TENSILE FATIGUE BEHAVIOR OF POLYESTER YARNS
IN AMBIENT AND SEA WATER ENVIRONMENTS

by

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ABSTRACT

The tensile fatigue behavior of a high-tenacity polyester
(PET) yarn was investigated in the context of its use in
marine ropes. Constant load-amplitude cyclic fatigue and
creep tests were conducted on a servohydraulic testing
machine; cyclic frequencies were 0.1 and 1.0 cycles per
second. Tests were conducted on dry yarn at ambient
conditions and in synthetic sea water.

The PET yarn S-N curve was found to be linear on a
semi-log plot; a single failure mechanism appears to be
operative throughout the fatigue range studied. Fatigue
lifetimes are compared with nylon 6.6 yarn data (ambient and
sea water) previously reported (1). The PET yarn is more
fatigue resistant than the nylon 6.6 yarn on both normalized
and absolute stress scales for these test conditions. The
presence of sea water has much less of an effect on the
fatigue behavior of the PET than on nylon, apparently due to
greater plasticization of the latter. Cyclic fatigue
lifetimes of the PET yarn are slightly longer than creep
lifetimes at similar maximum loads.

A simple creep mechanism appears to dominate the cyclic
fatigue behavior of PET yarn, as evidenced by: (1) the total
time to failure for a given maximum stress level is constant
regardless of test frequency, and (2) the total strain to
failure is the same in creep as in cyclic fatigue, and is
insensitive to stress level. Assuming a creep mechanism,
fatigue lifetimes are calculated using an established
cumulative damage model based on creep rupture data.

Data are also presented for the change of tensile
properties of the PET yarn during the fatigue process. The
residual ultimate tensile strength remains constant over at
least 80% of its lifetimes, which is consistent with a creep
mechanism. The extension on each cycle and the hysteresis
loss per cycle were monitored by a minicomputer. Initially,
both properties decreased rapidly, then stabilized for the
majority of the lifetime.

Thesis Supervisor: Frederick J. McGarry

Title: Professor of Polymer Engineering and
Civil Engineering
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1. INTRODUCTION

Polyester fibers, most notably Poly(ethylene terephthalate) or PET, are used in a very broad range of textile applications. In many end-uses, the textile structure is subjected to cyclic tensile stresses over the majority of its service lifetime. Marine ropes which are employed in the towing of large ships, in single point moorings, and in offshore platform applications, are reported to experience such cyclic tensile fatigue (2). In these situations, the rope may be at ambient conditions (dry) or submerged in seawater during the cyclic loading process. This type of load/environment history may result in deterioration and possibly failure of the rope structure. If failure occurs unexpectedly while in use at high loads, the rope may snap back resulting in violent accidents including serious injury and even death to ship personnel.

In recent decades, synthetic polymeric fibers such as nylon, PET, and polypropylene have largely displaced natural fibers (sisal, manila, hemp) in the construction of large diameter ropes (2). The synthetic ropes offer several advantages: high strength to weight ratio, much superior rot resistance (microbial attack), more shock resistance and easier handling characteristics (3). However, the violent accidents resulting from synthetic rope snap back have focused attention on the degradation mechanisms and causes of ultimate failure of these structures. This study is one part of a
multidisciplinary project devoted to this problem (4). The mode(s) of degradation and their relative importance vary upon the application (loading history), environmental exposure, rope construction and constituent fiber properties (4). Rope ultimate failure has been classified (2) into four main groups: (1) environmental failure, (2) surface wear, (3) tensile and structural failure, and (4) fatigue failures. The underlying mechanisms associated with fatigue failures include fiber fatigue, structural realignment fatigue, hysteretic heating, and internal abrasion. Several of these mechanisms have been confirmed by pathological studies of worn ropes (4).

One objective of understanding rope degradation mechanisms is to design more efficient ropes; rope properties can be tailored for optimum performance in specific applications. Properties are a function of rope construction (structural geometry) and constituent fiber properties. Thus, a data base of relevant properties of rope fibers is highly desired. As previously mentioned, individual fiber/yarn fatigue properties may be significant in terms of determining rope fatigue behavior. A previous investigation associated with this project focused on the fatigue behavior of nylon 6.6 fibers, yarns and small ropes (5). The present study examines the static and cyclic fatigue behavior of PET yarn under identical conditions (sample preparation, testing parameters, test equipment) and offers comparisons to the nylon 6.6 data. This includes fatigue testing in ambient and sea water environments.
Discussion is also presented in this thesis on the effect of test frequency on fatigue behavior and its relationship to underlying mechanisms associated with PET fiber fatigue. A model is presented which allows calculation of average lifetimes of the PET yarn over a broad range of loading conditions. Finally, the effects of the fatigue process on the tensile properties of the PET yarn are explored.
2. LITERATURE REVIEW

2.1 Polyester (PET) Fiber

Fibers are commercially prepared (Dacron/Dupont, Fortrel/Celanese, etc.) from the thermoplastic synthetic polymer poly(ethylene terephthalate) or PET. PET is a semicrystalline polymer with a glass transition temperature ($T_g$) of 70°C. A list of relevant physical properties is given in Table 1. In fiber form, PET is used in various textile applications such as rope products, tire cord, apparel, carpets, and conveyer belts. In addition to fiber products, PET is employed extensively in biaxially oriented film form in applications such as magnetic tape, photographic film and food packaging, and is also blow-molded into carbonated beverage bottles (6).

2.1.1 Chemical Synthesis

Poly(ethylene terephthalate) is a linear backbone polymer of the polyester family. It is formed in a condensation reaction following step growth kinetics. PET is commercially prepared in a two step ester interchange reaction (7) of the dimethyl ester of terephthalic acid (A) and ethylene glycol (B), shown in Figure 1. The reaction is generally catalyzed by weak bases and must proceed to high conversions to obtain desired high molecular weight distributions.
2.1.2 Fiber Morphology/Deformation Characteristics

In PET fiber formation, the polymer melt is extruded through a die, termed a spinneret, into a gaseous medium where cooling and solidification occur (8). The as spun semicrystalline fiber has a spherulitic morphology with a very low degree of orientation. To obtain useful properties, the fiber must go through a drawing process involving very large axial plastic deformation (several hundred percent strain) at elevated temperatures. Drawing transforms the material's lamellar structure into a highly oriented fibrous structure possessing a radically different morphology (9).

Although various post-draw fiber structural models have been proposed (10), the fibrillar morphology proposed by Peterlin appears to be currently most consistent with reported physical properties of melt spun fibers (11). The basic element of the model is a very long (about 10 microns) and thin (100 Å wide) microfibril containing alternating regions of fully oriented crystalline blocks and amorphous areas, as shown in Figure 2. The amorphous regions primarily consist of chain folds, chain ends, rejected impurities, and tie molecules which vary in degree of extension. Peterlin attributes the high longitudinal modulus and strength of the microfibril to the large number of taut tie molecules (fully extended) which bridge the crystalline blocks.

