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7/25/68

PROPERTIES OF SYNTHETIC FIBERS

AT HIGH STRAIN RATES

A THESIS

Presented to

The Faculty of the Division of Graduate

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Harry Stanley Padgett

In Partial Fulfillment

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PROPERTIES OF SYNTHETIC FIBERS

AT HIGH STRAIN RATES

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Chairman

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SUMMARY

This work involves a study of the tensile rupture stress, rupture strain, and initial modulus of Nomex, polypropylene, nylon, and polyester fibers at a strain rate of 43,000% per second under standard conditions. The tensile properties of type 728 nylon have also been determined wet, dry, and 250°F at the high strain rate. The testing device used in this work has been shown to be capable of testing single fibers at strain rates above 100,000% per second.

It is concluded that at these high strain rates there is a trend for rupture stress and initial modulus to increase while the rupture strain decreases. The amount of change is dependent on the fiber type, sample conditioning, test environment, and strain rate.

CHAPTER I

INTRODUCTION

Purpose

The properties of fibers at very high strain rates are of great practical importance. Properties such as breaking stress, breaking elongation, and initial modulus vary with the strain rate at which fibers are tested. As a result, standard Instron tensile tests which are considered quasi-static, are not adequate in all cases for predicting fiber behavior at strain rates above one percent per sec. It is estimated that a fiber can experience strain rates as high as 10,000% per sec in high speed sewing, tire cord impact, and in safety and parachute lines.[1] Thus, it is of interest to know what the physical properties of fibers are at these higher strain rates so that meaningful margins of safety can be introduced into the design of such items.

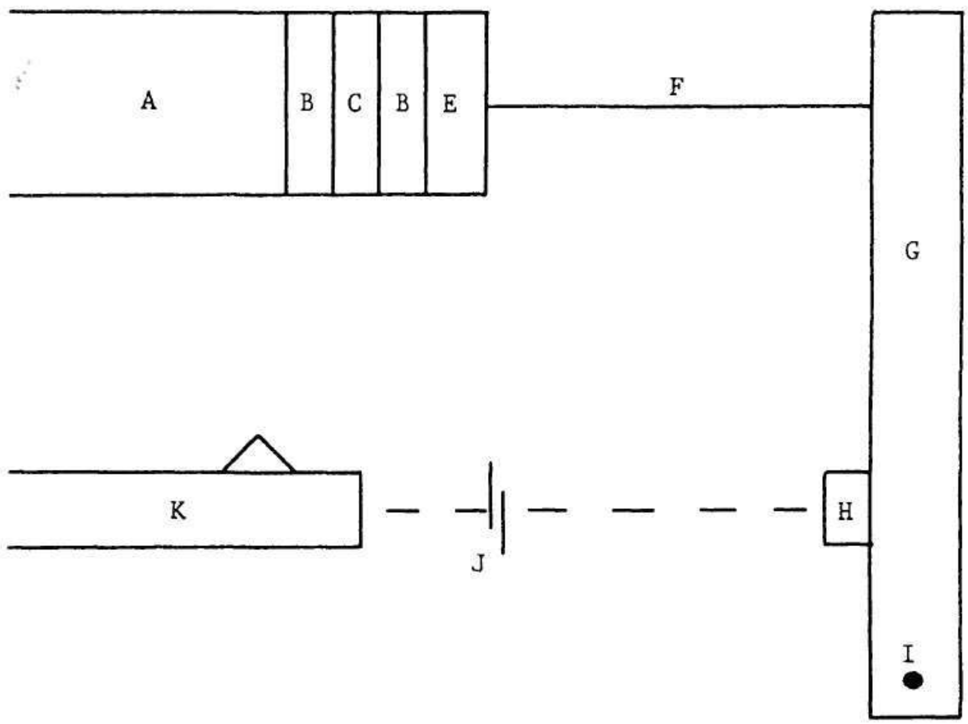
Previous Studies

The mechanical properties of yarns have been studied extensively at quasi-static strain rates on the conventional Instron Tensile Tester in the range of 0.01 to 1.0% per sec. Higher strain rates have been difficult to achieve due to the stringent requirements placed on the testing instrumentation. As a result there has been only a limited amount of work done in this field. However, the previous work which has been done shows a pattern of increasing strain rates beginning with 1,000% per sec by Meredith[6] in 1953, 23,000% per sec by Lewis[7] in

1957, and 66,000% per sec by Holden[8] in 1959. High strain rate testing appeared to reach a stationary level with the work done by Hall[9,10,11,12] from 1961 to 1968 during which time he reported the properties of textile fibers at various strain rates in the range of 33,000 to 49,000% per sec.

Meredith produced stress-strain curves at a constant rate from 20 to 1,000% per sec. The constant rate of extension was obtained by driving one fiber grip at a constant speed by means of a synchronous motor and allowing the other grip to move a very small distance, this movement measuring the tension by means of a cantilever and optical lever. Because of the mechanical limitations of the system and a sample length of 13 cm., Meredith was only able to reach a strain rate of 1,000% per sec.

The apparatus which allowed stress-strain curves at strain rates in the range of 23,000% per sec to be obtained was developed by Lewis and is shown in Figure 1. The filament F is attached by Sellotape to one end of the arm G which can rotate about the axis I. The arm is set in motion by the impact of a lead pellet from the air gun K as the pellet strikes the anvil H. The other end of the filament is attached with Sellotape to the steel disc E. When the fiber is extended, a stress pulse is propagated through the gauge consisting of the quartz crystals B and the brass disc C. The resulting voltage from the gauge is displayed on one trace of a dual-beam oscilloscope and photographed. The oscilloscope sweep is triggered by the passage of the pellet through the two metal foils J which close a circuit arranged to trigger the sweep. The rate of extension is calculated from the angular velocity of the moving arm, which is measured by arranging for the arm to intercept successively two beams of light focused on to a photocell whose output is displayed on the other



A Steel rod
B Quartz crystals
C Brass disc
E Steel disc
F Filament

G Arm
H Anvil
I Axis
J Metal foils
K Air gun

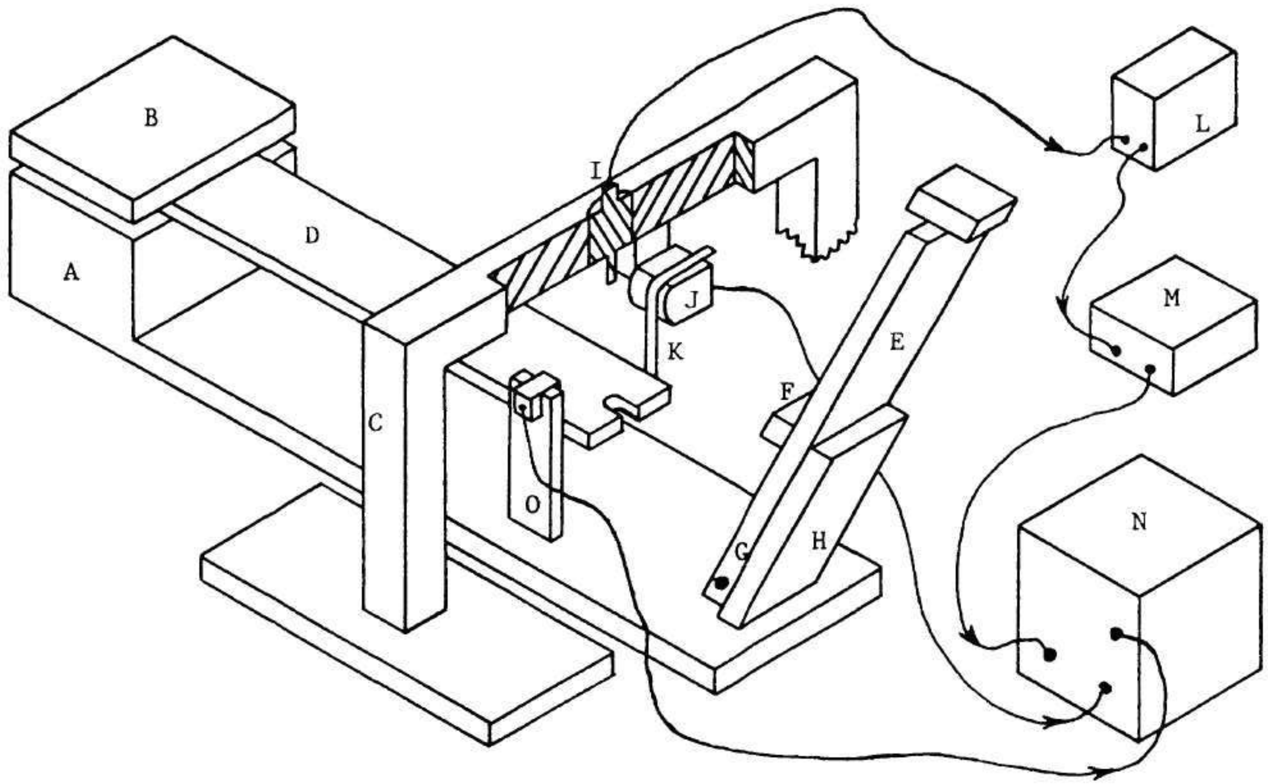
Figure 1. Diagram of the Lewis Testing Apparatus.

trace on the oscilloscope.

