The stress in the ligament at a particular value of K_I also depends upon factors other than the damage zone size which may affect the transfer of stress into the ligament [11]. A number of such factors, including a decrease in the shear modulus, increased delamination between plies, and weakening of the

individual fiber-matrix bond, could result in a decreased ligament stress, but none have yet been substantiated.

The second possibility, a change in the K-calibration due to the effect of water, could also be related to the inapplicability of the crack growth theory to the static case. If the modulus of the material were altered by time or environmental effects in those portions of the specimen which are highly stresed, then the effect could be similar to a change in specimen shape. Changes of K_I in the range of 10-20% would be sufficient to account for the anomalies in the data, and such a change is possible. A K-calibration study to include such effects is feasible [20], but has not yet been conducted.

The last possibility, that the ligament lifetime at a given local stress is actually extended by a water environment, appears doubtful on the basis of available evidence [4, 6, 13]. However, there have been reports of increases in glass strength with water exposure in some cases [24], and some fibers at the crack tip are exposed directly to the environment by the damage zone subcracking and delamination. However, a brief series of yarn strength tests from the 181-style fabric yielded a 10-20% drop in unimpregnated yarn strength with immersion in distilled water, and a further decrease was observed when the yarns were presoaked for one day.

Thus, although conclusive evidence is not available, it seems likely that the water environment has some effect in decreasing the stress on the ligaments, either by an alteration in K_I or by a relaxation of the stress on the ligament immediately at the crack tip. Any such hypotheses must also address the absence of the same effects in the cyclic tests, which results show no anomaly. The explanation appears to be that such effects may be present in the dynamic tests, but other effects tend

to dominate them. The damage zone is already greatly enlarged by cyclic loading (Table 5) so that water may not greatly increase the effective crack bluntness. Furthermore, the cyclic results are less sensitive to shifts in K_I, since the effective exponent for cyclic data on 181-style fabric laminates is 2-3 times lower than that given in Fig. 15 [18]. Although the specimen lifetime under cyclic loading does not appear to be severely reduced as compared to the static results in Table 5, it must be realized that the time given for the cyclic tests in the table are total times, only a small fraction of which is spent near the maximum load. Thus, the accumulated time under load is much shorter for the cyclic tests, as the effects of reversing the stress are apparently more severe than the static fatigue effects.

Stability of Cracks in Fiberglass

The data given in Figs. 15 and 16 provide useful evidence of the relationship between time and toughness in fiberglass laminates. The data in Fig. 14 may laso be interpreted as giving the fracture toughness as a function of time, since the fracture toughness, K_Q, has been interpreted as the value of K_I necessary to cause crack advance, crack advance being synonymous with ligament failure. In this interpretation, the effect of time on K_Q is consistent with earlier findings which considered the effects of loading rate on K_Q for similar materials [2].

The sharply increasing value of K_Q with decreasing time suggests that propagating cracks may not readily become unstable. In fact, cracks in typical fracture specimens such as the notched tension configuration are not commonly observed to propagate as rapidly as expected. The terminal velocity for a crack is expected to reach the order-of-magnitude of the

longitudinal stress wave velocity after a short distance of propagation [25]. Using notched tension tests of identical geometry, crack velocities in the expected range were measured for plexiglass and for graphite/epoxy laminates, but the velocity in Scotchply glass/epoxy reached only a few hundred inches/minute, about four orders of magnitude less than expected [9]. Although the graphite and glass reinforcements used in these tests differed by a factor of three in modulus, the reason for the extreme difference in behavior apparently derived primarily from the greatly reduced rate effects in the graphite. Thus, the increasing value of K_Q with loading rate, and the observation of slow crack propagation velocities in laboratory tests suggested that cracks in fiberglass may never become truly unstable.

The data in Fig. 15 suggest a different interpretation for the stability of cracks. The empirical relationship

$$dc/dt \propto K_I^{24} \tag{7}$$

has certain impliations for the crack velocity as a function of the crack length. For a crack in an infinite plate subject to a constant nominal stress σ normal to the crack, K_I is given by [26]

$$K_I = \sigma\sqrt{\pi C} \tag{8}$$

Substituting (8) into (7)

$$dc/dt \propto \sigma^{24}\ \pi^{12}\ c^{12} \tag{9}$$

A stable crack under constant applied stress should propagate at a rate propoitional to the 12th power of the crack length. Under these conditions, the crack velocity would increase by a vactor of about 4000 as the crack doubled in length, rapidly

bringing the crack under the control of the classical dynamic effects which lead to the predicted terminal velocity. This is hardly an inherently stable situation. The 24th power relationship between dc/dt and K_I is substantially greater than the 16th power relationship evident in data from homogeneous soda-lime glass plates for which unstable crack extension is well known [27].

While no conclusive experiments have been conducted to resolve this situation, the contradiction evident in the two preceding paragraphs may be clarified by consideration of the limitations on the available data. Most experiments have heretofore been conducted on relatively small, laboratory-size specimens under controlled displacement conditions. The initial crack size is usually relatively large, and the slow initial crack extension allows unloading of the specimen under controlled displacement conditions. In addition to this, a doubling in size of a 0.5 inch initial crack would only lead to an increase in crack velocity of a factor of 4,000, perhaps from 0.1 to 400 inches/minute, not out of line with measured crack velocities [9]. Laboratory-size notched tension specimens usually bend and unload significantly by the time the crack has doubled in length. Thus, while there is no inherent crack stability, the rate effects in fiberglass may serve to contain the crack velocity in small specimens well below the values observed in many other materials, where a crack would accelerate from 0 to perhaps 10^6 inches/minute as it doubled in length.

The increasing value of K_Q with loading rate does lead to significant advantages for fiberglass in some situations, such as impact loading. The data in Fig. 14 suggest a corresponding disadvantage, as cracks may propagate under relatively low, long duration loading, very slowly at first, but accelerating rapidly as the crack extends. Any cycling of the load under these conditions could lead to much more rapid failure.

Interpretation of Fracture Toughness Tests

The foregoing discussion contains certain implications for the interpretation and application of fracture test results. While it is generally realized that K_Q, as other fiberglass properties, is strongly rate sensitive, data such as those in Fig. 15 suggest that K_Q may be difficult to define properly.

The usual practice of defining K_Q as the value of K_I at which unstable crack propagation commences does not seem capable of treating the situation where stable and unstable conditions are ill-defined. Within a broad loading range, the crack is always propagating in fiberglass. The situation is analogous to that observed under fatigue loading in metals, where crack propagation rates and thresholds are the appropriate parameters, rather than instability conditions. A method of accounting for stable crack growth, the R-curve method, has been successfully applied to fiberglass laminates [28]. However, while such a method may appear to provide consistent fracture toughness results, the interpretation of the results still is unclear. The R-curve technique was developed as a means for fixing the instability point of materials which showed some stable crack growth prior to fracture, interpreted as an increasing crack-growth resistance with crack length [29]. However, in the case of fiberglass, the crack would propagate at values of K_I well below the "critical" value determined in this manner, given sufficient time.

CONCLUSIONS

Stable crack propagation has been observed in fiberglass laminates over a broad range of cyclic and static loading conditions. Under cyclic loading conditions the rate of crack propagation may be predicted by a simple theory, but the rate of propagation under static conditions was not predictable. A water environment reduces the ultimate tensile strength of unnotched samples for both static and cyclic loading. However, water tends to accelerate cracks under cyclic loading while declerating them under static loading. The origins of the anomalous effects of water on the rate of crack extension are not clear.

AKNOWLEDGEMENTS

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TABLE 1 Materials

Material	Specimen	No. Plies	Ave. Thickness(in)	Ave. Fiber Volume Fraction
181 Fabric/Polyester	Unnotched Tension	10	0.10	0.46
"	Cleavage	36	0.360	0.43
Woven Roving-Mat/plyester	Unnotched Tension	5-Mat 4-W.R.	0.216	0.31
"	Cleavage	"	"	0.31
0°/90° Scotchply	Cleavage	14-0° 30 -90°	0.34	0.55

TABLE 2, Dynamic Fatigue and Monotonic Properties for Woven Roving/Mat Laminates.