The macro-fibrous structure is comprised of highly aligned, densely packed bundles of these microfibrils, termed fibrils. As a result of the deformational mechanism of the
drawing process (12), the ends of the microfibrils most likely concentrate in the outer surface of the fibril (Figure 3). This effectively renders the surface of the fibril less uniform, decreasing the autoadhesion between adjacent fibrils which facilitates macro-deformation by shearing displacement or sliding of fibrils.

Peterlin has proposed micromechanisms for fiber tensile deformation and ultimate failure based on the fibrillar morphology(9). The mechanical behavior of these materials can be discussed in terms of their inherent cohesiveness (bond strengths) and of the distribution and size of defects which influence the nucleation and growth of cracks. It is speculated that the weak links or defects in the fibrillar morphology exist at the ends of microfibrils where axial taut-tie molecule connection to other microfibrils is essentially interrupted. Hence, these areas are the primary candidates for the nucleation of microcracks from an applied axial strain. Further deformation results in axial growth of these microcracks accomplished by a sliding motion of the strong microfibril and fibril elements. The resistance to this deformation is necessarily high; the quasi-viscous frictional forces which must be overcome for sliding are great due to the large surface area of these long and narrow structural elements. Peterlin speculates that such a sliding motion of microfibrils and fibrils is most likely the main mechanism of creep (9). The microcracks at microfibril ends may be considered point vacancies and serve as stress
concentrators; cracks will grow radially by the failure of tie molecules in highly stressed adjacent microfibrils. Coalescence of cracks will be accomplished by failure of interfibrillar tie molecules along the boundaries of adjacent microfibrils until a crack of critical proportions is reached.

2.2 Tensile Fatigue Studies of Polymeric Fibers

The use of highly drawn polymeric fibers in mechanically severe environments (i.e. tire cords, rope products, conveyer belts, etc.) has generated interest in the cyclic fatigue behavior of this class of materials. Studies in this area vary in fiber type, form (monofilament, textile fiber, yarn), loading conditions (tension, compression, torsion and combinations thereof), and test frequency. This survey will focus on phenomenological and mechanistic studies of tensile fatigue of synthetic polymeric fibers (and low twist yarns) over a wide range of frequencies. Mathematical modeling will be considered in section 4.6. Related investigations which are beyond the scope of this review include biaxial rotation fatigue studies (13), biaxial rotation over a pin (14), bending fatigue (15), and torsional fatigue studies (16).

D. Prevorsek, W. Lyons and coworkers have conducted a series of studies (17-21) on the fatigue behavior of polymeric fibers. PET and acrylic single textile fibers were the focus of their study, although testing also included nylon, polypropylene, viscose rayon, and aromatic polyamide. Most of the tensile fatigue data were obtained on a specially constructed
multistation tester in the cumulative extension mode. Cumulative extension refers to cyclic testing at a constant stroke amplitude where the specimen permanent deformation (creep) is taken up on each cycle (22). A less extensive study was conducted on similar fibers in constant force amplitude fatigue. Testing frequencies ranged from 1 to 10 Hz.

Data from the cumulative extension experiments (20) are presented in Figure 4 in a plot of strain amplitude (%) vs. log cycles to fail. Fibers are ranked in order of fatigue resistance: nylon 6 > nylon 6.6 > PET 420 > PET 52 > acrylic > rayon. The more resistant Type 420 PET was found to have a higher number-average molecular weight and higher % crystallinity than the Type 52. Curves of all fibers possess inflection points at approximately 100 cycles, dividing the curves into regions of short and long term endurance. Other fatigue lifetime data (both cumulative extension and constant force amplitude) were reported in plots of probability of survival (%) vs. log cycles to fail (17, 19). The authors report that both sets of data may be fitted by Weibull distributions.

In another study (20) in the cumulative extension mode by Prevorsek and Lyons, the cyclic extension (extension on cycle n/sample length on cycle n) and the creep extension were monitored for a series of fatigue tests. Results of these test indicated that the majority of internal structural changes of the fiber occurred during the initial part of the fatigue process. The authors also report that the tensile
strength of the fiber remains constant throughout most of its fatigue life (18).

Prevorsek and Lyons describe fatigue fracture in fibrous polymers (21) as a brittle crack nucleation process, based on their findings: (1) that the number of cycles to fail is frequency sensitive, and (2) that the extension at break under fatigue conditions increases with stroke (at constant frequency) and increases with decreasing frequency at constant stroke. The authors state "that creep is only an accompaniment of fatiguing by cyclic extension, and not the immediate cause of final rupture, which is believed to be the result of crack propagation." Based on this approach, they present a detailed mathematical treatment relating fatigue lifetimes to applied load, fracture surface energy, tensile modulus, and the activation energy associated with crack growth.

J. Hearle, A. Bunsell and coworkers (22-24) investigated the tensile fatigue behavior of nylon, PET, PAN and aromatic polyamide fibers, devoting particular attention to the relationship between loading conditions and the underlying failure mechanisms. Testing was performed under constant load amplitude conditions on a specially constructed apparatus. Test frequency was generally 50 Hz. Extensive fractographic studies were performed using the SEM.

The authors found that the mechanism responsible for fiber failure in cyclic fatigue changes from creep rupture to crack initiation and growth under certain loading conditions.
These conditions vary amongst fibers, but generally include cyclic loading at high frequencies (50 Hz) between a zero or near-zero minimum load and a maximum load of approximately 60% of the ultimate tensile strength (70% for PET). For example, a study on nylon 6.6 indicated that raising the minimum load from zero to 6% (with a maximum load of 55% UTS) resulted in a shift of failure mechanism from essentially all axial-crack growth breaks to all creep breaks (24).

Hearle and Bunsell classify the axial crack growth mechanism as a "true fatigue" failure. Fracture morphologies observed with the SEM were used to distinguish between true fatigue and creep rupture failures. The creep rupture morphology resembles the fractured surface of a fiber from a simple tensile test (23). In this type failure, a crack initiated at the fiber surface and grew radially (opening into a V-shaped notch) until the remaining cross-section failed catastrophically. Fracture morphologies attributed to true fatigue failures demonstrated a substantially different failure sequence. A crack initiated on the fiber surface but penetrated radially only approximately 1 micron (24). The crack then sharply deflected to run at a slight angle to the fiber axis, slowly making its way across the fiber diameter until catastrophic tensile failure occurred. Thus, one fracture end of the fiber possessed a long "tail" which rendered it easily distinguishable from the creep morphology. It was noted that the total strain to failure of fibers which failed in the true fatigue mode was consistently lower than
those which apparently failed in a creep mode (12% vs. 20% for PET).

The effect of exposure to sunlight (UV degradation) on the fatigue behavior of nylon 6.6 was examined. Samples which were exposed for 3 months demonstrated shorter lifetimes in fatigue and a modified fracture morphology (23). It was postulated that particles of titanium dioxide (commonly used as a delustering agent) within the fiber accelerated the UV degradation.