Holden continued on with the ballistic method by modifying Lewis' apparatus to increase the maximum rate of strain to 66,000% per sec. The weight of the arm was reduced by using a hard aluminum alloy to obtain a higher arm velocity of 3,300 cm. per sec as opposed to 1,700 cm. per sec achieved by Lewis and the sample length was shortened from 7 to 5 cm.

Hall obtained stress-strain curves in the range of strain rates from 0.01 to 49,000% per sec by using the ballistic method of Lewis and Holden, the synchronous motor method of Meredith and the conventional Instron method. The results of these previous works reported by these authors show that the trend is for breaking stress to increase and breaking elongation to decrease as the rate of strain increases for most textile materials.

Further investigation of high strain rate testing was carried on by Fabric Research Laboratories who designed a single fiber tensile tester capable of obtaining strain rates of the same order of magnitude as the ballistic method of Lewis and others. The basic principles of this FRL tester were retained for the studies reported herein and only the design was altered to achieve still higher strain rates without vibrational disturbances. See Figure 2.



A	Beam support		G	Hinge		L	Charge amplifier
B	Cap		H	Jack support		M	Filter
C	Transducer support		I	Quartz pressure transducer and adaptor		N	Dual-beam oscilloscope
D	Beam		J	Tape pickup head		O	External trigger
E	Jack		K	Magnetic tape			
F	Foot						

Figure 2. High Speed Testing System.

CHAPTER II

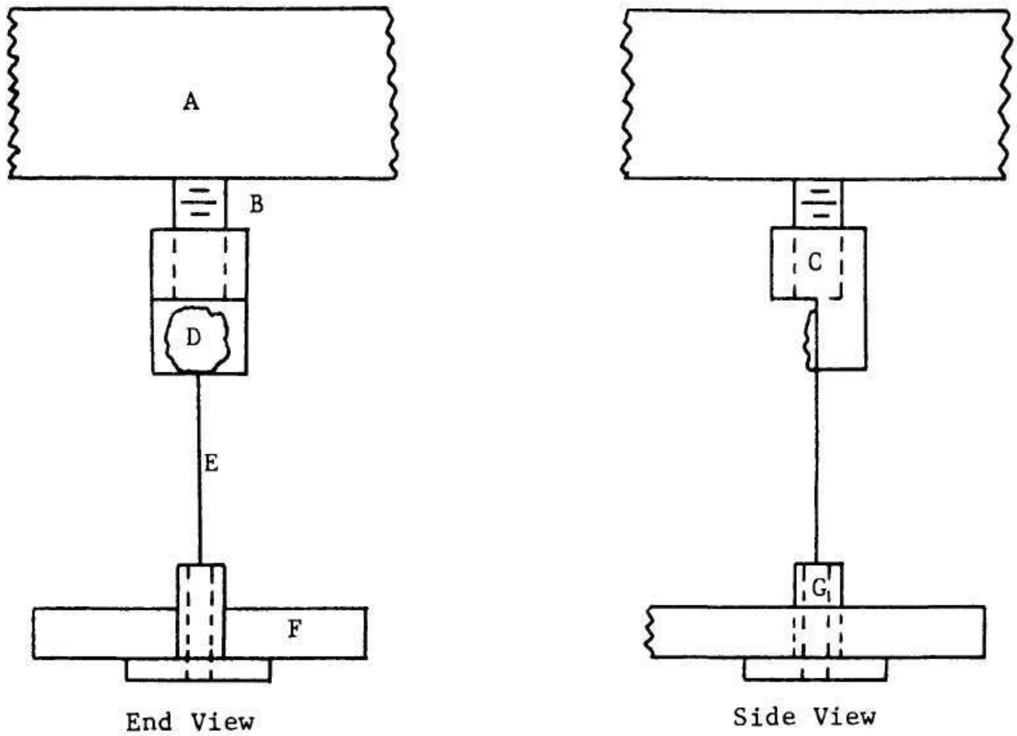
PROCEDURE

Experimental Procedure

The requirements imposed on a tensile tester become more stringent as the strain rate increases. Special attention must be given to system response time, sensitivity, and ability to give reproduceable results. The system shown in Figure 2 meets the requirements necessary to produce accurate stress-strain curves.

The beam support A, cap B, and transducer support C are made of stainless steel to resist rusting which could occur in a high humidity laboratory environment. The cap and beam support are held together by 8 set screws which are tightened firmly to hold the protruding beam D, thus the free length of the cantilever beam is that distance from the face of the support to the end of the beam. Also on the beam support there is a securely fastened slide E, converted to a jack by attaching the foot F to the sliding mechanism. The jack is free to pivot about the hinge G and the support H provides a resting place for the jack. Mounted in the center of the transducer support there is a quartz crystal pressure transducer and adaptor I. A tape head J is mounted on the support so that its face is parallel with the edge of the beam and aligned vertically above this same edge. Actually the tape head is mounted to a block of stainless steel with Duco cement and the block is positioned and cemented to the support to accomplish the above alignment. A strip of magnetic tape K with a fixed, known frequency recorded on it is taped to the end of the beam and threaded over the tape head as shown. To insure that the tape maintains close contact with the tape head, a piece of felt is cemented to the support just in front of the tape head. The wires from the tape head are connected to one trace of the dual-beam oscilloscope N. The transducer wire is connected to the input receptacle of the charge amplifier L whose output wire is connected to the input receptacle of the frequency filter M. The output of the filter is finally connected to the other trace of the oscilloscope. The external triggering device O is mounted to the base of the beam support and is connected to the external trigger input receptacle on the oscilloscope.

To operate the system a single fiber is glued between two nylon buttons as shown in Figure 3. The notched button is tapped with #1-72 UNF -2A threads so it can be screwed to the threaded stud of the transducer. The flanged button is inserted into the slotted end of the cantilever beam. The end of the beam is raised .75 inches of an inch by pivoting the jack until the foot is beneath the beam and slowly turning the jack screw clockwise. The jack is then pivoted out from under the beam allowing the beam to speed downward carrying the flanged button with it. For extensions beyond that at which the fiber is fully extended, the transducer will produce a corresponding electrical signal proportional to the amount of stress being applied by the extending fiber. This signal is sent through the amplifier to a low pass frequency filter which attenuates interferring frequencies and finally to the lower trace on the oscilloscope. Meanwhile, the magnetic tape is pulled by the tape head and the resulting electrical signal is displayed on the upper trace simul-



A Transducer support
B Threaded stud
C Notched button
D Cement

E Fiber
F Cantilever beam
G Flanged button

Figure 3. Nylon Button Mounting.

taneously with the lower trace. It is desirable to have the traces sweep just before the filament begins to extend so the trigger is positioned accordingly. The lower trace corresponding to the stress acting on the filament and the upper trace representing the position of the beam is photographed using the conventional open shutter technique. A typical record is shown in Figure 4.

Equipment

The general functions and relative position of each component of the system is discussed in greater detail beginning with the cantilever beam.

The physical dimensions of the beam depend upon the strain rate desired once a sample length is chosen which is one inch to allow direct comparisons of data at low and high strain rates. To achieve a strain rate of approximately 50,000% per sec with a sample length of one inch, the beam velocity, V, must be 500 inches per sec from Equation (1).

$$V = \frac{L \ \epsilon}{100} \tag{1}$$

where

L = sample length (inches)

ϵ = strain rate (% per sec)

With the beam velocity of 500 inches per sec and a maximum allowable beam deflection of .75 inch, the time, τ, for the beam to return to zero deflection and maximum velocity is .0094 seconds from Equation[16] (2).