	Dry	Salt Water
Measured σ_{fm}^{*} (Ksi)	40.0	35.5
Extrapolated σ_f from S-N data (Ksi)	31.0	27.0
S (Ksi/decade)	3.48	3.14
K_Q (Ksi $\sqrt{in.}$)*	27.8	24.8
Ligament Width, d (in.)	0.125	0.125

* σ_{fm} measured at 60 in/min. and K_Q measured at 20 in/min. displacement rate, both consistent with cyclic displacement rates.

TABLE 3. Effect of Water Immersion on the Lifetime of 181-Style Fabric/Polyester Cleavage Specimens Under Static Loading.*

Average Load (lb)	Average Lifetime (min)		Lifetime Ratio $\left(\frac{wet}{dry}\right)$
	Dry	Immersed	
1400	33.8	1375.	41
1500	10.4	332.	31
1600	1.4	30.	21

* Wet : Immersed in Distilled H_2O ; dry : 50-70% relative humidity ; temperature : 70-75° F.

TABLE 4

Effect of Presoaking 181 Style Fabric/Polyester Specimens for 40 days Prior to Testing in Distilled Water

		Time to Fracture for Immersed Specimens (min)	
		Not Presoaked	Presoaked
Unnotched	Average	19.3	21.5
	Range	14.6 - 28.0	13.1 - 37.5
Cleavage	Average	46.5	36.9
	Range	46.3 - 46.6	17.9 - 46.5

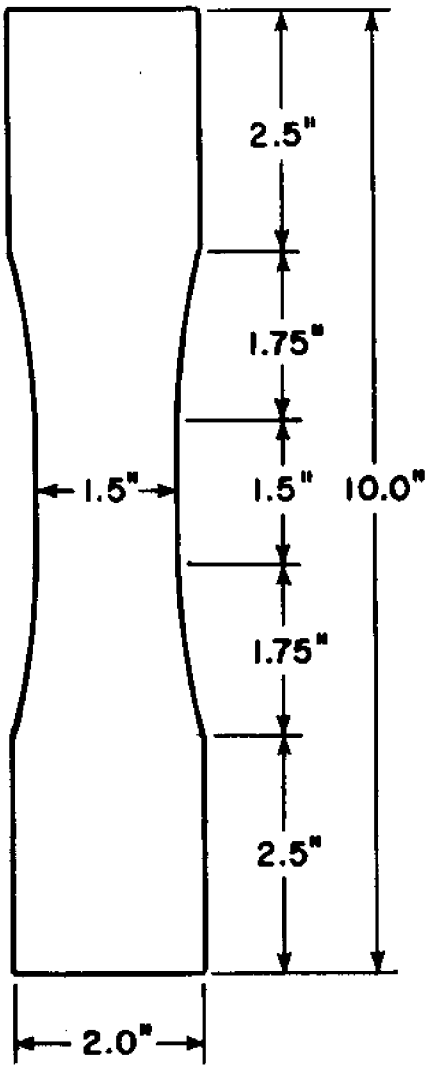
TABLE 5. Effect of Water Immersion on the Lifetime of 0°/90° Scotchply Cleavage Systems Under Static and Dynamic Loading*

		Static Loading		Dynamic Loading***	
		Dry	Wet	Dry	Wet
Average Lifetime min. or (cycles)		211	877	87.9(10,550)	32.1(3,848)
Range min.or(cycles)	High	240	1,826	91.6(11,000)	39.9(4,770)
	Low	187	324	87.2(10,460)	27.9(3,350)
Average Damage Zone Size (in.)**		0.40	0.40	0.70	0.70

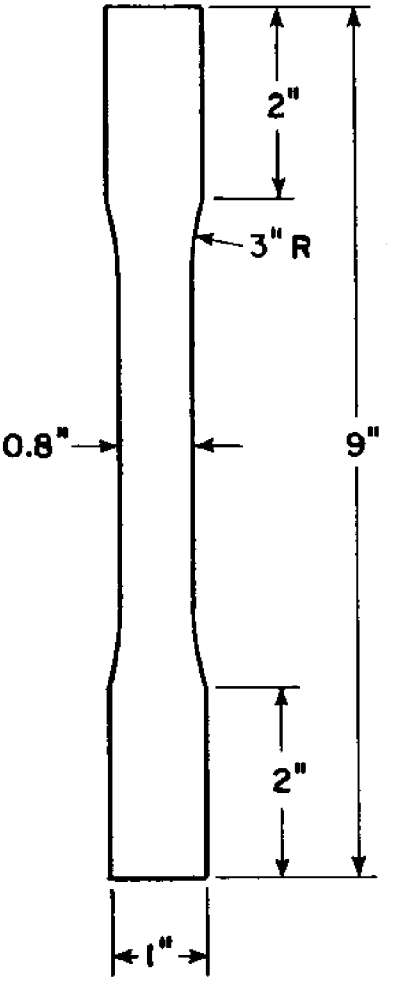
* Wet : Immersed in distilled H_2O; dry : 70% relative humidity; temperature : 70-75°F; replication factor 3 (dry), 4 (wet); initial value of K_I for all tests = 25.3 Ksi $\sqrt{in.}$

** Average length of subcrack in 0°plies in first 1/2 inch of crack growth .

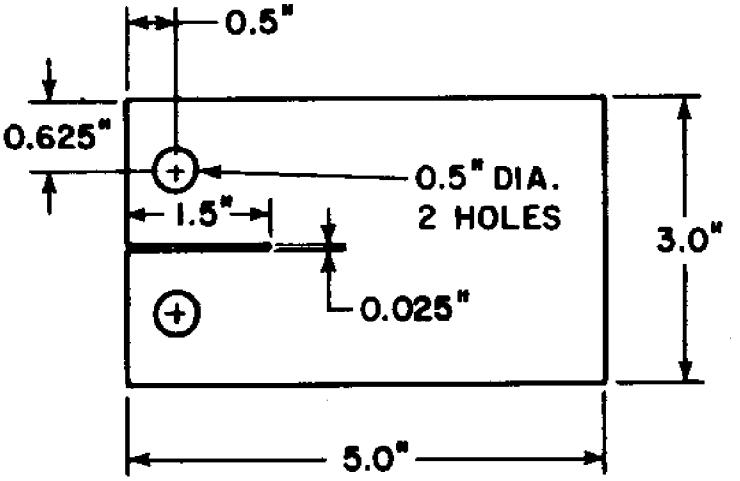
*** Sinusoidal load vs time, 5 cycle/second.



UNNOTCHED DYNAMIC



UNNOTCHED STATIC



CRACK PROPAGATION

FIGURE 1.

TEST SPECIMENS.