I. Narisawa, M. Ishikawa and H. Ogawa examined the micromechanisms involved in the fatigue process of nylon 6 monofilaments (90 den) by observing changes in the structural and mechanical properties (25). Cyclic fatigue testing was conducted under constant displacement (stroke) conditions at a frequency of 1.2 Hz. Fatigue tests were interrupted at various points and changes in the fiber structure were probed with several analytical techniques such as small- and wide-angle X-ray scattering, birefringence, molecular weight determination, dye diffusion and mechanical testing.

Their findings may be summarized as follows. Mechanical testing revealed that the fiber's ultimate tensile strength remained relatively constant (after a slight initial increase) while the elongation to break decreased with fatigue cycles. They observed a monotonic increase in the long period (using small-angle X-ray scattering) over $2 \times 10^4$ cycles at 20% stroke. Both birefringence and dichroism studies showed an increase in the degree of orientation with fatigue.

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Wide-angle X-ray scattering revealed no appreciable crystallite deformation resulting from cyclic loading. A slight decrease in molecular weight detected by reduced viscosity measurements was reported for samples cycled at 20% stroke for $1 \times 10^4$ cycles.

From these results, the authors suggest that the fatigue process can be divided mechanistically into two stages. In the first stage, structural changes are occurring primarily in the microfibril tie-molecule region (Peterlin model). This is evidenced by the initial increase in long period with no corresponding crystallite deformation, the increase in degree of orientation, the strain hardening effects or decrease in strain to failure, and the slight increase in ultimate tensile strength. From the reduction in molecular weight and the continued increase in long period at longer fatigue intervals, the authors speculated that the second stage of the process results from increased load bearing and rupture of taut tie molecules and from fibril and microfibril sliding. The authors express their agreement with Prevorsek and Lyons that fiber lifetimes cannot be predicted from measurements of structural or mechanical property changes during fatigue since final rupture is precipitated by a localized crack.

M.C. Kenney, J.F. Mandell and F.J. McGarry (1, 5) investigated the tensile fatigue behavior of polymeric single fibers, yarns, and small ropes in the context of a broader study of the degradation of marine ropes (4). Fatigue testing was conducted in load control on servohydraulic testing
machines using the sine wave function. Test frequencies were 0.1, 1.0, and 10 Hz. A stress ratio \( R = \min \text{ stress}/\max \text{ stress} \) of 0.1 was generally used; results were compared to slack load testing (zero minimum load during cycling). Emphasis was placed on nylon 6.6 fibers and yarns (1260 den, lightly interlaced); a limited amount of data was also reported for nylon ropes, and PET and aramid (Kevlar/Dupont) fibers. Fatigue lifetime data were presented in the form of S-N curves. Testing was conducted on dry samples (ambient conditions) and also in an environmental chamber which allowed continual immersion in synthetic sea water.

The authors report that nylon 6.6 single fibers, yarns and small ropes possess nearly identical normalized S-N curves at all frequencies tested. The single fiber fatigue behavior appears to determine the yarn and small rope fatigue behavior without significant complications due to interfiber effects. (It was noted that larger ropes may have considerably altered fatigue properties due to more pronounced fiber interactions.) A simple creep rupture model was proposed as the single failure mechanism operative at all three structural levels throughout the fatigue range studied. This was evidenced by (1) the fatigue lifetimes were time under load sensitive, and (2) the total strain to failure (at a given structural level) is independent of the type of loading (ramp, creep, cyclic fatigue), the load levels, and the test frequency. A cumulative damage model based on the nylon 6.6 single fiber creep rupture data provided fatigue lifetimes which were in

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good agreement with experimental lifetimes of the fiber, yarn, and rope. PET and Kevlar cyclic fatigue data were also consistent with the creep rupture model. Slack loading of nylon yarn resulted in similar fatigue lifetimes compared to cycling at R=0.1. Fracture surfaces in both cases show a mixture of the transverse and axial crack growth modes reported in the literature (23).

Immersion of nylon fibers and yarns in synthetic seawater during fatigue reduced lifetimes by approximately 10% lower load (or one decade of cycles). Similar behavior was observed for immersion in distilled water, LiBr and LiCl solutions. The relatively mild effect of the aqueous environments was attributed to plasticization which apparently accelerates the creep rupture mechanism. The highly oriented fibrous structure of nylon filaments suppresses any environmental stress cracking effects, presumably because transverse crazing is inhibited.

The residual tensile strength of nylon single fibers and yarns remained constant up to at least 75% of their lifetimes, hence failing in a sudden-death fashion. The residual strain to failure and energy absorbing capability did show considerable reductions during the fatigue process. Yarn and rope hysteresis loops achieved a stable shape after a low number of cycles, then translated in the direction of greater permanent strain. The hysteresis loss of nylon 6.6 yarns was found to be approximately ten times greater than PET yarns for cycling at 1 Hz.
2.3 Rope Construction/Fatigue Studies

Ropes are linear, fibrous assemblies which are generally employed as flexible, tension members. Materials commonly used in their construction include synthetic fibers (nylon, PET, polypropylene, aramid), natural fibers (hemp, sisal, manila), and various types of metallic wire. In rope manufacture, textile yarns are generally combined into larger substructures, such as plied or rope yarns, which are converted by some type of twisting or interlacing process into the final rope structure. The common rope constructions in use today (26) are the 3-strand twisted, 8-strand plaited, the double braid, and the parallel strand. Materials and constructions may be chosen to obtain desired properties such as strength, modulus, flexibility, corrosion/environmental resistance, shock absorbing capability, durability and handling characteristics. A review of synthetic ropes with emphasis on marine applications is given in Reference 3.

The cyclic fatigue behavior of rope structures has not been thoroughly characterized. Recent investigations (2, 4) have attempted to identify the dominant failure mechanisms of ropes subjected to applied cyclic loads. Although most of these studies focus on nylon and not PET, they are relevant to this study since much of the degradation occurs on the rope structural level. Hearle and Parsey (2) classify rope failures into 4 main groups: (1) Environmental failure, (2) Surface wear, (3) Tensile and structural failures, and (4) Fatigue. Failure mechanisms associated with
fatigue include cyclic creep, hysteresis heating (fiber and structural), fiber fatigue, structural realignment fatigue, and internal abrasion. The authors make note of the difficulties involved in predicting the fatigue lifetimes of these materials over a broad range of loading conditions due to the large number and interdependence of operative failure mechanisms.

Backer and coworkers have attempted to identify and characterize the relative importance of the various active failure modes and deterioration mechanisms by performing detailed, pathological studies of worn ropes (4). Their results indicate that the type and extent of deterioration depends on the mode of usage, environmental exposure, rope construction and constituent fiber properties. The study to date has focused on two rope systems: (1) three-strand twisted nylon 6.6 ropes (6-9 inches circumference) employed as pierside mooring lines, and (2) double braided nylon 6.6 ropes (4 inch circumference) used as buoy moorings. Analytic techniques used included visual and SEM observations, residual tensile property determination, and molecular weight and DSC studies.

Several degradation modes were observed in the 3-strand twisted/pierside mooring line. SEM photographs reveal localized surface deterioration due to abrasion with external objects and due to photochemical attack. Filaments located at the contact points between strands showed visual signs of significant damage and measured strength loss due to
internal abrasion. Filaments at the interstrand pressure points often welded, reflecting elevated temperatures (hysteretic heating) and localized transverse pressures during rope deployment.