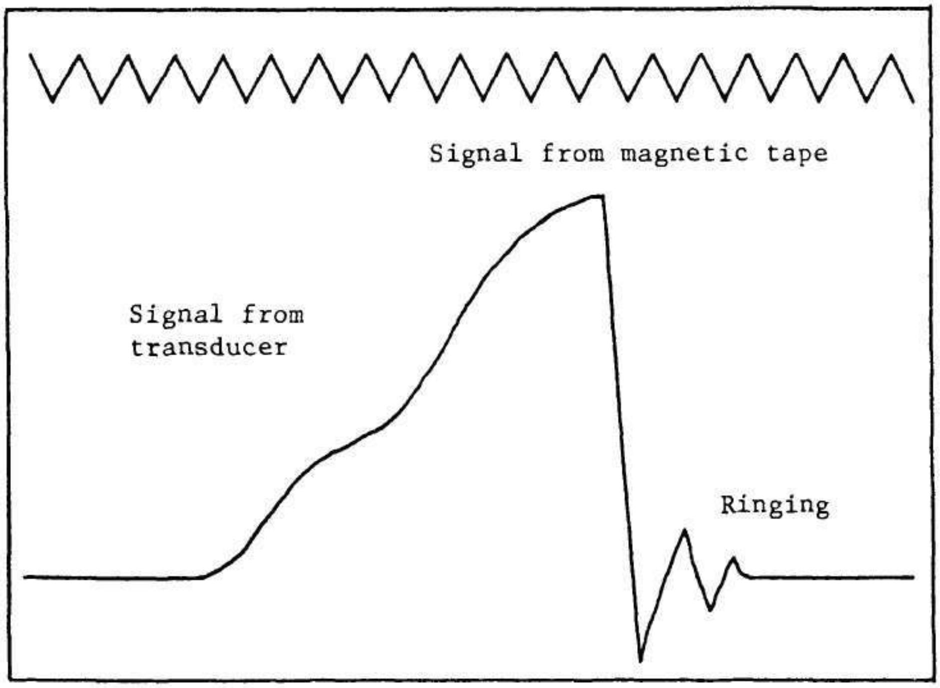


Figure 4. Typical Oscilloscope Record

$$\tau = \frac{2\ \pi\ \delta}{V} \tag{2}$$

where

δ = deflection (inches)

V = beam velocity (inches per sec)

Having found V and τ, the thickness of the beam, h, must be .125 inches from Equation[16] (3) by assuming a beam free length of six inches, material modulus of 29.0 x 10^6 psi., and density of 489 lbs/ft^3.

$$h = \frac{2\ \pi\ \ l^2}{\tau\ 3.515} \sqrt{\frac{12\ \gamma}{EIg}} \tag{3}$$

where

l = beam free length (inches)

τ = time (sec)

δ = deflection (inches)

E = modulus (psi)

γ = density (lbs/ft^3)

g = gravitational constant = 32 ft/sec^2

Thus, a cantilever beam with a thickness of .125 inches and free length of six inches will reach a maximum velocity of 500 inches per sec when released from a deflection of .75 inches.

Additional calculations are made to insure that the force required to deflect the beam does not exceed the load capacity of the jack and that the beam is not stressed beyond its yield. The load P necessary to deflect the beam 0.75 inches is found to be 51.3 pounds from Equation[16] (4) assuming a beam width, w, of one inch. The 51.3 pounds is below the load capacity of the jack. In view of the mass and velocity of the beam, the energy change in the work required to rupture the fiber is considered negligibly small.

$$P = \frac{E\ w\ h^3}{4\ l^3} \tag{4}$$

Assuming the maximum stress, σ max, at yield for heat treated steel to be 150,000 psi. and substituting the same unknown values previously defined in equations (2) and (3), the maximum deflection, δ max, of the beam before it breaks is found to be .96 inches from Equation[16] (5). Therefore, the beam will not break and the difference of .21 inches provides an adequate safety margin.

$$\delta\ \text{max} = \frac{2\ l^2\ \sigma\ \text{max}}{3\ E\ h} \tag{5}$$

If the strain rate is constant then the velocity of the beam must also be constant. However, any vibrating mechanical system is described by a sinusoidal displacement versus time curve as illustrated in Figure 5. It can be seen that it is necessary to conduct the test in the region AB to achieve an essentially constant strain rate.

There is one more parameter to consider and that is the critical velocity of the fiber, the velocity at which a fiber will break upon impact before it has time to extend. McCrackin[13] and Smith[14] have investigated those velocities just sufficient to cause immediate rupture in various fibers and have found this velocity to be on the order of 10,000 inches/sec. The beam velocity calculated from equation (1) of 500 inches/sec is well below the predicted critical velocity.

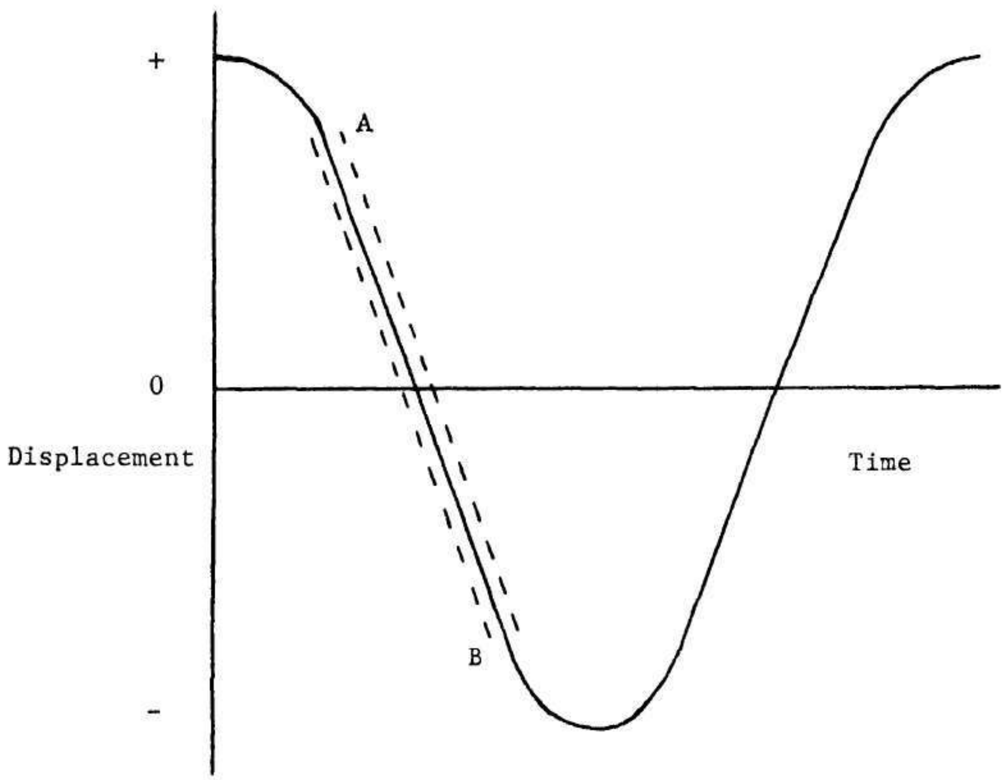


Figure 5. Beam Displacement Curve.

The calculated beam velocity of 500 inches/sec is actually a good approximation of the true velocity of the beam after it is mounted. An error in mounting to give a free length other than 6 inches and an error in measuring the .75 inches deflection could compound to cause the beam velocity to vary considerably. Therefore, it is necessary to measure the true velocity under test conditions as the beam travels down. This is accomplished by bonding a strip of magnetic tape with a frequency of 78.7 cps prerecorded on it to the edge of the beam and allowing the tape to be pulled past a Nortronic Model 9102 tape head. The signal from the head is displayed on the upper trace of the oscilloscope as shown in Figure 4. By knowing the frequency on the tape and the sweep rate of the trace, the velocity of the beam is calculated by observing the resulting frequency displayed on the screen.