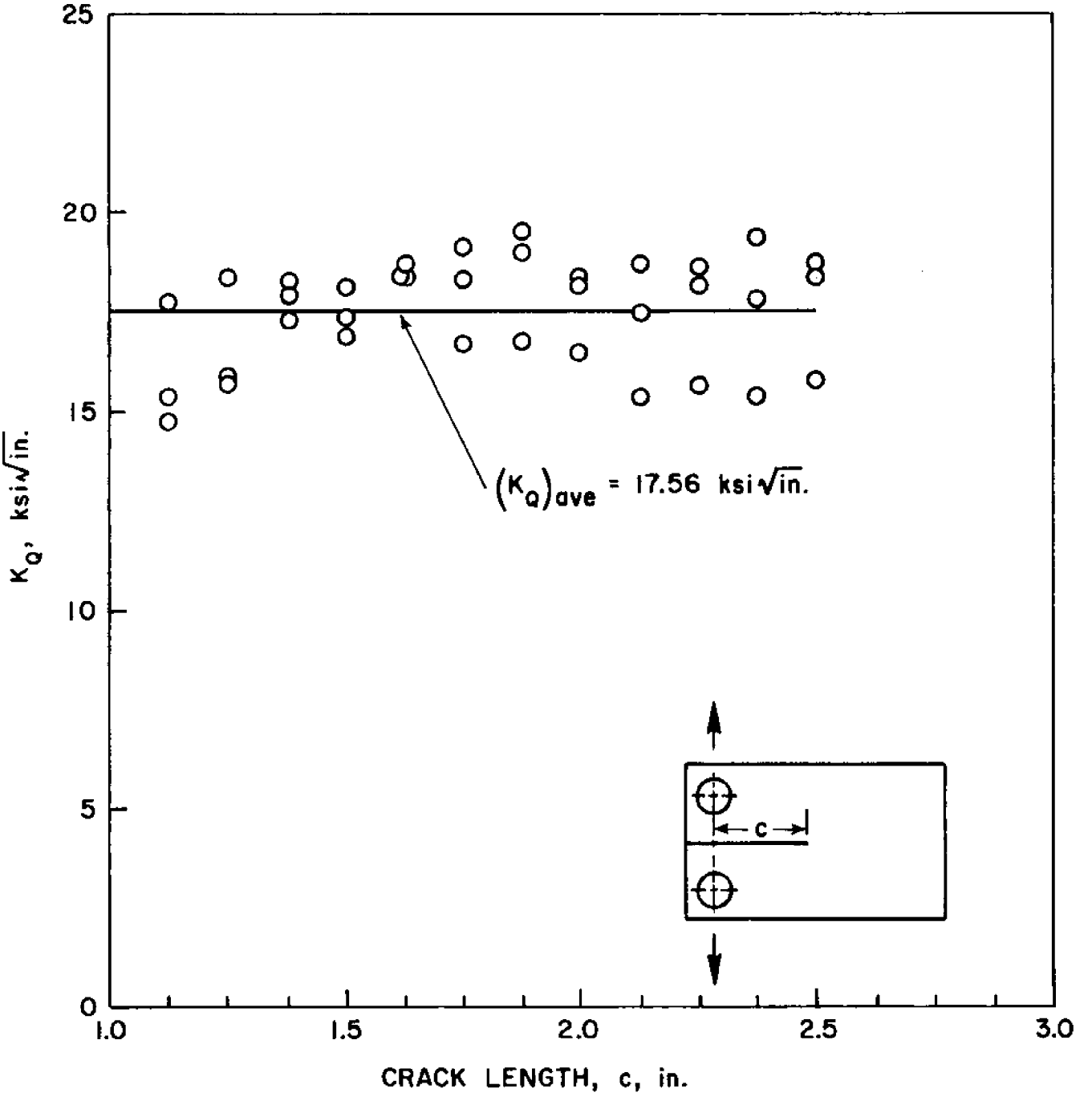


FIGURE 2.

K_Q vs. CRACK LENGTH FOR WOVEN ROVING/MAT REINFORCED POLYESTER.

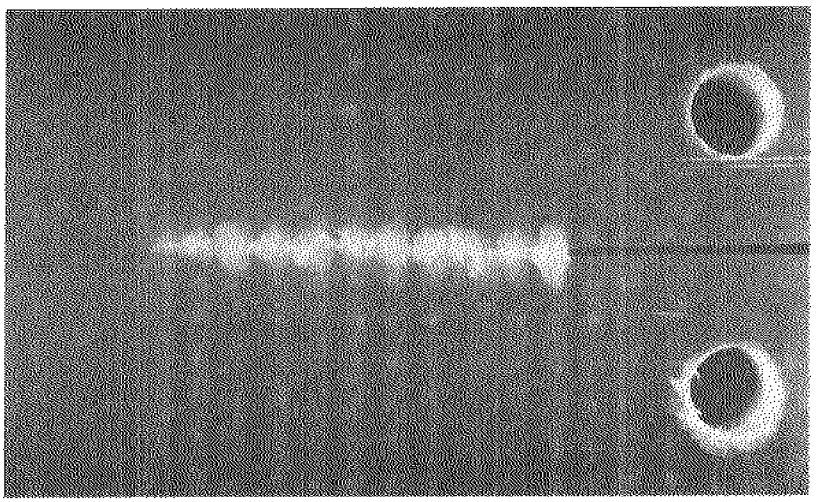


FIGURE 3.

CRACK PROPAGATING IN 0°/90° WOVEN ROVING/CHOPPED FIBER MAT REINFORCED POLYESTER LAMINATE.

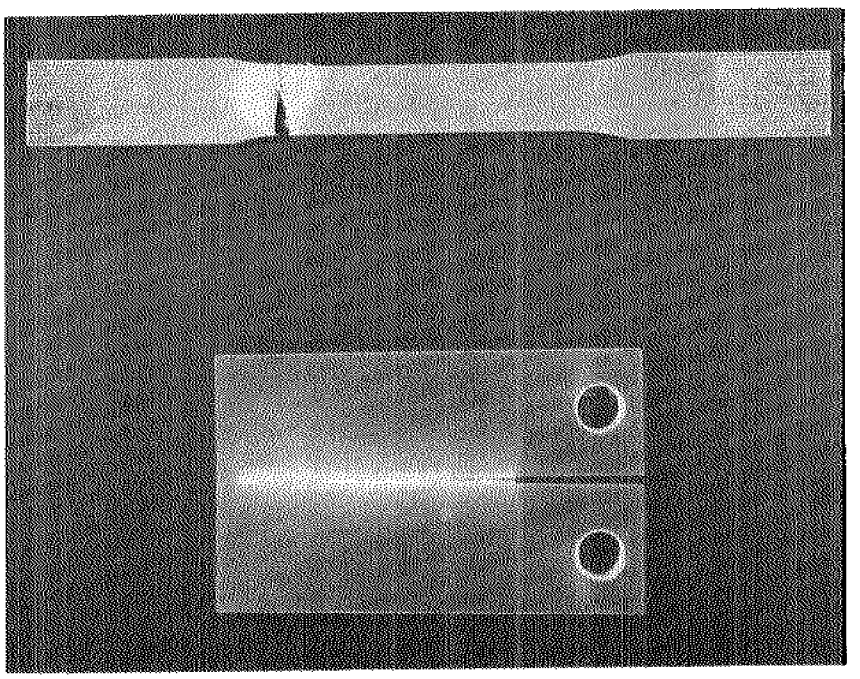


FIGURE 4.

STATIC FATIGUE SPECIMENS AFTER FAILURE.

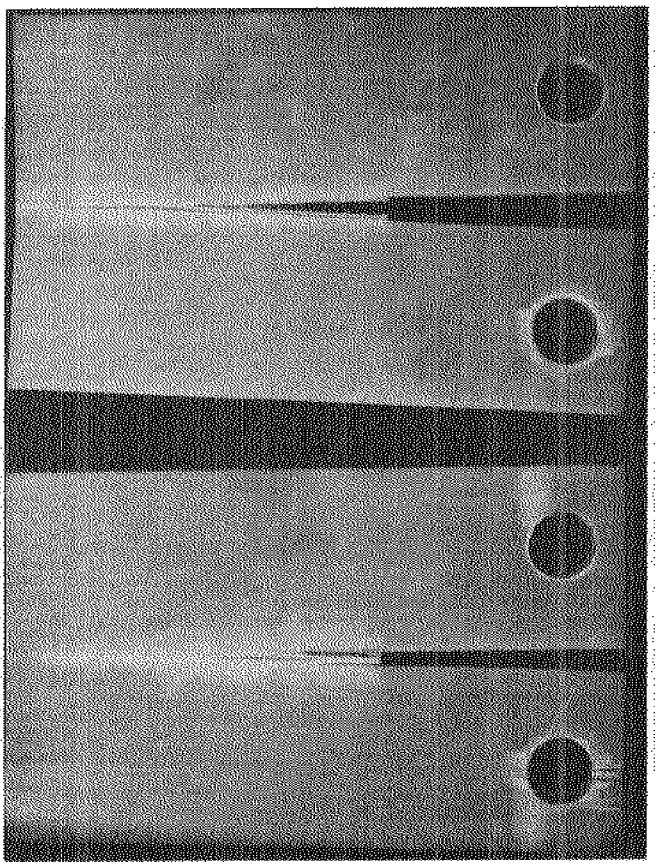
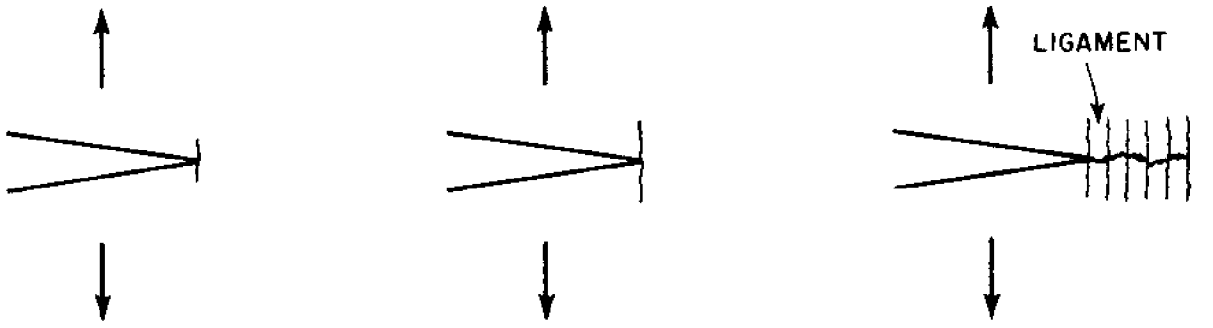