The double braided/buoy mooring lines possessed a substantially different degradation pattern. These ropes were submerged for most of their lifetimes, hence no surface photochemical damage and less external abrasion damage were noted. The investigators observed extensive filament abrasion in contact zones between crossing ply-yarn helices and between parallel helix yarns in the core and sheath. Residual tensile strengths of the ropes ranged from 40% to 60% of the manufacturer's reported new rope strength. The strain to failure of unabraded fibers were reported to be above that of the new fiber, implying that fiber shrinkage occurred. This suggests that fiber cyclic creep due to fatigue was not operative for these conditions, since creep would reduce the residual strain to failure. The authors conclude that internal abrasion is a primary factor in rope deterioration in certain applications.

A limited amount of S-N data for large synthetic fiber ropes has been reported. Parsey (27) has reported linear regressions of S-N curves of wet polyamide, polyester and polypropylene ropes. The author ranked the wet fatigue performance: Polyester > Polypropylene > Polyamide. The poor wet performance of the nylon rope was speculated to result from a combination of higher internal friction and poorer wet
yarn-on-yarn abrasion properties. Parsey also found that fatigue lifetimes were relatively insensitive to rope construction for these test conditions. Bitting (28) conducted snap loading tests (zero minimum load cyclic fatigue) at 0.5 Hz on nylon 8-strand plaited rope (0.5 inch diameter) and reported lifetimes of about $2 \times 10^5$ cycles at a maximum load of 30% of the rated breaking strength. He suggests that snap loading of rope structures may result in shorter lifetimes compared to cyclic fatigue with a positive minimum load.
3. EXPERIMENTAL PROCEDURES

3.1 Materials

All testing was performed on PET fibers in yarn form. A Dupont Dacron 1000 den (1110 dtex) high tenacity yarn which is currently used in rope manufacture was chosen. The yarn consists of 192 filaments of approximately 5.2 den each (23 microns in diameter). The yarn has zero twist but is air jet interlaced, implying that the filaments are roughly parallel to each other but have areas of slight entanglement at periods of a few inches. All samples were taken from one yarn package of Dupont Type 1000-193-R02-D608-B.

A representative stress-strain curve of the yarn is given in Figure 5. All tensile tests were performed at a constant rate of loading of 175 Ns\(^{-1}\) (ramp function at 2 Hz) on a servohydraulic machine. This is equivalent to the averaged rate of the loading portion of a fatigue cycle at a master frequency of 1 Hz. The yarn possessed an ultimate tensile strength of 9.0 g/den (1.58 \(\times 10^5\) psi), breaking strain of 15.9 %, and an initial modulus of 126 g/den (2.13 \(\times 10^6\) psi).

3.2 Gripping Methods

Specimens to be tested in cyclic fatigue must be gripped carefully in order to prevent premature failure by undesired mechanisms (stress concentration factors at grip, abrasion). The tabbing method which was selected produces gauge-section failures in over 80% of all tests. All data from
non-gauge-section failures (jaw breaks) were discarded. The system parallels the tabbing method used in a previous study on nylon (5).

Different tabbing materials were required for testing dry (at ambient conditions) and for testing during continual immersion in sea water. The materials and their uses are presented in Figure 6. Adhesive A primarily secured the yarn to the tab while Adhesive B (silicone rubber) minimized stress concentrations and abrasion at the end of the tab.

For testing at ambient conditions (dry), the tabbed specimens were mounted in standard screw action grips (200 pound capacity). Specimens tested in sea water were mounted in the grips of the environmental chamber (refer to section 3.5).

3.3 Cyclic and Static Fatigue Testing

Cyclic fatigue and static fatigue (creep) tests were conducted on closed-loop servohydraulic machines. All tests were performed in load control; loads were monitored with a Nicolet digital oscilloscope. Load cells were mounted in a specially constructed vibration isolation stand to reduce feedback noise from the hydraulic pump system and floor.

Cyclic fatigue experiments may be characterized by the following parameters: mean load, load amplitude, frequency and waveform. A sinusoidal waveform was used exclusively in this study. Testing was conducted at master frequencies of 1.0 Hz and 0.1 Hz. Actual test frequencies were calculated
for each maximum load ($\text{freq} = \text{master freq}/(\text{maximum load}/\text{UTS})$) in order to maintain a constant averaged rate of loading for all tests at a given master frequency. For presenting data, it is more convenient to report the maximum load per cycle and the stress ratio ($R = \text{minimum load}/\text{maximum load}$), rather than the mean and amplitude loads. This permits the reporting of data in the form of $S$-$N$ curves ($S$: maximum stress per cycle, $N$: number of cycles to fail). A stress ratio of 0.1 was used for all cyclic fatigue tests.

Static fatigue (creep) tests were performed on both the servohydraulic machine and on a support stand with dead weights. The servohydraulic creep tests were accomplished using a load controlled ramp function (0.5 sec to maximum load). Creep data from the dead weight experiments were in agreement with the servohydraulic results.

3.4 Computer Assisted Data Acquisition and Analysis

A MINC 11 digital computer (Digital Equipment Corporation) was interfaced to the servohydraulic machine. This permitted controlled sampling of load and piston displacement (stroke) voltages throughout the duration of the fatigue (static and cyclic) tests. The acquired data were used to calculate the hysteresis loss per cycle, the extension per cycle, and the cumulative or creep extension as a function of fatigue cycles.
3.5 Environment

Ambient tests were conducted in an air conditioned laboratory without humidity control. Previous work on nylon (5) showed that creep results obtained in this environment were identical to those obtained in a chamber at 65% R.H.

To simulate a marine environment, a series of cyclic fatigue tests were conducted in synthetic sea water. An environmental chamber mounted on the Instron piston allowed continual immersion of the PET yarn throughout the fatigue test. Tabbed specimens were held by the plastic grips of the chamber. The sea water was a synthetic preparation specified by ASTM D1141-75. All specimens were preconditioned by immersion in the sea water for 10 minutes prior to testing.
4. RESULTS AND DISCUSSION

4.1 PET and Nylon Yarn Cyclic Fatigue Behavior

The S-N curve of the PET yarn at ambient conditions is given in Figure 7; fatigue test parameters are given on the Figure. Each data point represents one test; the curve is a least squares linear regression of all points except the single cycle tensile data. The equation of the S-N curve can be found in Table 2. Fatigue lifetimes are slightly longer than the constant load amplitude fatigue data for PET fibers in the literature (19, 23). This may be due to slightly different loading conditions (minimum load, frequency) or to inherent differences in properties of PET fiber types (17). The data are highly linear (correlation coefficient of 0.97) on a semi-log plot, a behavior common to many polymers (29). No fatigue limit (or decrease in slope of the S-N curve) was found at low stresses in the range studied.