Assuming a beam velocity of 500 inches/sec, i.e. 1,270 cm/sec, and an elongation of 20% for a 2.54 cm sample, that is .51 cm, the time from impact to rupture would be .51 cm ÷ 1270 cm = .0004 sec. If impact to rupture is to be displayed over the entire 10 cm screen, the sweep rate must be .0004 sec. ÷ 10 cm = .00004 sec/cm., 40 μ sec/cm. However, the nearest calibrated sweep rate on the oscilloscope which is slower than 40 μ sec/cm is 50 μ sec/cm. The resulting frequency on the screen is desired to have a distance between peaks or cycles of .2 cm. Given a sweep rate of 50 μ sec/cm., i.e. 20,000 cm/sec, and a tape velocity of 1,270 cm/sec, the ratio of tape velocity to sweep rate is 1/15.748. To achieve a period of .2 cm/cycle on the screen requires a period of .2 cm/cycle ÷ 15.748 = .0127 cm/cycle on the tape which corresponds to a frequency of 1 ÷ .0127 cm/cycle = 78.74 cps. In order to put this frequency on the tape, the velocity of the tape recorder, 19.05 cm/sec, was considered in the same manner and a resulting frequency of 1,666 cps was fed to the recorder. A sine wave generator monitored by a crystal controlled frequency counter was used to generate an accurate signal to the recorder.

The velocity of the beam and tape was checked by photographing the frequency on the upper trace just before the beam reached zero deflection. The average number of cycles/cm taken from five photographs was found to be 4.3. Since 5 cycles/cm corresponds to a beam velocity of 1,270 cm/sec, 4.3 cycles/cm corresponds to a beam velocity of 1,092.2 cm/sec. Consequently, the strain rate instead of being 50,000% per sec, is 43,000% per sec. The ratio of beam velocity to sweep rate, 1,092.2 cm/sec ÷ 10,000 cm/sec = 9.16, was used to calculate the extension of a sample from the distance in cm from impact to rupture on the photographs. A sweep rate of 0.1 μ sec/cm, 10,000 cm/sec was used instead because the previous assumption of 20% elongation did not allow for those fibers with greater than 20% rupture elongations.

High speed testing places most stringent requirements on the load sensing and recording instrumentation. For this reason the Kistler Quartz Pressure Transducer Model 701A108 is used to convert applied pressures to electrical charge signals. In tensile testing, there is a negative applied pressure to the diaphragm of the transducer which is converted to a force acting on the transducer crystals, which generate the electrical charge output proportional to the pressure input. Transducers such as this are dynamic measuring instruments whose high natural frequency, a minimum of 60,000 cps, permits measurement of high-frequency pressure variations with fast rise-time components. The natural frequency of the transducer drops however when a mass is joined to it. By using the small nylon button as a top grip, the natural frequency is reduced only slightly. To verify this it was observed that after the sample ruptured, the transducer continued to ring or oscillate at its natural frequency. The number of cycles/cm on the scope were counted and knowing the sweep rate, the natural frequency with the button attached was found to be 5.5 cycles/cm $\div$ 10,000 sec/cm = 55,000 cps. Thus its rise-time or response is found to be approximately 5 μ sec from equation[17] (6).

$$\tfrac{1}{4}\ (\text{natural frequency cps})^{-1} \tag{6}$$

The time it takes for a 2.54 cm sample with a 15% elongation, extended at a velocity of 1,092 cm/sec to rupture is approximately 350 μ sec. Thus the response time of the transducer is 70 times greater than the occurrence of the event.

The electrical signal from the transducer travels through a Kistler Model 121M5 Low Noise Cable to the "CHARGE" (not the PIEZOTRON) receptacle of the Model 504D Charge Amplifier. This amplifier converts the high-impedence charge signal from the transducer to a low-impedence voltage for recording on the oscilloscope. The amplifier has three time constants, short, medium and long, the latter allows conventional static calibration of the transducer. The switch is returned to the short position for dynamic testing conditions. The amplifier has a variable gain which allows a known weight to be suspended from the transducer and by adjusting either the gain on the amplifier or the sensitivity of the oscilloscope trace, the deflection of the load trace can be adjusted to correspond to a given vertical distance on the screen.

The output of the charge amplifier is passed through a KHRON-HITE Model 3202 filter. This is a variable filter capable of acting as a high or low pass cutoff filter. The charge amplifier also contains a 150 kHz low pass filter which means that all the frequencies less than 150 kHz will pass to the oscilloscope and those above 150 kHz will be filtered out. It was pointed out that the natural frequency of the transducer is approximately 55,000 cps or 55 kHz. This frequency was also visable in the load trace as well as after sample rupture when the previously discussed ringing occurrs. A typical unfiltered trace with the transducer oscillations superimposed on the load trace is shown in Figure 6. A similar disturbance was also noticed by Lewis[7] who attributed it to spurious vibrations arising from the inertia of his apparatus. Interpretation of the actual load would be difficult even if a mean line could be drawn through the trace. Thus the KHRON-HITE filter was used to smooth out the trace as shown in Figure 4. A low pass setting with a cutoff frequency of 15 kHz was used. Photographs were taken of load traces using 10, 15, 20, 40, and 150 kHz cutoff frequencies. The breaking stress, breaking elongation, and modulus were compared and it was concluded that the filter had no effect on any of the above parameters which could be measured.

Figure 2 shows that the transducer support is separated from the beam support and it is supported by low frequency damping material. This was done to prevent low frequency vibrations from being transferred to the transducer.

Strain wave reflections were not ignored when the source of the superimposed oscillations on the load trace was being verified. It was

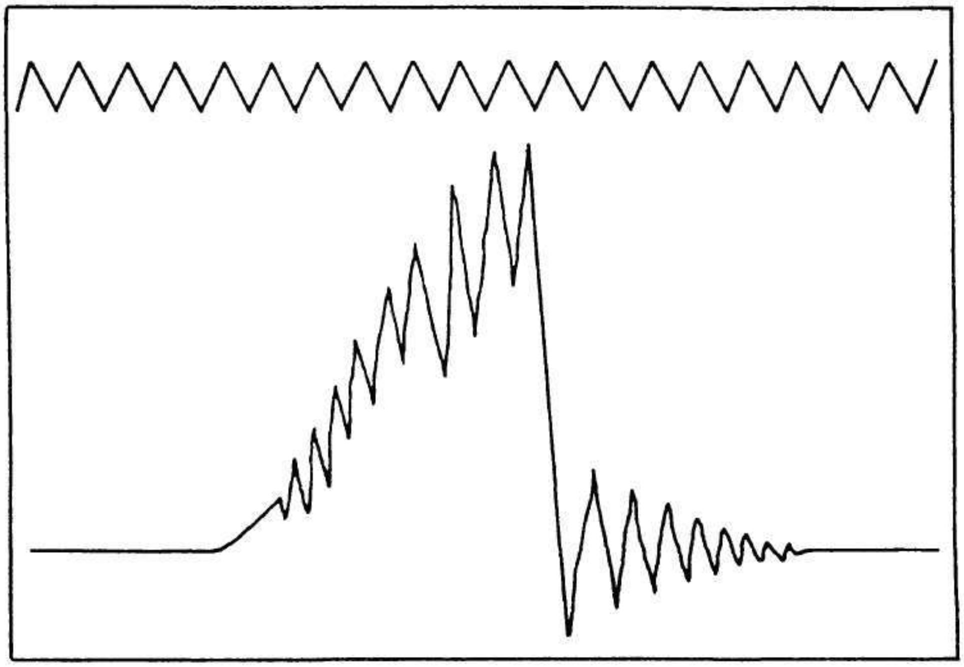


Figure 6. Unfiltered Oscilloscope Record

considered that the oscillations could be the result of traveling strain waves building up as they were reflected from the top and bottom grips. During static testing these waves are reflected many times and the stress-strain curve appears smooth because each increment of the sample is essentially being strained simultaneously. At high strain rates, the strain waves may be reflected only a few times because of the short duration of the test and the waves will thus appear as step-wise increases in the stress-strain curve. The approximate number of reflections, n, that can occur within a 1 inch sample during 350 μ sec and assuming the velocity of a wave to be 120,000 inches/sec is found to be 42 from equation[17] (7).

$$n = \frac{C\ t}{L} \tag{7}$$

where

C = wave velocity (inches/sec)