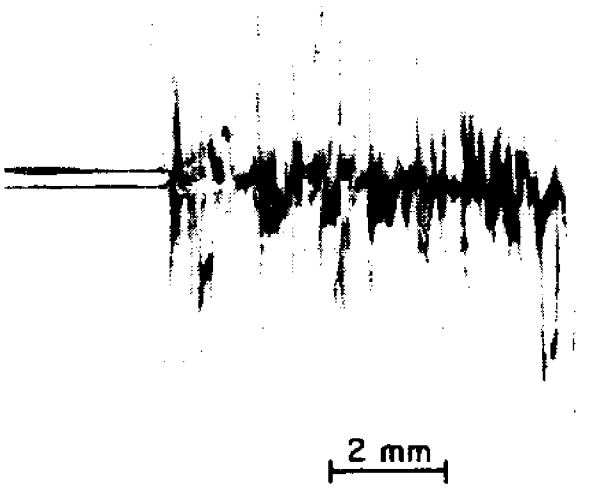
FIGURE 5.

FAILED 0°/90° GLASS/EPOXY FATIGUE SPECIMENS, STATIC (TOP) AND DYNAMIC (BOTTOM).



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 6.
FATIGUE CRACK PROPAGATING IN 0° PLY OF [90/0/90/0/90] GLASS/EPOXY LAMINATE.

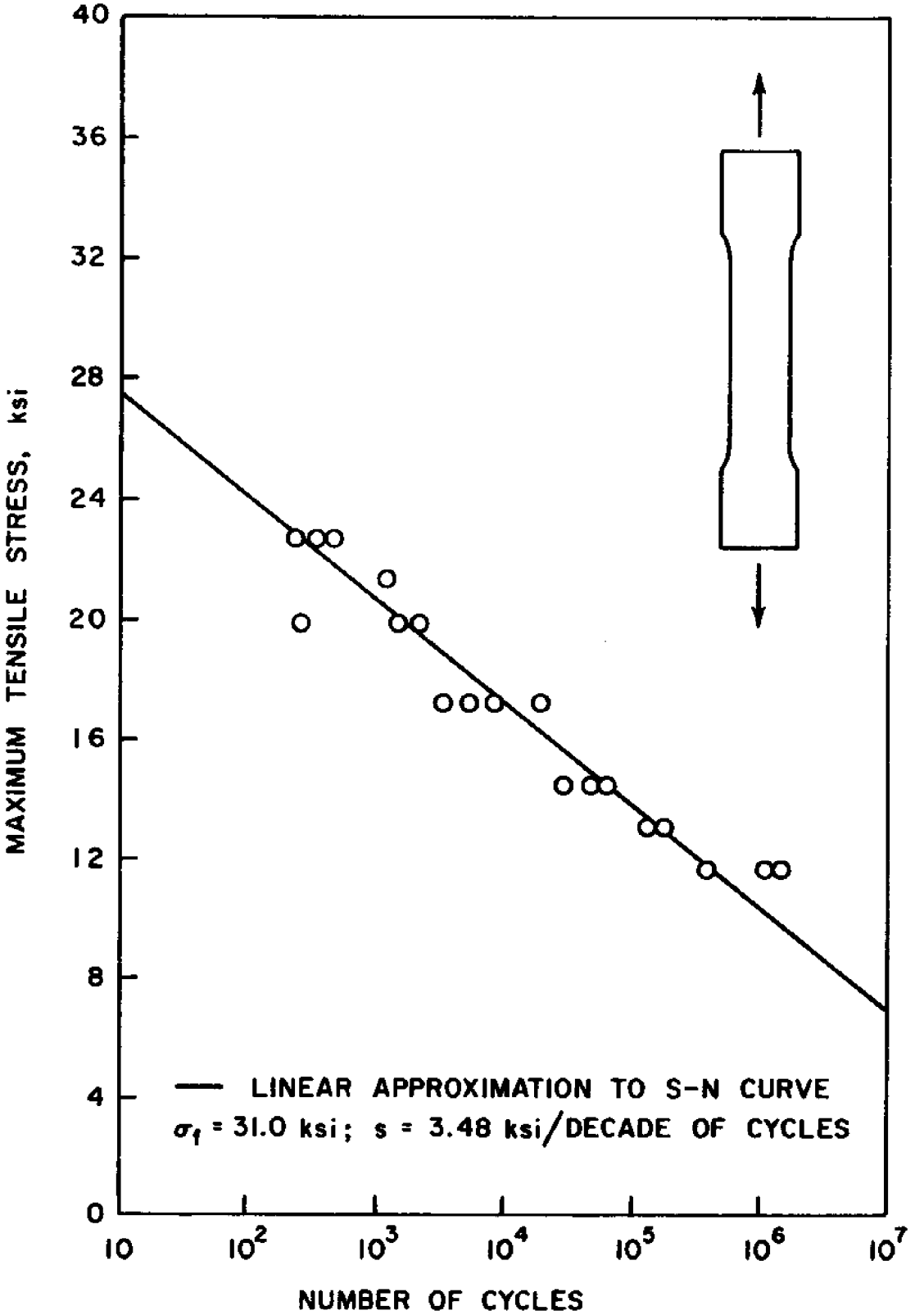


FIGURE 7.

DYNAMIC S-N CURVE (DRY ENVIRONMENT).