The S-N curve of a nylon 6.6 yarn obtained on the same equipment (5) is included in Figure 7 for comparison with PET data. (The two fibers are presently used extensively in marine ropes, hence there is an active interest in identifying the relative merits of each.) Sample size, sample preparation, and test parameters (frequency, R ratio, waveform) for the PET study rigorously paralleled those used in the nylon study (refer to Experimental Procedure and to Reference 5). Stresses in Figure 7 are normalized to the single cycle tensile strengths of each material. On a
normalized basis, the PET yarn is substantially more fatigue resistant than the nylon 6.6 yarn. Linear regression equations may be compared in Table 2; the rate of degradation for PET yarn is approximately a 4.5% loss of the single-cycle tensile strength per decade of cycles vs. a 9.0% loss per decade for nylon (at 1 Hz). For example, a maximum load of 75% UTS results in an average lifetime of approximately 1000 cycles for nylon 6.6 vs. approximately 150,000 cycles for the PET. This is in agreement with reports in the literature (23) of PET having considerably greater lifetimes than nylon in constant load amplitude fatigue, although only a limited amount of data had been previously given. However, these findings may be contrasted to data presented in Figure 4 by Prevorsek and Lyons on the behavior of the two fibers in cumulative extension fatigue (refer to Section 2.2), which would suggest that nylon possesses longer lifetimes than PET under constant stroke amplitude conditions. These results may not be inconsistent with the findings of this study; a given extension translates into a lower load for the lower modulus nylon than the PET (shown schematically in Figure 8). Therefore, it is difficult to directly compare the data obtained in the two studies. Each test method is representative of loading environments which exist in actual applications of textile materials. Designers of such materials should thus consider whether their applications more closely resemble constant load-amplitude or constant
stroke-amplitude conditions before selecting a fiber type based on relative fatigue performance.

4.2 Effect of Sea Water on Fatigue Behavior

The effect of sea water on the cyclic fatigue behavior of PET was examined in the context of its use in marine rope applications. As mentioned in the Experimental Procedure, fatigue testing was conducted in an environmental chamber which allowed continual immersion in a synthetic sea water preparation. Specimens were preconditioned in the sea water for ten minutes prior to testing. Testing conditions were identical to dry testing, except for a slightly modified tabbing system described in Section 3.2.

S-N curves for PET yarn in ambient and sea water conditions are given in Figure 9, again with comparable nylon 6.6 yarn curves from the literature (5). Linear regression equations are given in Table 2. Stresses are normalized to the single cycle tensile strengths for each material and condition. Testing of PET in sea water results in slightly shorter lifetimes compared with ambient results, although the magnitude of the effect may also reflect the additional difficulties of conducting fatigue tests in aqueous environments. On a normalized plot, fatigue performance of PET appears to be less sensitive to the presence of sea water than is nylon. Previous reports (5) indicate that sea water acts as a mild plasticizing agent within the amorphous regions of the nylon fiber; a similar mechanism is consistent with
results for PET. The greater sensitivity of nylon's mechanical properties to aqueous solutions could be expected based on its higher moisture absorption (30) and on evidence which suggests that water can disrupt the hydrogen bonding of the nylon structure (31). Previous investigations (5) report a change in the stress-strain behavior of nylon, especially a decrease in initial modulus, when tested in sea water. Tensile tests were conducted on PET in ambient and sea water conditions for comparison. Results listed in Table 3 reveal essentially no change in ultimate strength, strain at failure, or initial modulus; hence supporting the insensitivity of PET to aqueous environments.

It is convenient to normalize fatigue loads when plotting S-N curves in order to delineate fatigue resistance from differences in tensile strength. However, an end user would most likely prefer a comparison of the fiber fatigue performance on an absolute stress scale. Two such plots are given for PET and nylon yarn in ambient and sea water conditions in Figure 10, where the stresses are expressed in KSI (psi x 10³) and in grams per denier. (Denier is a measure of linear density referring to the weight in grams of 9000 meters of yarn.) Relative ranking of fatigue performance remains essentially unchanged since the ultimate tensile strengths of the two fibers (in both conditions) do not differ substantially (Table 2). However, load normalization by cross-sectional area (KSI) enhances the relative fatigue performance of the higher
density (1.38 g/cm\(^3\)) PET, whereas normalization by linear
density (gpd) favors the lower density (1.14 g/cm\(^3\)) nylon.

4.3 Static Fatigue (Creep) Behavior of PET

Creep Tests on the PET yarn were performed using two
procedures: (1) a servohydraulic Instron in the
load-controlled ramp mode, and (2) a support stand with dead
weights. The latter method was chosen for tests at lower
loads (below 80%) and longer times to fail. Data from both
procedures is plotted in Figure 11, along with a nylon 6.6
curve from the literature (5). The PET curve is highly linear
on a semi-log plot, with a correlation coefficient of 0.97.
The relative performance of PET and nylon 6.6 in creep is
qualitatively similar to their behavior in cyclic fatigue.
Equations of the creep curves of both fibers are given in
Table 2.

A plot of both the creep and cyclic fatigue lifetimes of
the PET yarn is given in Figure 12. Note that cyclic fatigue
lifetimes are plotted in terms of total time to fail rather
than cycles to fail. Creep lifetimes are slightly shorter
than corresponding cyclic fatigue lifetimes. Linear
regression equations of both curves are found in Table 2.

4.4 Frequency Effects

Many end uses of PET fiber structures, such as marine
ropes, involve cyclic loading over a broad range of
frequencies. A useful characterization of fatigue behavior
thus demands the investigation of the effect of frequency on fatigue lifetime. The results of this type of investigation can also be used to delineate between the possible failure mechanisms associated with polymers in cyclic fatigue. Reports in the literature (22, 29) indicate that failure in polymers subjected to cyclic loading conditions may result from a variety of possible mechanisms, such as cyclic creep, crack initiation and growth (as is common in metals), and hysteretic/thermal failure. Fatigue behavior may be dominated by one or a combination of these mechanisms, depending on various material characteristics (polymer type, crystallinity, orientation, the presence of additives, etc.) and on testing conditions (frequency, temperature, specimen size and geometry, environment).

Cyclic fatigue lifetimes (expressed as time to fail) of PET yarn conducted at master frequencies of 0.1 Hz and 1.0 Hz are compared in Figure 13. Lifetimes at both frequencies fall on the same curve (with scatter which is typical for this type of material), indicating that the total time to failure at a given maximum load is constant over the range of frequencies tested. This behavior is generally referred to as time under load sensitivity and is characteristic of materials which exhibit cyclic creep failures. (Materials which fail by a crack initiation and growth mechanism exhibit cycle sensitivity, referring to a situation where failure occurs at a constant number of cycles at a given maximum load.) Reports in the literature (5, 21, 23) are contradictory as to whether
polymeric fibers fail in fatigue by cyclic creep or crack
growth mechanisms. It is most likely that either mechanism
can be forced to dominate by proper control of loading
conditions. Reports indicate that high test frequencies (50
Hz) and slack loading conditions have resulted in a high
percentage of axial-crack growth type failures, whereas
frequencies in the range of this study (0.1 to 1 Hz) appear to
result in transverse crack failures. However, results
presented for nylon in Ref. 5 indicate that axial-crack
failures may occur in creep as well, and that the lifetimes
with axial crack failures are not significantly different than
those with transverse cracks. Aramid fibers always fail in
the axial crack mode, but their lifetime appears to be
consistent with time under load domination (5).