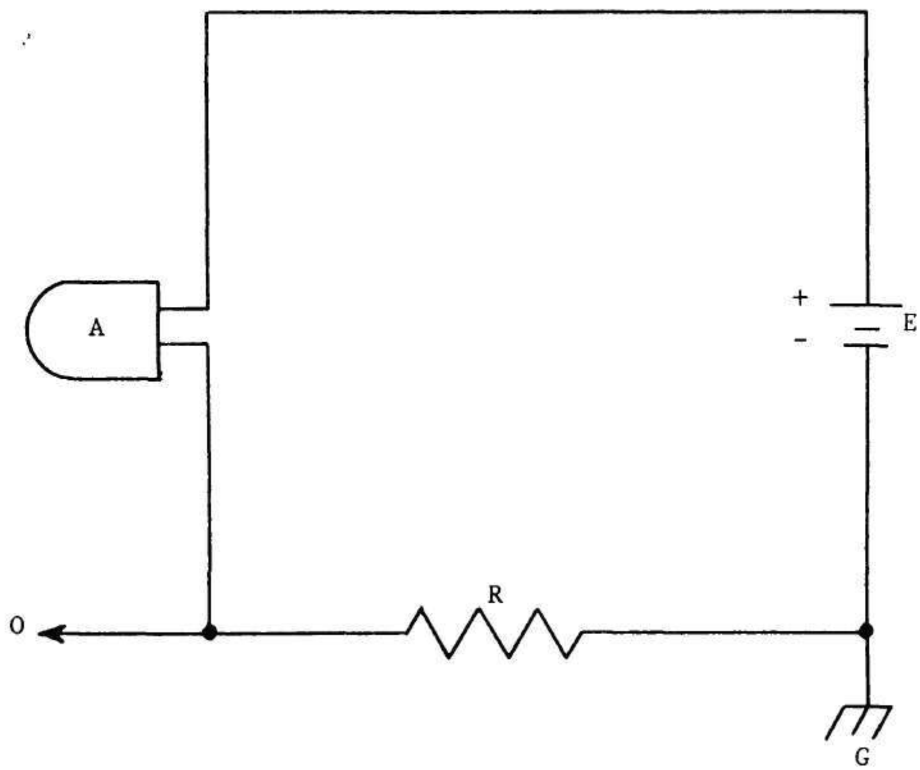
t = time from impact to rupture (sec.)

L = sample length (inches)

These 42 reflections would correspond to approximately 120 kHz which is clearly above the 55 kHz that was found superimposed on the stress-strain curve.

The output of the filter is connected to the lower trace receptacle of a Tektronix Dual-Beam Oscilloscope Model 555. The plug-in unit had a pre-amp rise time of .06 μ sec which is much faster than the 5 μ sec rise time of the transducer. The operating manual for the amplifier recommended that the recording device sensitivity be as high as possible and the amplifier gain adjusted to produce the desired amount of trace deflection. The lower trace sensitivity was set as high as possible, .05 mv/cm. and the amplifier gain adjusted to produce the desired trace deflection as was suggested by the operating manual for the charge amplifier.

Since the time from impact to rupture for a sample is only 350 μ seconds, it would be almost impossible to manually open the shutter of the camera at the proper time to capture the entire stress-strain curve on film. If the sweep mode on the oscilloscope were in the auto baseline position, the sweep would be continuous and appear as a solid line. This would mean that the beginning of the curve could be near the right side of the screen and the end portion of the curve, showing fiber rupture, would be at the left side of the screen. To overcome these problems the shutter of the camera is set in the open position, the trigger source switch is set to external, and the sweep mode is set to single sweep. The trigger coupling switch is also set to DC. In order to trigger the sweep, the ready button is pushed and when a change in voltage occurs in the external circuit, the sweep will start. The external circuit which is used to generate this voltage change is shown in Figure 7 and it's position in the system is shown in Figure 2. The circuit consists of a small photocell, a 9.5 volt transistor battery and a 1,000 ohm resistor. A light source is positioned across from the photocell so that a constant source of intense light is directed at the photocell which causes the generation of a constant output of .8 volts from the circuit to the oscilloscope. When the light beam is broken, so is the circuit and the output goes to zero which triggers the sweep. Thus



A LS 400 photocell
E 9.5 volt transistor battery
R 1 ohm resistor
O .8 volts output to oscilloscope
G Ground to oscilloscope

Figure 7. Triggering Circuit

the photocell is positioned so that when the beam goes by it, the circuit will be broken which will trigger the sweep at the desired time. The position of the trigger is determined by conducting preliminary tests so the sweep is started just before the sample begins to extend.

The data at low strain rates was collected from standard Instron tensile tests. The "B" load cell was used and jaw speeds of 0.2 and 20 inches per minute giving strain rates of 0.33 and 3.33% per second respectively were used. The normal procedure of recording the curves on chart paper and interpreting the results was followed.

Fibers Evaluated

The different fibers which were chosen from continuous multifilament yarns are listed in Table 1. A high tenacity polyester, type 52, and high tenacity nylons, types 728, 330, and A07 were tested and compared to the low tenacity polyester, type 56, and the low tenacity nylon, type 865.

Since only one filament or fiber was used from each yarn, the average denier per filament was calculated for each sample. Random fibers from the polyester type 56 and Nomex were tested on the Insco Vibroscope according to ASTM method 1577. The findings were that the denier per filament had a maximum coefficient of variation of 1.34%. This variation was considered to be insignificant and the average denier per filament for the samples was taken to be equal to the denier of the yarn divided by the number of filaments in the yarn for all the fibers tested.

Fiber Mounting

A major difficulty in most tensile tests regardless of the strain

Table 1. Fibers Evaluated

Yarn	Identification	Denier per filament
Polyester (DuPont)	150-34-R10-56	4.4
Polyester (DuPont)	1100-250-R02-52	4.4
Nylon (DuPont)	840-140-R20-728	6.0
Nylon (DuPont)	420-68-Z-330	6.2
Nylon (DuPont)	70-34-R25-865	2.1
Nylon (Chemstrand)	840-140-1/3Z A07	6.0
Nomex (DuPont)	200-100-430	2.0
Polypropylene (Hercules)	840-140-0	6.0

rate is selecting a suitable method of holding the ends of the sample. For single fibers, various types of hard wax, epoxy glue, and cements of different kinds are used to bond the fibers to paper, aluminum, or some other type of tab. In this work Duco cement was found to be satisfactory in bonding the samples to the nylon buttons. Also, the buttons were reused after removing the cement with acetone.

The task of holding the buttons one inch apart while the cement was being applied was simplified by using the sample rack shown in Figure 8 which is capable of holding 20 samples. A 1/32 inch diameter hole was drilled in the center of each button and the notched button was tapped with #1-72 UNF-2A threads so it could be screwed onto the threaded stud of the transducer. Once the samples were mounted in the rack, a piece of fine guage wire bent at one end to form a hook was used to thread the fibers through the buttons. One end of the fiber was taped to the desk and the other allowed to hang freely with a small piece of tape attached which caused the fiber to remain straight between the buttons. After all the buttons were threaded, an 18 guage hypodermic needle whose end had been ground blunt, was fitted over the end of a tube of cement. The cement was forced into the back of the flanged button, and deposited on the notched button by gently squeezing on the tube. This was done beneath a magnifying glass exercising care to prevent any significant amount of cement wicking on the fiber. The cement was allowed to dry for 24 hours in standard conditions before testing.

The sample mounting for the Instron tests carried out at standard conditions was done by mounting a sample directly in thumbscrew, rubber lined grips for the top jaw and air operated, rubber lined grips for the

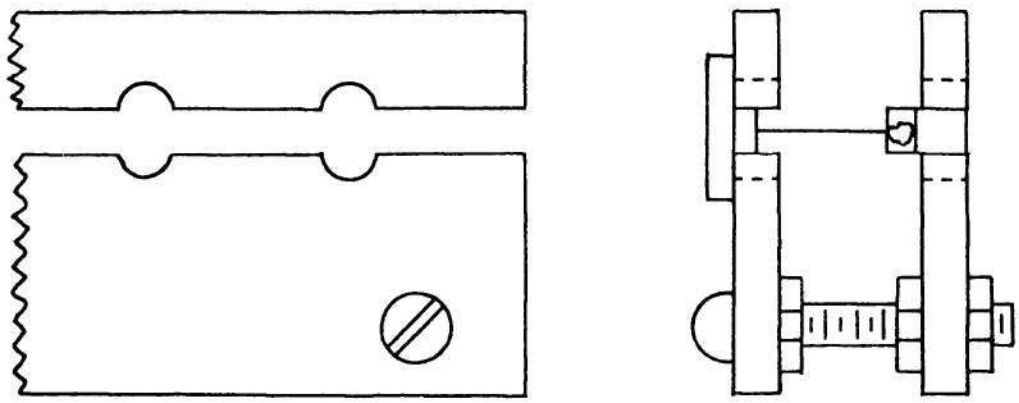


Figure 8. Sample Rack.

bottom jaw. When the samples were tested under non-standard conditions, the nylon button precedure was used. An aluminum bar with a large alligator clip was used to hold the notched buttons while another aluminum bar slotted similar to the cantilever beam held the flanged button.