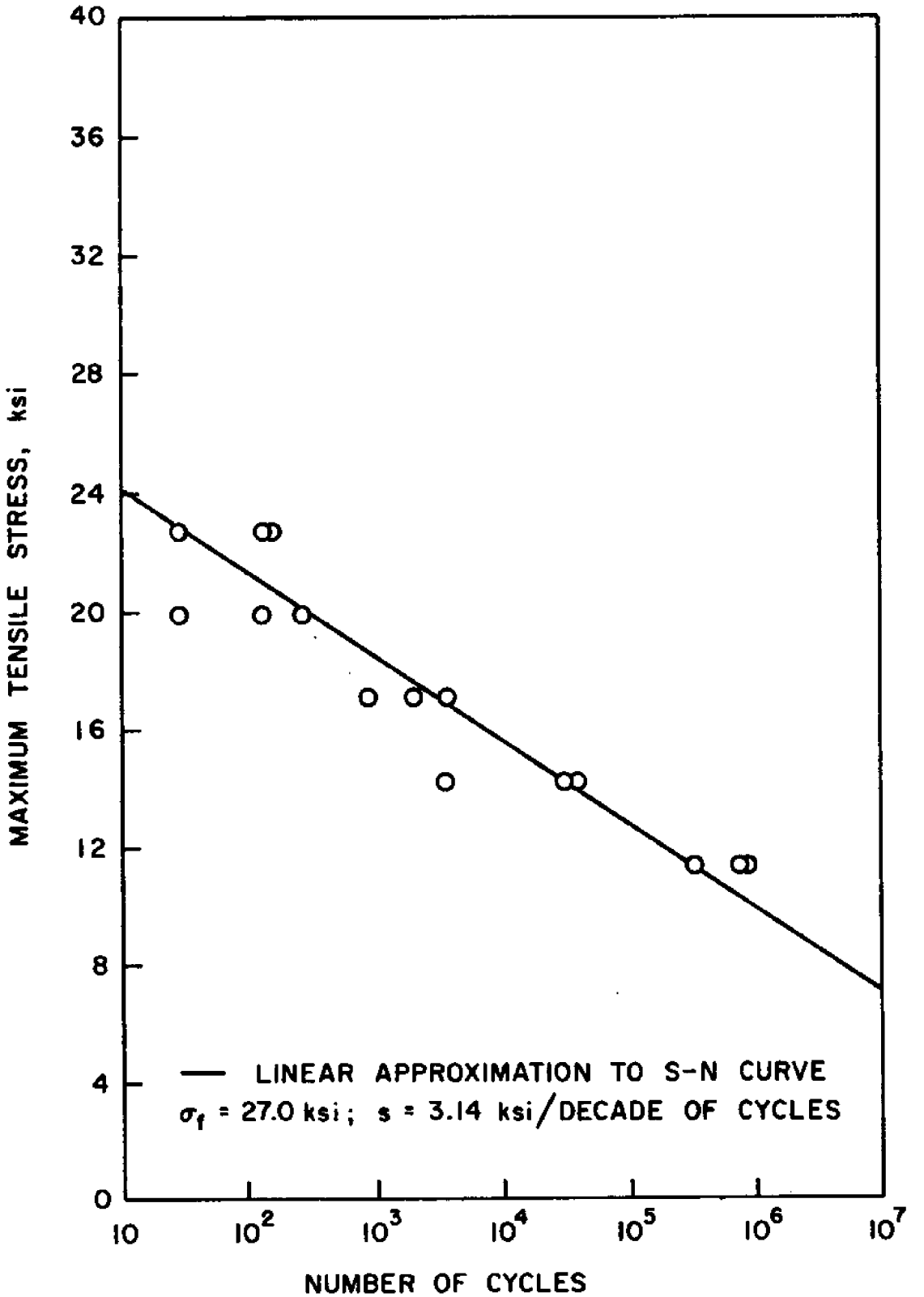


FIGURE 8.

DYNAMIC S-N CURVE (SALT WATER ENVIRONMENT).

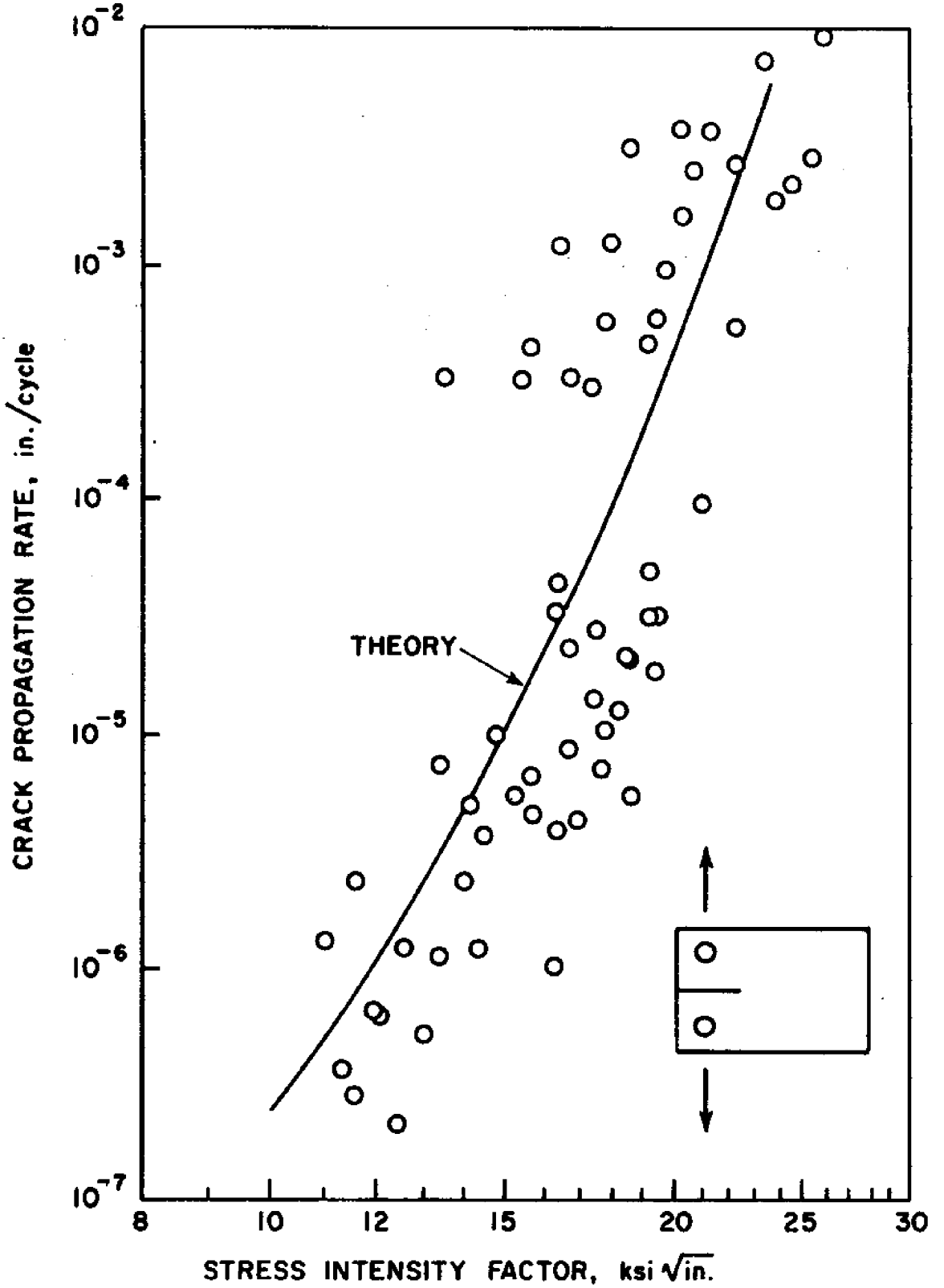


FIGURE 9.

DYNAMIC FATIGUE CRACK PROPAGATION RATE vs. STRESS INTENSITY FACTOR (DRY ENVIRONMENT).

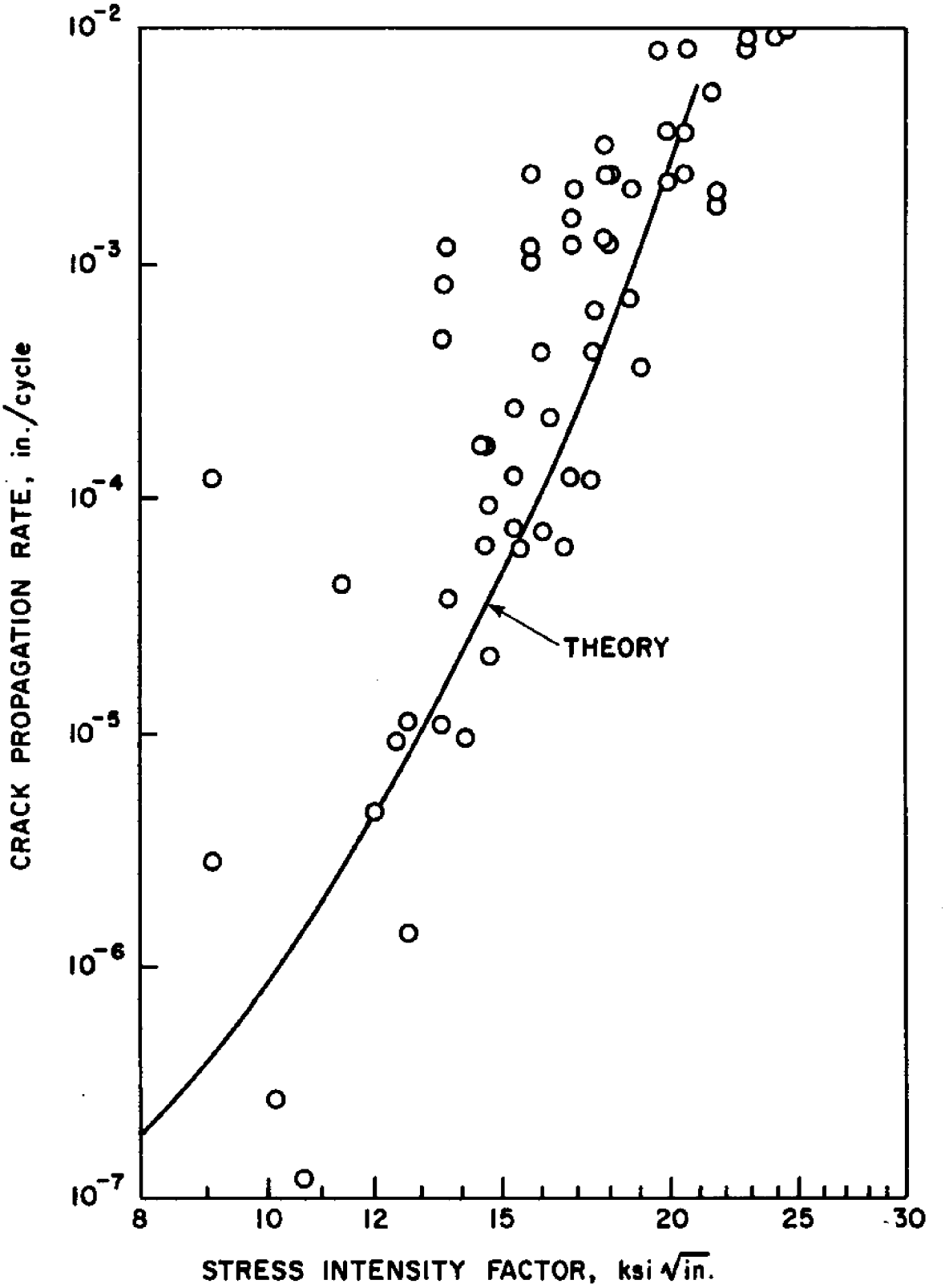


FIGURE 10.