No evidence was found in this study to suggest that
hysteretic heat build-up was significant for PET in yarn form
over the range of test frequencies. This most likely reflects
the large surface area/volume ratio of the small diameter
fiber assembly which allows efficient heat transfer. This is
in agreement with a treatment in the literature (23) which
indicates that temperature rise should be minimal for these
test conditions. However, larger diameter fiber assemblies,
such as marine ropes, may be subject to hysteretic heating
effects (2).
4.5 Strain at Failure: Creep and Cyclic Fatigue

Specimen elongation was monitored throughout creep and cyclic fatigue tests of the PET yarn by a minicomputer interfaced to the servohydraulic machine, as described in the Experimental Procedure. Plots of cumulative extension vs. log cycles for two maximum load levels (90% and 75% UTS) are given in Figure 14, along with the average creep strain to failure. These curves are representative of the fatigue behavior of this material in general; the fibers experience a gradual increase in length at a rate determined by the maximum load, irrespective of frequency, until failure occurs at a strain level very near the strain to failure of the material in creep. The average % strain to failure in creep and cyclic fatigue was in fact observed to be equivalent: creep = 16.92 ± 0.69, cyclic = 16.80 ± 1.3. This behavior would suggest that a single failure mechanism was operative in both cases, offering additional support to the cyclic creep mode of failure.

4.6 Creep Rupture Model for Fatigue Lifetime

Evidence has been presented supporting a creep rupture mechanism for PET yarn under the cyclic fatigue test conditions used in this study. It was shown (Figure 12) that creep and cyclic fatigue lifetimes at a given maximum load were nearly identical; the cyclic lifetimes generally being slightly longer. It was found that cyclic fatigue lifetimes were dominated by time under load effects, as the total time to
failure was constant at a given maximum load regardless of test frequency (Figure 13). Finally, it was shown that the total strain to failure for creep and cyclic fatigue tests was equivalent (section 4.5), indicating that a similar failure mechanism was operative in each loading condition.

Assuming that a creep rupture mechanism dominates cyclic fatigue behavior, several models based on creep rupture data have been proposed to calculate fatigue lifetimes over a broad range of loading conditions. In the mid-1950's, Coleman (32) applied reaction rate theory to the tensile behavior of polymeric filaments (nylon) under various stress conditions, including sinusoidal loading. His treatment was based on "bond slip" or secondary bond rupture as the primary mechanism responsible for ultimate failure. Coleman's model predicts that the cyclic fatigue lifetime should be insensitive to frequency and that a sinusoidally varying stress should result in only slightly longer lifetimes than static stress at a given maximum load, both of which are consistent with the findings of this study. Coleman has also given a treatment (33) on the statistical nature of mechanical breakdown of fibrous assemblies in various loading conditions, including cyclic fatigue. Henderson (34) has reviewed other reaction rate approaches for predicting the ultimate failure of polymers, including treatments based on the rupture of primary valence bonds such as the Zhurkov model.

Cumulative damage models have long been used to estimate the lifetimes of metals (35) and inorganic glasses (36) in
cyclic fatigue. Cumulative damage models are purely phenomenological; the Coleman and Zhurkov (reaction rate theory) treatments are based on molecular considerations. Cumulative damage models are based on the assumption that the application of a given stress results in damage accumulation at a specific rate; failure occurs when the accumulated damage reaches some constant, critical value. McKenna and Penn (37) employed a simple cumulative damage approach to the cyclic creep of polymers (Polyethylene and PMMA). A similar approach has been applied to the fatigue behavior of the PET yarn employed in this study. In this model, the damage rate is taken to be the fractional value of the time spent at the given load divided by the creep time to failure at that load. Failure is predicted to occur when the sum of fractional values equals one, expressed in the following equation:

\[
\frac{t_1}{\tau(\sigma_1)} + \frac{t_2}{\tau(\sigma_2)} + \frac{t_3}{\tau(\sigma_3)} + \cdots + \frac{t_n}{\tau(\sigma_n)} = \sum_{i=1}^{n} \frac{t_i}{\tau(\sigma_i)} = 1
\]  

(1)

where \(t_n\) is the time spent at load \(\sigma_n\), and \(\tau(\sigma_n)\) is the average time to fail in creep at \(\sigma_n\). This may be expressed in integral form,

\[
\int_{0}^{t_f} \frac{dt}{\tau(\sigma)} = 1
\]

(2)

where \(t_f\) is the total time to failure. An expression for \(\tau(\sigma)\) was easily arrived at through a series of creep tests, reported in Section 4.3. As previously mentioned, the creep data were highly linear on a semi-log plot, hence can be given in the form:
\[ \tau(\sigma) = A \exp^{-B\sigma} \] (3)

where \( A \) and \( B \) are experimentally determined constants with values of \( 1.99 \times 10^{22} \) and \( 0.525 \) respectively for PET yarn. It is noted in passing that this is the form of \( \tau(\sigma) \) arrived at by Coleman from molecular considerations.

Assuming that cyclic fatigue behavior is dominated by creep, any stress-time function or loading history may be given for \( \sigma \) in equation (3). The appropriate equation for a sinusoidally varying stress such as used in this study is:

\[ \sigma(t) = p + q \sin(2\pi f)t \] (4)

where \( p \) is the mean load, \( q \) is the amplitude, and \( f \) is the test frequency. Substitution of Equations (4) and (3) into (2) and integration yields:

\[ t_f = \frac{\tau(p)}{I_0(Bq)} \] (5)

where \( \tau(p) \) is the time to fail in creep at the mean load \( p \), and \( I_0(Bq) \) is a zero-order modified Bessel function of the product \( B \cdot q \). Equation (5) is similar in form to the solution derived by Coleman (32).

Fatigue lifetimes calculated using Equation (5) are in good agreement with experimental results (Figure 15) for the PET yarn. However, limitations of the model should be recognized. Any change in testing conditions which results in a failure mechanism other than cyclic creep will render the model inappropriate. For example, the model may not provide adequate predictions for testing at relatively high frequencies (50 Hz), where reports (23) indicate a cycle
sensitive failure mechanism may dominate. The model may also fail when applied to the cyclic fatigue of large fibrous assemblies such as marine ropes, where other mechanisms such as internal abrasion (4) and hysteretic heating (2) have been shown to exist. It has also been shown (5) that fiber reloading even in lightly interlaced yarns may be important at constant load, but the fibers may work free from the yarn under cyclic loading at low R values. Thus, yarn structural effects which vary with load history may make cyclic performance difficult to predict from creep rupture data, despite the commonality of failure modes.

4.7 Residual Property Analysis

Structural changes in polymeric fiber microstructure during the cyclic fatigue process have been reported (25) to affect the residual tensile behavior. A limited investigation was conducted to explore the effect of constant load amplitude fatigue on PET yarn properties such as tensile strength, extension per cycle, and hysteresis loss per cycle. Observed trends in yarn behavior may offer insights into the reported residual tensile behavior of large fibrous assemblies such as marine ropes in cyclic fatigue.