Test Conditions and Strain Rates

The test conditions and strain rates of each test are summarized in Table 2. In all cases a 2.54 cm sample length was used except for the strain rate of 109,000% per sec in which case a one cm sample length was used. All samples were conditioned for 24 hours at standard conditions, 70°F 65% RH ± 2, except those specified as having special conditioning immediately prior to testing. As can be seen from Table 2, nylon 728 was subjected to different conditions prior to and during testing as well as standard conditions. So that the effect of varying strain rates of a sample conditioned in water could be compared, samples were premounted on the nylon buttons and placed in a pan of water at 70°F for 6 hours. At the time of testing each was removed from the water and mounted in the Instron or high speed tester within one minute. Those samples which were dried were also tested within one minute after removal from the desicator. The Instron environmental chamber was used to test the samples at 250°F ± 5 at low strain rates. The previously mentioned aluminum bars were enclosed inside the chamber which was preheated to 255°F. While the door was open during sample mounting, the temperature dropped to 245°F. It only took about 15 seconds to mount the samples and the door was immediately closed which enabled the temperature to slowly rise back up to 255°F after three minutes. A Blue M Oven was used

Table 2. Test Conditions and Strain Rates

Yarn Types	Conditioning prior to testing	Conditions during testing	Strain Rate % per sec
All 8	std. cond.*	std. cond	.33
All 8	std. cond.	std. cond.	3.33
728	3 min. @ 250°F ±5, 0% RH	250°F ±5, 0% RH	.33
728	3 min. @ 250°F ±5, 0% RH	250°F ±5, 0% RH	3.33
728	6 hrs. in water @ 70°F	std. cond.	.33
728	6 hrs. in water @ 70°F	std. cond.	3.33
728	6 hrs. in oven @ 120°F, 24 hrs. in desicator @ 70°F, 0% RH	std. cond.	.33
728	6 hrs. in oven @ 120°F, 24 hrs in desicator @ 70°F, 0% RH	std. cond.	3.33
All 8	std. cond.	std. cond.	43,000
728	3 min. @ 250°F ±5, 0% RH	250°F ±5, 0% RH	43,000
728	6 hrs. in water @ 70°F	std. cond.	43,000
728	6 hrs. in oven @ 120°F, 24 hrs in desicator @ 70°F, 0% RH	std. cond.	43,000

Table 2 (Continued). Test Conditions and Strain Rates

Yarn Types	Conditioning Prior to testing	Conditions during testing	Strain Rate % per sec
728	std. cond.	std. cond.	24,000
728	std. cond.	std. cond.	109,000

* $70^{\circ}F \pm 2$, 65% RH ± 2

to test at 250^{o}F $\pm$5 at the high strain rate. The test device was mounted on an aluminum plate which allowed the sample to be mounted and ready to be fired outside the oven. When the oven door was opened the temperature dropped from 260^{o}F to 245^{o}F while the device was being placed inside and a piece of wire looped at the end placed around the top of the jack. The wire extended out through a vent opening in the side of the oven and by pulling on it the beam could be released. The oven door was open for only 20 seconds and after the door was closed the temperature rose to 255^{o}F after three minutes. At 250^{o}F the relative humidity was not measured but it was believed to be zero. The effect of temperature on the sensitivity of the transducer is approximately .025% per ^{o}C with an operating range of -320^{o}F to +450^{o}F. Therefore the data collected at the high strain rate were considered to be uneffected by the 250^{o}F condition.

To simplify further discussion, the conditions described above for the evaluation of nylon 728 are referred to as standard, wet, dry, and 250^{o}F in the remainder of this report.

CHAPTER III

RESULTS AND DISCUSSION

The results for breaking stress, breaking elongation, and initial modulus are summarized in Table 3 for all sample types except nylon 728 which is summarized in Table 4. The data used to compute these average values are found in Appendices A through G and the procedure used to attain the 109,000% per second strain rate is discussed in Appendix H. The strain rate of 24,000% per second was reached by using a beam with a free length of eight inches, width one inch, and a thickness of 0.093 inches. The method for calculating the desired beam velocity and measuring the actual velocity follows the same procedure previously outlined for the 43,000% per second strain rate beam. The magnitude of possible error for the average values of stress, strain, and modulus is estimated to be 3%, 7%, and 11% respectively. The discussion for these estimates is found in Appendix I.

Tables 5, 6, and 7 perhaps better illustrate the effects of increased strain rate by comparing the percent changes from a base strain rate. Tables 5 and 6 show that the percent increase from 0.33 to 43,000% per sec strain rate in rupture stress is the highest beginning with polypropylene, followed by Nomex, the nylons, and finally the polyesters. The percent decrease in rupture strain is greatest for polypropylene, followed by the polyesters, nylons, and finally Nomex. The percent increase in modulus is in still another order starting with polypropylene, the nylons,

Table 3. Fiber Tensile Properties at Standard Conditions

Yarn Type	Strain Rate % per sec.	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Polyester 56	0.33	4.7	42.8	63.4
	3.33	5.1	37.0	94.5
	43,000	5.5	23.1	115.4
Polyester 52	0.33	7.9	25.4	73.1
	3.33	8.7	18.6	123.1
	43,000	8.9	14.4	123.0
Nylon 330	0.33	8.2	27.2	30.0
	3.33	8.9	23.9	46.9
	43,000	9.9	17.4	57.9
Nylon 865	0.33	5.3	41.1	24.9
	3.33	5.9	34.4	32.4
	43,000	6.5	20.2	40.2
Nylon A07	0.33	9.9	28.3	35.0
	3.33	10.4	20.4	59.8
	43,000	11.5	17.8	67.6
Nomex	0.33	5.3	40.4	74.1
	3.33	5.8	35.3	141.8
	43,000	6.6	31.9	137.6
Polypropylene	0.33	5.2	86.6	36.8
	3.33	5.4	42.7	61.4
	43,000	7.2	36.4	107.6

Table 4. Tensile Properties of Nylon 728

Condition	Strain Rate % per sec.	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Standard	0.33	9.6	25.0	25.1
Wet		8.9	26.8	19.0
Dry		10.6	20.7	44.6
250°F		7.5	25.6	16.7
Standard	3.33	11.0	23.3	52.6
Wet		10.0	24.5	16.6
Dry		11.1	21.7	53.5
250°F		8.3	22.2	26.0
Standard	43,000	12.1	17.6	63.0
Wet		10.1	18.0	36.8
Dry		11.4	18.8	49.3
250°F		9.7	21.7	34.3
Standard	24,000	11.7	17.7	61.2
Standard	109,000	12.2	24.9	50.0

Table 5. Percent Changes in Tensile Properties with Increasing Strain Rate

Yarn Type	Strain Rate % per sec.	Rupture Stress	Rupture Strain	Modulus
Polyester 56	0.33		Base	
	3.33	+ 8	-13	+ 49
	43,000	+17	-46	+ 82
Polyester 52	0.33		Base	
	3.33	+10	-27	+ 68
	43,000	+13	-43	+ 68
Nylon 330	0.33		Base	
	3.33	+ 9	-12	+ 56
	43,000	+21	-36	+ 93
Nylon 865	0.33		Base	
	3.33	+11	-16	+ 30
	43,000	+23	-51	+ 61
Nylon A07	0.33		Base	
	3.33	+ 5	-28	+ 71
	43,000	+16	-37	+ 93
Nomex	0.33		Base	
	3.33	+ 9	-13	+ 90
	43,000	+24	-21	+ 85
Polypropylene	0.33		Base	
	3.33	+ 4	-50	+ 66
	43,000	+38	-58	+192

Table 6. Percent Changes in Tensile Properties with Increasing Strain Rate for Nylon 728

Condition	Strain Rate % per sec.	Rupture Stress	Rupture Strain	Modulus
Standard	0.33		Base	
	3.33	+15	- 7	+110
	43,000	+26	-30	+151
Wet	0.33		Base	
	3.33	+12	- 9	- 13
	43,000	+16	-33	+ 94
Dry	0.33		Base	
	3.33	+ 5	+ 5	+ 20
	43,000	+ 8	- 9	+ 11
250°F	0.33		Base	
	3.33	+11	-13	+ 56
	43,000	+29	-15	+105
Standard	0.33		Base	
	24,000	+22	-29	+143
Standard	0.33		Base	
	109,000	+27	- 1	+ 99

Table 7. Percent Changes in Tensile Properties for Nylon 728 at 43,000% per sec. Strain Rate Under Non-Standard Conditions

Condition	Rupture Stress	Rupture Strain	Modulus
Standard	-------------------	Base -------------------	-------------------
Wet	-17	+ 7	-42
Dry	- 6	+ 7	-22
250°F	-20	+23	-45

Nomex, and finally the polyesters. It appears that the polypropylene is generally the most affected, however, the above observations are only trends and neglect the exceptions of overlapping due to the high and low tenacity nylon and polyester fibers. These results coincide quite well with those reported by Holden. For a high tenacity nylon, he observed an increase in stress in the range of 25% and a decrease in strain in the range of 30% using a .03% per second strain rate base compared with 66,000% per second strain rate data. From Table 5 it can be seen that a range of 25% increase in stress and a decrease in the range of 35% in strain using a .33% per second base compared with 43,000% per second data for the high tenacity nylons.