DYNAMIC FATIGUE CRACK PROPAGATION RATE vs. STRESS INTENSITY FACTOR (SALT WATER ENVIRONMENT).

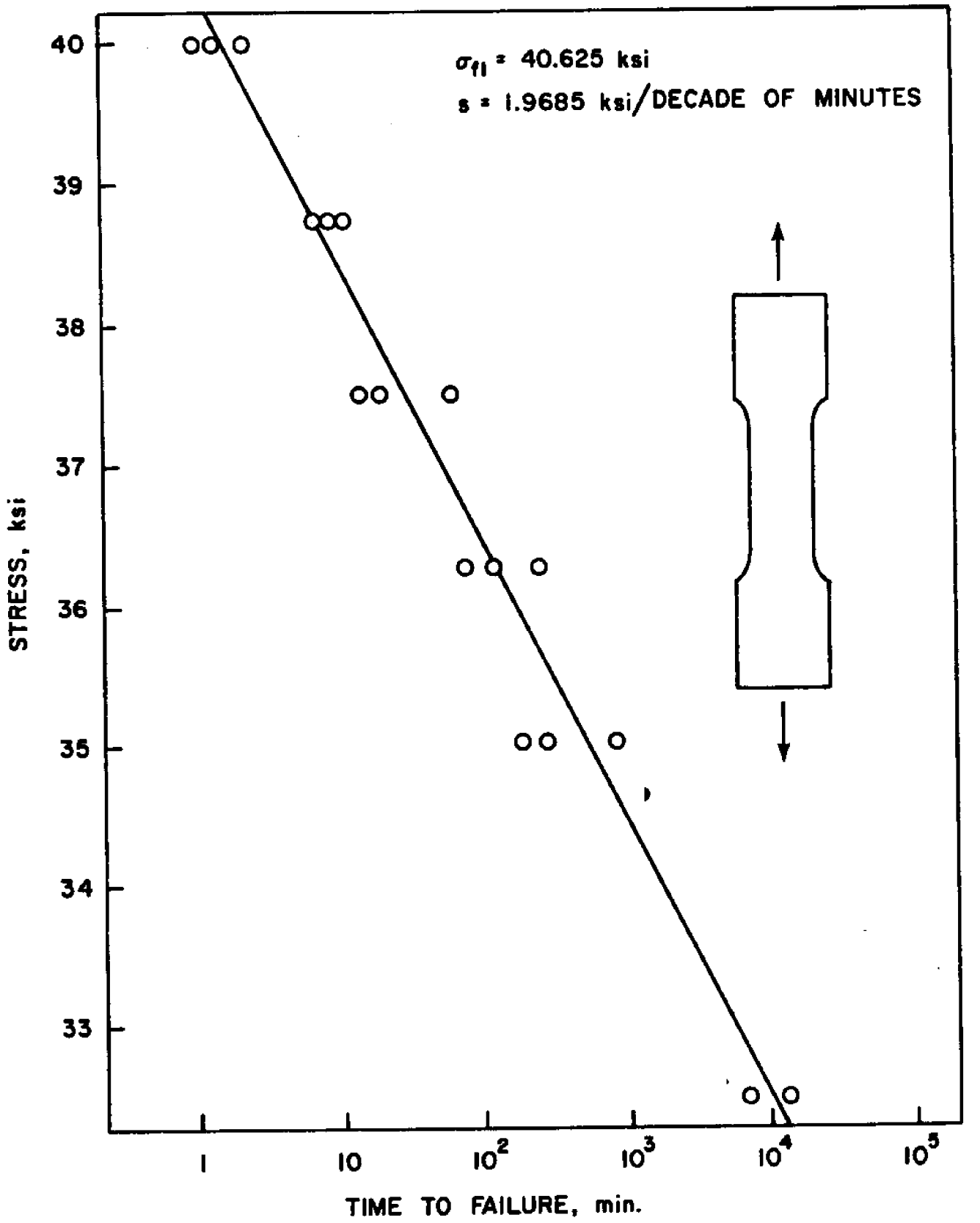


FIGURE 11.

STATIC STRENGTH-TIME CURVE (DRY ENVIRONMENT).

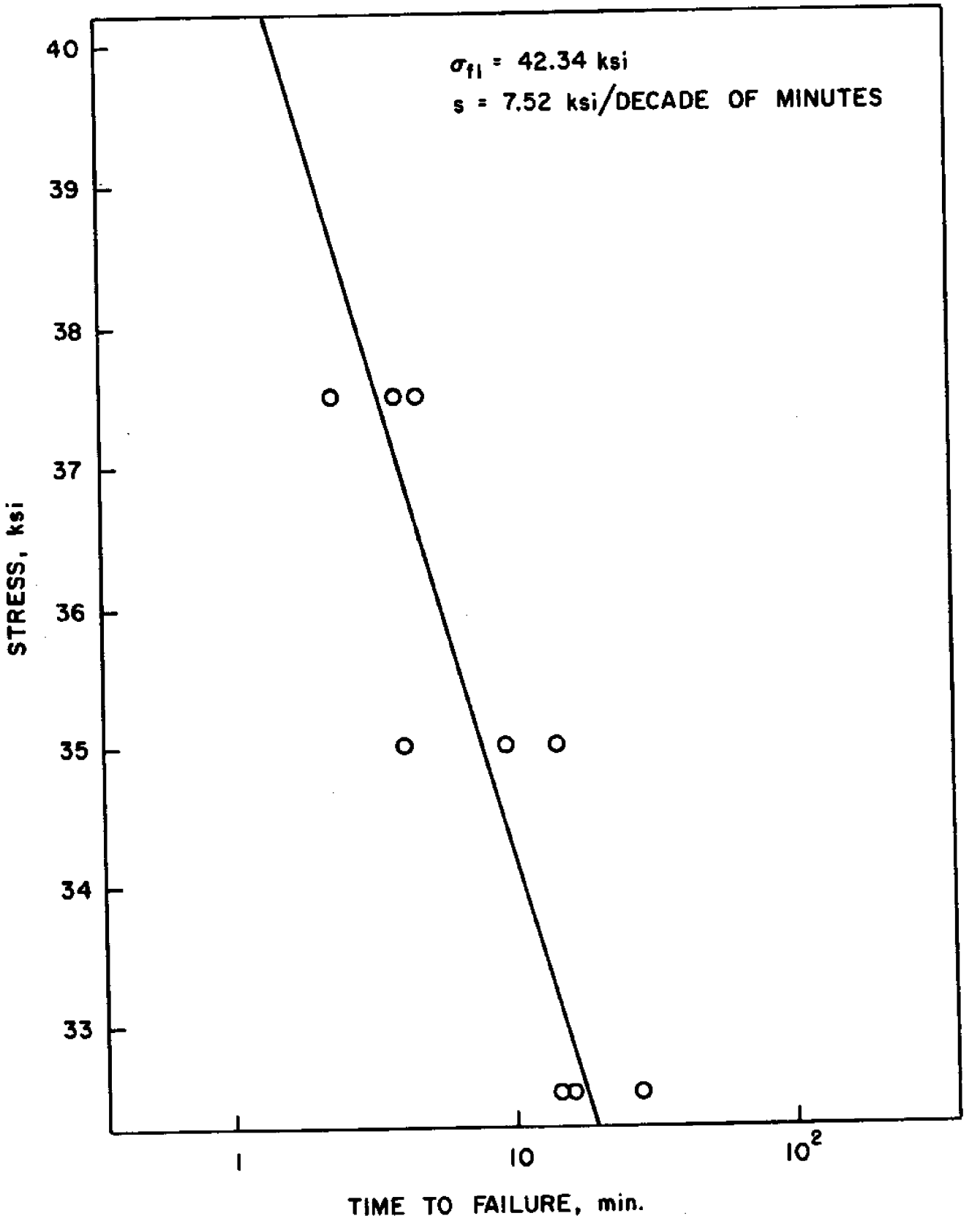


FIGURE 12.