The effect of cyclic fatigue on the ultimate tensile load of PET yarn is given in Figure 16. Fatigue tests at several loads and frequencies were interrupted at various percentages of their respective average lifetimes (from the PET yarn S-N curve in Figure 7); the ultimate tensile load was
then immediately evaluated (load-controlled ramp function at 2 Hz). The figure indicates that residual tensile ultimate load remains relatively constant over at least 80% of its expected fatigue lifetime. This is consistent with a creep rupture mechanism for cyclic fatigue. The slight increase (approximately 5%) in tensile strength shown in the Figure may be attributed (25) to better orientation and a larger number of taut tie molecules resulting from cyclic creep effects, or to increased yarn efficiency due to better alignment. These results imply that failure on the fiber/yarn level occurs in a sudden-death fashion, with no apparent gradual decay in tensile strength with fatigue cycles. This behavior is not in agreement with the residual tensile behavior (4) of larger fibrous assemblies such as marine ropes, where other degradation mechanisms may be active due to fiber interactions in the highly twisted rope structure.

Cyclic extension (defined as the extension on cycle n/sample length on cycle n) and the hysteresis energy loss per cycle of the PET yarn were continuously monitored throughout the fatigue process by a minicomputer (refer to Experimental Procedure). Representative curves of each are given in Figure 17 and 18 respectively. Each property exhibits an initial stage of rapid decay followed by relative stabilization; qualitatively similar behavior was exhibited at all load levels and frequencies. Each property exhibits a slight increase at the end of its lifetime, apparently due to the failure of a small number of fibers within the yarn which
increases the stress level on the survivors. This results from the typical scatter in fatigue lifetimes of individual polymeric fibers or from unequal loading of fibers.

The rapid decay of cyclic extension observed in the PET yarn has also been reported for large rope structures (27). The rope behavior most likely reflects a combination of a structural shakedown of the rope structure itself as well as the change in fiber properties.
5. CONCLUSIONS

Several conclusions can be drawn from the results presented in this study. In these conclusions, PET yarn refers to the Dupont D608 Dacron Polyester yarn described in section 3.1; nylon yarn refers to Dupont 707 Nylon 6.6 yarn described in Reference 5.

(1) The S-N curve of a high-tenacity PET yarn is highly linear on a semi-log plot; a single failure mechanism appears to be operative throughout the fatigue range studied. Cyclic fatigue and creep lifetimes at a given maximum load are nearly identical, the cyclic lifetimes generally being slightly longer.

(2) PET yarn is more cyclic fatigue resistant than the nylon yarn (data from Ref. 5) on both normalized and absolute stress scales for these test conditions (constant load-amplitude fatigue). The rate of degradation for PET yarn is approximately a 4.5% loss of single-cycle tensile strength per decade of cycles, compared with a 9.0% loss per decade for nylon yarn (ambient conditions, 1 Hz). The PET also possessed longer creep lifetimes than the nylon. However, these results may be contrasted to cyclic fatigue data obtained from constant strain-amplitude tests, where nylon apparently demonstrates better fatigue performance than the PET (20).

(3) Immersion of the PET yarn in synthetic sea water during cyclic fatigue causes a slightly shorter lifetime compared with ambient conditions (dry), apparently due to a
mild plasticization mechanism. Reductions in lifetime for the PET yarn are substantially less severe than reductions suffered by the nylon yarn in wet vs. dry fatigue (5).

(4) A simple creep mechanism appears to dominate the tensile fatigue behavior of PET yarn, as evidenced by: (1) the total test time to failure for a given maximum stress level is constant regardless of the test frequency, and (2) the total strain to failure is the same in creep as in cyclic fatigue, and is insensitive to stress level and frequency. A creep mechanism is consistent with the fatigue behavior reported for other polymeric fibers under similar test conditions (1).

(5) A cumulative damage model based on creep rupture data of the PET yarn can predict with acceptable accuracy the fatigue lifetimes of the yarn for a broad range of cyclic loading histories. However, by definition, the model is sensible only when applied to cyclic creep failures. In larger fiber structures such as marine ropes, other degradation mechanisms such as internal abrasion and hysteretic heating may be the direct cause of ultimate failure, rendering the model inapplicable.

(6) The residual tensile strength of the yarn remains constant over at least 80% of its cyclic fatigue lifetime. Thus, failure occurs in a sudden-death fashion, which is consistent with creep dominated behavior.

(7) The cyclic extension and hysteresis loss per cycle both decrease rapidly in the early stages of a cyclic fatigue
test, then stabilize for the majority of the sample lifetime. This is consistent with reports in the literature (25) which suggest that the initial stage of fiber fatigue involves considerable microstructural rearrangement. The resulting change in the tensile properties of rope fibers would most likely translate into qualitatively similar changes in rope stress-strain behavior, although the magnitude of such changes is also sensitive to structural rearrangements of fibers within the rope unit.
6. RECOMMENDATIONS FOR FUTURE WORK

The findings of this study suggest that further work in the following areas may be profitable:

(1) In this study, specimens were cycled continuously until catastrophic failure occurred. In actual applications such as a marine tow-rope, the structure may be employed intermittently, suggesting that the constituent fibers may experience periods of zero load. Creep recovery effects during these unloaded periods should be examined, as well as their effect on total fatigue lifetime.

(2) The fatigue behavior of other rope fibers, such as aramid, polypropylene, and possibly natural fibers, should be thoroughly characterized and compared to PET and nylon (5) data.

(3) The normalized fatigue resistance of fiber assemblies which fail by a cyclic creep mechanism appears in some cases to be substantially greater than structures which apparently fail due to interfiber effects (internal abrasion) and/or hysteretic heating (2,5). Rope constructions, such as the parallel strand structure (26), which make efficient use of this behavior should be further studied.

(4) Hysteretic heating of large diameter fiber assemblies such as marine ropes may be substantial in certain loading environments (2). It is expected that elevated temperature would accelerate the cyclic creep process which appears to dominate single fiber fatigue performance. A comparison of
the temperature sensitivity of the fatigue behavior of PET and nylon would be helpful.

(5) Changes in fiber tensile properties during the fatigue process were reported in this study. This type of data may be incorporated into models of rope mechanical behavior.
7. REFERENCES


Two-step ester interchange synthesis of poly(ethylene terephthalate). (Allcock, Ref 7)

Figure 1.
Schematic model of the Peterlin microfibrillar structure with many intrafibrillar (A) and few interfibrillar (B) taut-tie molecules.

(Peterlin, Ref 9)

Figure 2.
Peterlin fibrillar model of fibrous structure with microfibril ends concentrated on the outer boundary of fibrils. (Peterlin, Ref 9)

Figure 3.
LIFETIME OF POLYMERIC FIBERS IN LOG (CYCLES TO FAILURE) AS FUNCTION OF STRAIN AMPLITUDE. FREQUENCY, 4.16 Hz. (PREVORSEK AND LYONS, REF 20)

FIGURE 4.
Figure 5.