For nylon 728 tested under wet conditions, Table 7 shows that at 43,000% per second the rupture stress and modulus decreased from the 0.33% per second strain rate approximately 17% and 42% respectively while the rupture strain increased slightly, about 7%. Similar effects can be seen for the 250° F condition except the rupture strain increases approximately 23%. The discussion of the mechanisms which cause these changes in fiber properties at this high strain rate and these conditions, is beyond the scope of this work. However, these same trends were observed at low strain rates where the theory exists that water penetrates between the molecular chains of the fiber and thus reduces the forces existing between the chains and allows them to slip past each other more easily. Consequently, the stress and modulus decrease while the strain increases slightly. At 250° F, it is believed that the increased molecular motion also permits increased freedom of chain slippage and facilitates the breaking of molecular bonds within the chains. Thus the stress and modulus decrease while the strain increases significantly. However, the results shown in Tables 6 and 7 serve only to show that the trends observed at low strain rates under wet and 250° F conditions are also observed at the high strain rate.

The changes in tensile properties under dry conditions were opposite to what was anticipated. However, the actual changes were small and are probably within the range of experimental accuracy. Since the moisture regain of nylon is approximately 5%, no significant change from standard conditions was expected.

At the high strain rate of 109,000% per second, there was essentially no change in rupture strain compared to the 0.33% per second strain rate base. This seems unlikely and the error is attributed to the measurement of the sample length of one cm. Using this short sample length magnifies the possible magnitude of error approximately three times from the possible error in using a 2.54 cm sample length.

Several of the fibers tested at the high strain rate were examined by a microscope at a magnification of 200 times. At this magnification it could only be observed that the ruptured ends did not appear to be flat and did not appear as a distinct mushroom form which would suggest melting. The ends did however appear jagged.

The influence of heat generated during fiber extension has been studied[2, 3, 4, 18] and various phenomena have been attributed to this heating. When a fiber is extended, some of the work done in producing deformation will appear as heat. At high rates of deformation the heat will be generated too quickly to be lost to the atmosphere and the temperature of the fiber will increase as extension proceeds. This rise in temperature and effect on the breaking properties of yarns has been investigated by Hall[5] with the conclusion that there is no evidence to suggest that it significantly affects the breaking properties at high strain rates.

A final observation of the stress-strain photographs was that the shape of the curve for a particular yarn type was independent of the rate of strain. Even at 109,000% per second the yield point of the nylon 728 fiber could be observed. Holden[8] also reported this retention of curve shape to the strain rate of 66,000% per second.

CHAPTER IV

CONCLUSIONS

The high speed tensile testing device and testing procedure described in this paper are suitable for testing at strain rates in the range of 43,000% per sec with capabilities up to approximately 109,000% per sec.

At high strain rates there is a trend for breaking stress and initial modulus to increase while the breaking strain decreases. The amount of these changes is dependent on the yarn type, sample, conditioning, test environment, and strain rate.

CHAPTER V

SUGGESTIONS FOR FUTURE RESEARCH

In addition to the three yarn parameters discussed in this paper, the amount of work to rupture for fibers tested at high strain rates should be studied. Also since the system has a rise time of 5 μ seconds, additional cantilever beams should be designed to attain higher velocities and strain rates with the system. Photographs from an electron microscope should be taken of broken fiber ends, ruptured at high strain rates, for examination as has been done with fibers at low strain rates by Bunsell and Hearle[(15)]. Finally, several materials wet, dry, and at various temperatures should be studied over a complete range of strain rates from one % per sec to 100,00% per sec and high speed photographs of the testing should be taken to observe the transverse vibrations of the sample during testing.

APPENDIX A

0.33% per sec. Strain Rate Results

Yarn Type	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Polyester 56	4.9	41.0	63.4
	4.8	42.5	64.8
	4.7	41.7	60.1
	4.8	45.2	64.1
	4.5	45.7	64.8
	4.7	42.8	63.4
	CV 3.2%	CV 4.9%	CV 3.1%
Polyester 52	7.8	24.2	72.1
	8.2	25.0	72.1
	8.1	28.1	67.9
	7.5	23.8	81.3
	7.2	26.1	72.1
	7.9	25.4	73.1
	CV 5.4%	CV 6.8%	CV 7.7%
Nylon 728	10.2	27.1	28.2
	9.4	20.4	22.3
	9.3	20.4	23.5
	9.1	27.2	28.2
	10.0	29.6	23.5
	9.6	25.0	25.1
	CV 4.9%	CV 17.1%	CV 11.3%
Nylon A07	9.8	24.2	38.5
	9.4	28.9	38.5
	10.9	28.5	30.2
	9.9	30.8	32.5
	9.9	29.3	35.3
	9.9	28.3	35.0
	CV 5.6%	CV 8.7%	CV 10.5%

APPENDIX A (Continued)

0.33% per sec. Strain Rate Results

Yarn Type	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Nylon 330	8.1	26.5	25.6
	7.7	26.5	29.3
	8.5	26.9	31.5
	8.4	30.0	29.3
	8.3	26.2	34.2
	8.2	27.2	30.0
	CV 3.9%	CV 5.9%	CV 10.6%
Nylon 865	5.4	40.6	26.9
	5.3	43.3	22.4
	5.1	38.6	24.2
	5.4	39.0	25.7
	5.5	44.1	25.2
	5.3	41.1	24.9
	CV 2.8%	CV 6.0%	CV 6.8%
Nomex	4.8	41.3	79.4
	5.4	43.7	74.7
	5.4	37.8	74.7
	5.7	38.2	66.8
	5.3	41.0	74.7
	5.3	40.4	74.1
	CV 6.1%	CV 6.0%	CV 6.1%
Polypropylene	5.0	88.5	32.5
	5.5	95.2	35.3
	5.5	86.2	35.3
	5.0	80.0	42.3
	4.8	83.1	38.5
	5.2	86.6	36.8
	CV 6.2%	CV 6.7%	CV 10.2%

APPENDIX B

3.33% per sec. Strain Rate Results

Yarn Type	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Polyester 56	5.4	36.7	115.4
	5.1	39.4	82.4
	4.8	35.9	82.4
	5.3	38.2	96.2
	5.1	34.7	96.2
	5.1	37.0	94.5
	CV 4.5%	CV 5.0%	CV 14.3%
Polyester 52	8.3	18.7	115.4
	9.0	17.2	144.3
	8.4	17.9	115.4
	8.9	21.5	96.2
	9.1	17.6	144.3
	8.7	18.6	123.1
	CV 4.2%	CV 9.3%	CV 16.9%
Polyester 728	10.3	24.0	47.0
	12.0	23.2	60.4
	10.8	23.0	60.4
	11.0	22.1	52.9
	10.7	24.4	42.3
	11.0	23.3	52.6
	CV 5.8%	CV 3.9%	CV 15.3%
Nylon A07	10.0	19.5	60.4
	9.9	18.7	70.5
	10.7	19.1	60.4
	10.4	23.4	47.0
	11.2	21.1	60.4
	10.4	20.4	59.8
	CV 5.1%	CV 9.5%	CV 14.0%

APPENDIX B (Continued)