STATIC STRENGTH-TIME CURVE (WET ENVIRONMENT).

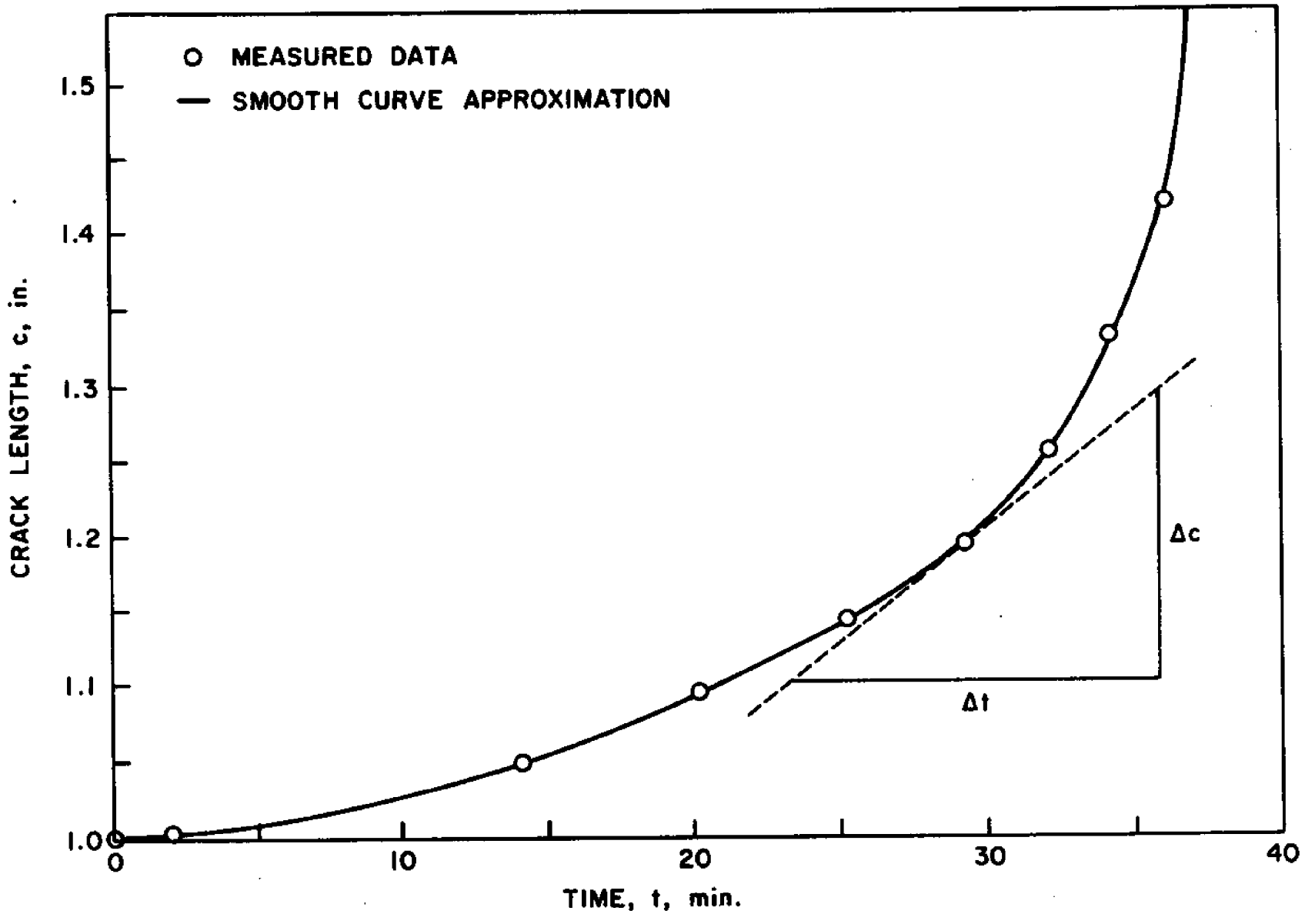


FIGURE 13.

TYPICAL CRACK LENGTH vs. TIME CURVE, STATIC TEST.

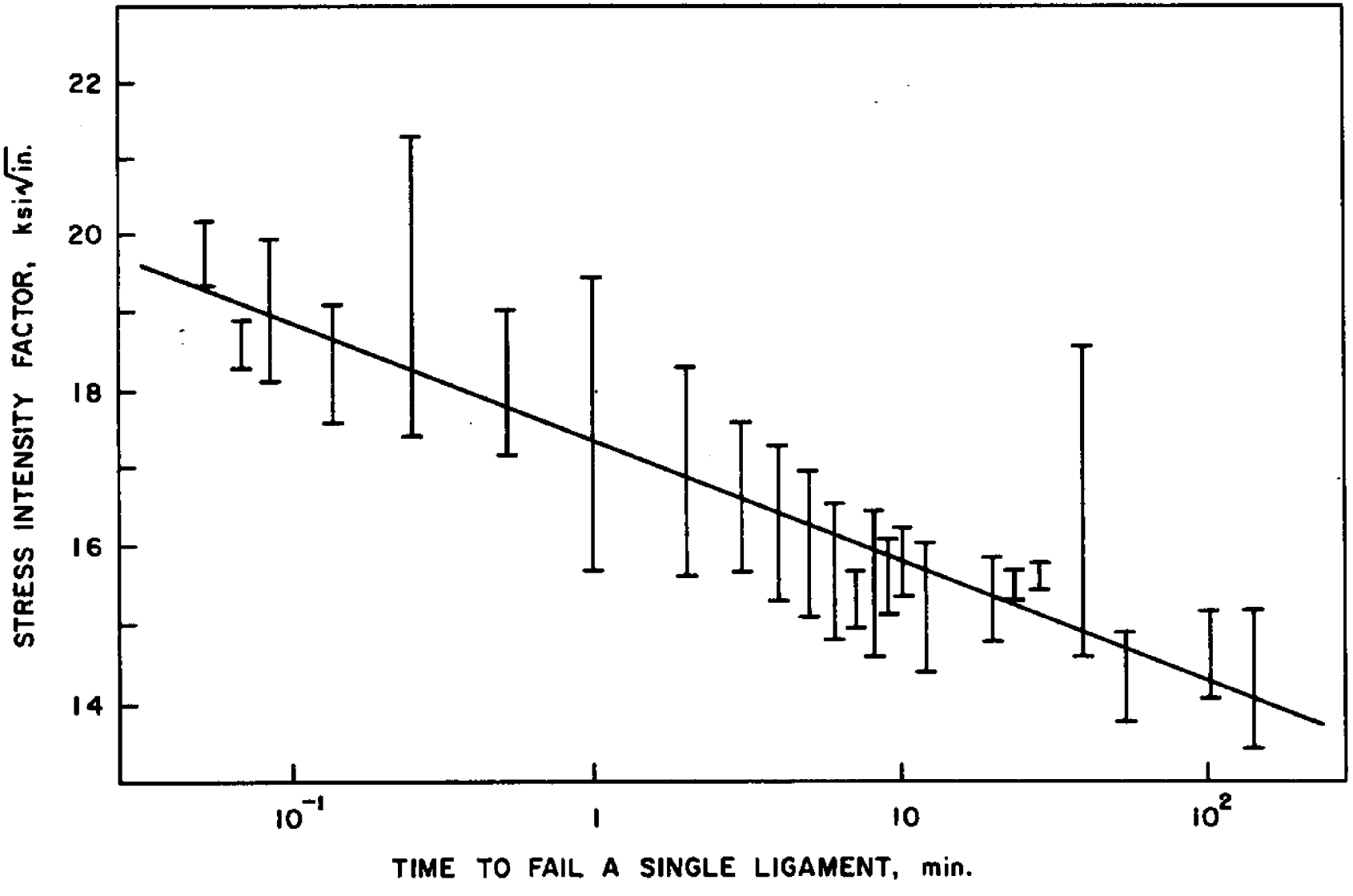


FIGURE 14.