Typical Stress-Strain Curve
Dupont D608 PET Yarn (1000 Den)
**Figure 6.**

**Yarn Tabbing System**

![Diagram of Yarn Tabbing System]

<table>
<thead>
<tr>
<th></th>
<th><strong>Ambient</strong> (dry)</th>
<th><strong>Sea Water</strong></th>
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<td><strong>Tab</strong></td>
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<td></td>
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<tr>
<td>Material</td>
<td>Cardboard</td>
<td>PVC Sheet</td>
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<tr>
<td>Dimensions</td>
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<td><strong>Adhesive &quot;A&quot;</strong></td>
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<td><strong>Adhesive &quot;B&quot;</strong></td>
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<td>Silicone RTV Rubber</td>
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58
Figure 7.

S-N Curves at Ambient Conditions (Dry)
Dupont D608 PET Yarn
Dupont 707 Nylon Yarn (Ref 1)
R = 0.1 1 Hz

Maximum Stress (% Ultimate Tensile Strength)

Log Cycles to Fail
Figure 8.

Effect of Modulus on Stress Level in Cumulative Extension Fatigue (Ref 20)
Figure 9.

NORMALIZED S-N CURVES

DUPONT D608 PET YARN: AMBIENT AND SEA WATER
DUPONT 707 NYLON YARN: AMBIENT AND SEA WATER (REF 1)

R = 0.1  1 Hz

[Graph showing normalized S-N curves for PET and Nylon yarn under different environmental conditions]
Figure 10.

S-N Curves: Absolute Stress Scale
Dupont D608 PET Yarn: Ambient and Sea Water
Dupont 707 Nylon Yarn: Ambient and Sea Water (Ref 1)
R = 0.1          1 Hz
Figure 11.

Creep Lifetimes

DuPont D608 PET Yarn
DuPont 707 Nylon Yarn (Ref 5)
Figure 13.

EFFECT OF FREQUENCY ON FATIGUE LIFETIME
DUPONT D608 PET YARN \[ R = 0.1 \]

MAX STRESS (% ULTIMATE TENSILE LOAD)

- **MASTER FREQ**
  - \( 1.0 \) Hz (filled circles)
  - \( 0.1 \) Hz (open squares)

(LOG TIME TO FAIL (SEC))

(frequency varies with max stress)
Figure 14.

CREEP EXTENSION DURING FATIGUE

DUPONT D608 PET YARN  R = 0.1

\[ \% \varepsilon \pm 1 \text{s.d.} \]

\[ \text{LOG CYCLES} \]

\[ \% \text{CREEP EXTENSION} \]
Figure 15.
EXPERIMENTAL FATIGUE LIFETIMES AND MODEL PREDICTION
DUPONT 1668 PET YARN

MODEL

R = 0.1

MAX STRESS

% ULTIMATE TENSILE LOAD

LOG TIME TO FAIL ( SLF )

MASTER FREQ

• 1.0 Hz
□ 0.1 Hz

100 90 80 70 60 50 40 30 20 10 0

0 1 2 3 4 5 6
Figure 16.

Residual Tensile Ultimate Load After Fatigue

Dupont D608 PET Yarn (1000 Den) \( R = 0.1 \)

| Time Under Fatigue Load / Avg Time to Fail at Given Load \( \frac{T}{T_f} \) |
|---------------------------------|---|
| 90% UTS, 1.0 Hz                |
| 85% UTS, 1.0 Hz                |
| 80% UTS, 0.1 Hz                |

U.T.S. before fatigue
Figure 17.

Cyclic Extension During Fatigue
Dupont D608 PET Yarn  R = 0.1

75%UTS  1.0 Hz

Cyclic Extension (% E) vs. Log Cycles (N)
Figure 18.

Hysteresis Energy Loss per Cycle

DuPont D608 PET Yarn  \( R = 0.1 \)

Max Stress: 75%  \( 1 \text{ Hz} \)
<table>
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<tr>
<th>Property</th>
<th>Value</th>
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<td>Moisture Absorption</td>
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<td>Young's Modulus **</td>
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<tr>
<td>Oriented fiber</td>
<td>121.1 g/den</td>
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</table>

* Fuzek, Ref 30.
** Hearle, Ref 10.
### Table 2.
**Linear Regression Equations**

**Dupont D608 PET Yarn**

**Dupont 707 Nylon Yarn (Ref 5)**

<table>
<thead>
<tr>
<th>Yarn</th>
<th>Test**</th>
<th>Condition</th>
<th>Linear Regression***</th>
<th>Freq (Hz)</th>
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<td>Cyc Fat</td>
<td>Ambient</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>$P/P_u = -4.36(\log \text{sec}) + 97.97$</td>
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<td>&quot;</td>
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<tr>
<td>&quot;</td>
<td>Creep</td>
<td>Ambient</td>
<td>$P/P_u = -4.55(\log \text{sec}) + 96.88$</td>
<td>1.0</td>
</tr>
<tr>
<td>Nylon</td>
<td>Cyc Fat</td>
<td>Ambient</td>
<td>$P/P_u = -9.0 (\log \text{cyc}) + 102.0$</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>Sea Wat</td>
<td>$P/P_u = -11.1 (\log \text{cyc}) + 97.2$</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>Creep</td>
<td>Ambient</td>
<td>$P/P_u = -6.0 (\log \text{sec}) + 96.0$</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* Yarn Ultimate Tensile Strengths (grams/den; KSI)
  
  - PET/Ambient 9.0 ; 150
  - Nylon/Ambient 9.2 ; 134
  - PET/Sea Wat 9.0 ; 159
  - Nylon/Sea Wat 9.6 ; 140

** All Cyclic Fatigue Tests: $R = 0.1$, Sine Wave Function

*** $P = \text{Maximum Stress}$

  $P_u = \text{Ultimate Tensile Strength}$
### Table 3.
**Tensile Properties**

**Dupont D608 PET Yarn** (1000 denier)

**Ambient (Dry) and Sea Water Conditions**

<table>
<thead>
<tr>
<th></th>
<th>Ambient</th>
<th>Sea Water*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultimate Tensile Strength</strong> (gram / denier)</td>
<td>8.96</td>
<td>9.01</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.055</td>
<td>0.19</td>
</tr>
<tr>
<td>%C.V.</td>
<td>0.61</td>
<td>2.1</td>
</tr>
<tr>
<td>(psi)</td>
<td>1.58 x10^5</td>
<td>1.59 x10^5</td>
</tr>
</tbody>
</table>

| % Strain to Failure   | 15.9    | 14.2       |
| s.d.                  | 0.36    | 0.43       |
| %C.V.                 | 2.3     | 3.1        |

| **Initial Modulus** (gram / denier) | 126.4  | 127.1      |
| s.d.                                | 7.9    | 6.9        |
| %C.V.                               | 6.3    | 5.5        |
| (psi)                               | 2.13 x10^6 | 2.14 x10^6 |

* Preconditioned in synthetic sea water for 10 minutes