TIME TO FAIL A SINGLE LIGAMENT vs. STRESS INTENSITY FACTOR, STATIC TEST.

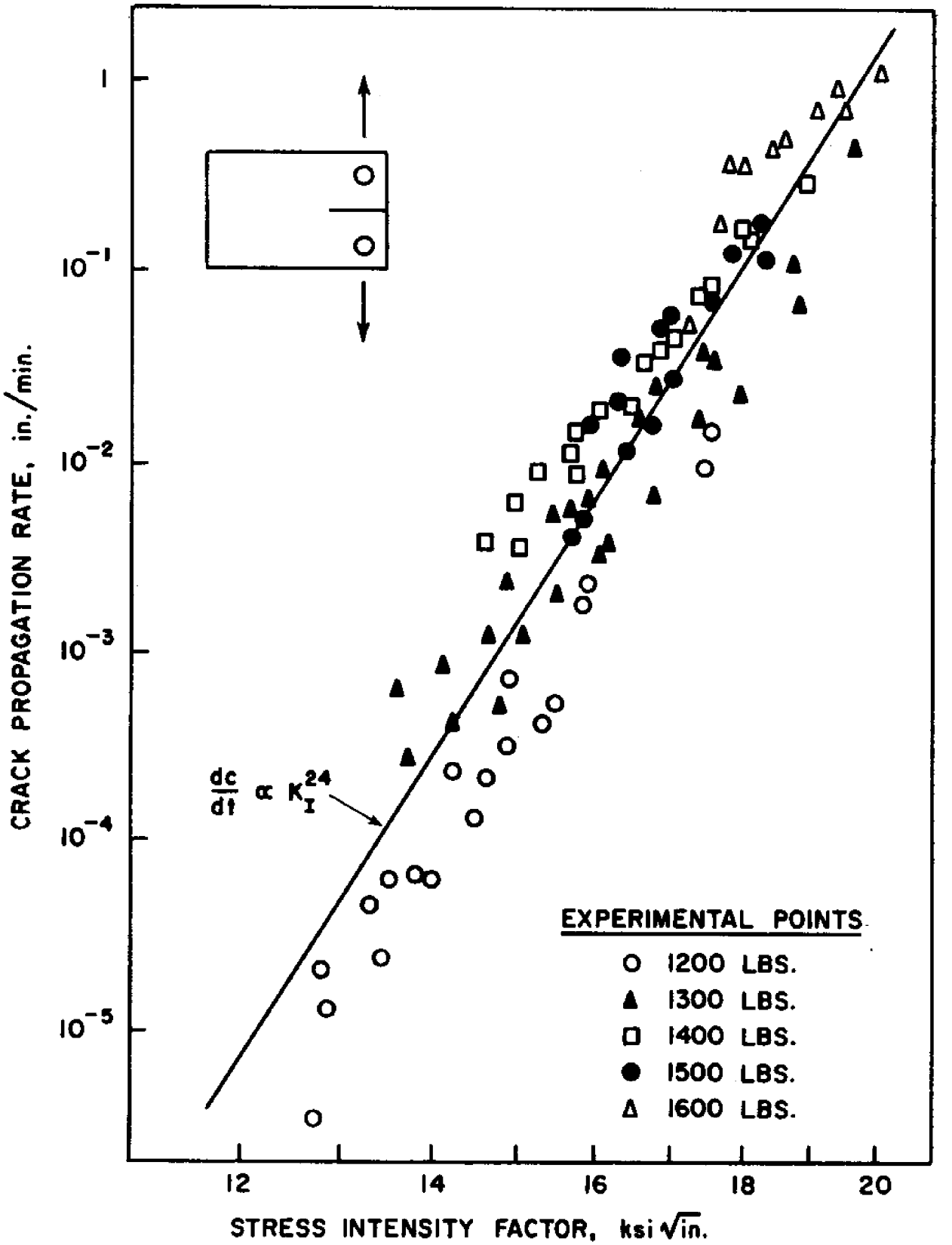


FIGURE 15.

CONSTANT LOAD CRACK PROPAGATION RATE vs. STRESS INTENSITY FACTOR (DRY ENVIRONMENT).

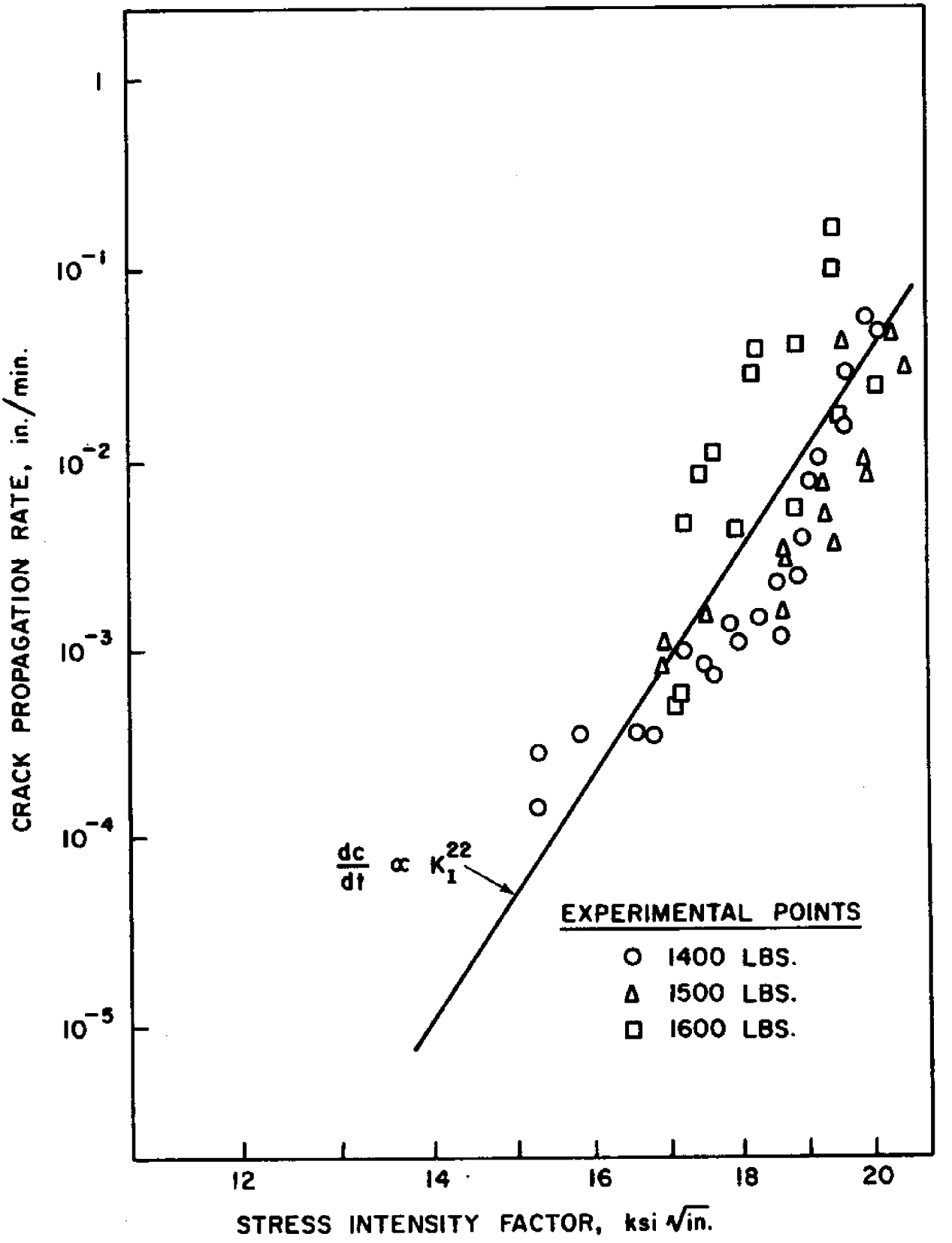


FIGURE 16.

CONSTANT LOAD CRACK PROPAGATION RATE vs. STRESS INTENSITY FACTOR (WET ENVIRONMENT).