3.33% per sec. Strain Rate Results

Yarn Type	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Nylon 330	8.5	25.4	51.3
	8.9	22.2	41.0
	8.7	24.6	45.6
	9.3	25.0	51.3
	9.4	22.6	45.6
	8.9	23.9	46.9
	CV 4.3%	CV 6.1%	CV 9.3%
Nylon 865	5.7	28.9	33.6
	6.2	36.7	31.0
	5.5	32.0	31.8
	5.8	33.5	31.0
	6.1	40.9	34.6
	5.9	23.9	46.9
	CV 4.9%	CV 13.3%	CV 5.0%
Nomex	6.1	34.7	141.1
	5.9	36.3	127.0
	5.1	37.1	158.8
	5.7	33.9	141.1
	6.0	34.3	141.1
	5.8	35.3	141.8
	CV 6.9%	CV 3.9%	CV 8.0%
Polypropylene	6.0	44.9	70.5
	5.4	44.1	60.4
	5.5	41.3	70.5
	4.9	42.5	52.9
	5.4	41.0	52.9
	5.4	42.7	61.4
	CV 7.2%	CV 4.0%	CV 14.4%

APPENDIX C

43,000% per sec. Strain Rate Results

Yarn Type	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Polyester 56	5.5	24.1	104.7
	5.5	24.9	123.2
	5.8	22.8	95.2
	5.6	22.4	130.9
	5.0	21.5	123.2
	5.5	23.1	115.4
	CV 5.4%	CV 5.9%	CV 12.9%
Polyester 52	8.2	14.6	132.2
	9.3	14.2	110.2
	8.4	13.8	120.2
	8.6	15.1	132.2
	10.2	14.2	120.2
	8.9	14.4	123.0
	CV 9.1%	CV 3.4%	CV 7.6%
Nylon 728	12.3	18.5	64.6
	12.0	16.8	55.4
	10.7	16.8	55.5
	12.5	18.9	62.0
	13.1	17.2	77.6
	12.1	17.6	63.0
	CV 7.3%	CV 5.6%	CV 14.4%
Nylon A07	11.3	17.2	69.2
	12.5	18.5	69.2
	11.0	17.6	64.6
	11.7	16.8	74.5
	11.2	18.9	60.6
	11.5	17.8	67.6
	CV 5.1%	CV 4.9%	CV 7.8%

APPENDIX C (Continued)

43,000% per sec. Strain Rate Results

Yarn Type	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
Nylon 330	11.0	17.2	62.1
	9.7	18.9	58.6
	8.9	17.6	58.6
	9.8	16.8	55.2
	10.0	16.3	55.2
	9.9	17.4	57.9
	CV 7.6%	CV 5.7%	CV 5.0%
Nylon 865	6.1	18.9	32.6
	6.4	20.6	50.4
	6.6	19.4	34.7
	6.7	22.4	36.9
	6.7	19.8	46.2
	6.5	20.2	40.2
	CV 3.9%	CV 6.8%	CV 19.2%
Polypropylene	6.7	38.7	100.8
	7.7	32.7	110.8
	7.7	36.1	110.8
	6.6	34.4	92.3
	7.5	40.0	123.1
	7.2	36.4	107.6
	CV 7.5%	CV 8.2%	CV 10.8%
Nomex	6.3	34.8	129.2
	6.5	27.5	116.3
	7.1	29.6	155.1
	6.6	35.2	149.1
	6.4	32.6	138.4
	6.6	31.9	137.6
	CV 4.7%	CV 10.4%	CV 11.3%

APPENDIX D

43,000% per sec. Strain Rate Results Under Non-Standard Conditions for Nylon 728

Condition	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
(250°F)	9.7	21.1	31.0
	9.9	20.6	36.9
	9.2	22.4	33.7
	9.8	23.2	33.7
	9.7	21.1	36.1
	9.7	21.7	34.3
	CV 2.8%	CV 5.0%	CV 6.8%
(Wet)	9.7	17.2	35.3
	10.6	19.8	35.3
	10.0	18.1	39.8
	9.9	18.5	36.1
	10.5	16.3	37.8
	10.1	18.0	36.8
	CV 3.9%	CV 7.4%	CV 5.2%
(Dry)	10.8	20.6	50.8
	10.7	19.8	45.6
	13.3	19.8	51.7
	10.7	14.6	48.2
	11.3	19.4	50.0
	11.4	18.8	49.3
	CV 9.8%	CV 12.8%	CV 4.9%

APPENDIX E

0.33% per sec. Strain Rate Results Under
Non-Standard Conditions for Nylon 728

Condition	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
(250^oF)	7.4	25.4	19.2
	6.5	26.9	18.4
	7.4	25.4	14.1
	8.3	22.7	16.9
	8.0	22.6	15.1
	7.5	25.6	16.7
	CV 9.2%	CV 7.7%	CV 12.8%
(Wet)	8.8	25.7	23.5
	9.5	27.7	16.9
	8.2	29.3	16.9
	9.2	24.2	21.2
	8.8	26.9	16.3
	8.9	26.8	19.0
	CV 5.5%	CV 7.2%	CV 16.9%
(Dry)	10.9	23.4	47.0
	11.3	20.3	60.4
	10.9	21.1	52.9
	11.3	23.0	47.0
	11.5	20.7	60.4
	11.1	21.7	53.5
	CV 2.4%	CV 6.4%	CV 12.5%

APPENDIX F

3.33% per sec. Strain Rate Results Under
Non-Standard Conditions for Nylon 728

Condition	Rupture Stress (gpd.)	Rupture Strain (%)	Modulus (gpd.)
(250^{o}F)	8.5	22.6	26.4
	8.8	22.6	23.5
	8.3	19.9	21.2
	8.4	20.7	32.5
	7.6	25.0	26.4
	8.3	22.2	26.0
	CV 5.3%	CV 8.9%	CV 16.3%
(Wet)	10.3	27.3	17.6
	9.8	21.5	16.9
	10.2	22.6	17.6
	10.0	25.0	14.6
	9.5	26.1	16.3
	10.0	24.5	16.6
	CV 3.2%	CV 9.8%	CV 7.5%
(Dry)	10.4	23.4	47.0
	11.3	20.3	60.4
	10.9	21.1	52.9
	11.3	23.0	47.0
	11.5	20.7	60.4
	11.1	21.7	53.5
	CV 4.0	CV 6.5	CV 12.5%

APPENDIX G

24,000% per sec. Strain Rate Results
Under Standard Conditions

Yarn Type	Rupture Stress (gpd.)	Rupture Stress (%)	Modulus (gpd.)
Nylon 728	11.0	18.5	61.1
	11.8	17.2	73.3
	11.3	16.3	54.4
	11.7	16.8	62.1
	12.5	19.8	55.0
	11.7	17.7	61.2
	CV 4.9%	CV 8.0%	CV 12.4%

109,000% per sec. Strain Rate Results
Under Standard Conditions

Yarn Type	Rupture Stress (gpd.)	Rupture Stress (%)	Modulus (gpd.)
Nylon 728	12.7	25.1	50.9
	12.5	26.2	50.9
	11.3	24.0	61.1
	11.7	25.1	43.6
	12.8	24.0	43.6
	12.2	24.9	50.0
	CV 5.4%	CV 3.7%	CV 14.4%

APPENDIX H

The maximum attainable strain rate with the present beam whose free length is six inches, width one inch, and thickness 0.125 inches and with a minimum sample length of one cm, is 109,000% per sec. Since the beam oscillates at a sinusoidal frequency as shown in Figure 5, it can be seen that it must travel downward a given distance in a given time before it reaches the essentially linear portion of the curve. Photographs were taken at the moment the beam was fired and it was observed that it accelerated to 430 inches per sec in 10 cm on the screen. At a sweep rate of 0.1 sec/cm the time for the beam to reach this velocity is 10 cm x 0.1 msec/cm = one msec. The average velocity of the beam from zero to 430 inches/sec is 215 inches/sec. Given the time of travel and the velocity, the distance the beam travels is one msec x 215 inches/sec = 0.215 inches. Thus the beam must be allowed to travel 0.215 inches before extending the fiber. This means that the shortest sample length must be greater than this distance and for convenience a 0.39 inch or one cm sample length was used. With this shortened length and beam velocity of 1,092.2 cm/sec, the corresponding strain rate, $\dot{\epsilon}$, is found to be approximately 109,000% per sec from the following equation:

$$\dot{\epsilon} = \frac{V \times 100}{L}$$

where

V = Beam velocity (cm/sec)

L = Sample length (cm)

APPENDIX I

The following calculations for possible errors for rupture stress, rupture strain, and initial modulus represent the extreme maximums. However, the results contained in this report can be considered to be more accurate than the extremes because the data are an average value and the actual coefficient of variation would not be as high as the maximum errors.

Investigation showed that the average denier per filament had a coefficient of variation of approximately 1.34% which means a 6.0 den/fil sample could actually be 6.08 rounded off to 6.1. Also the photographs could only be read with a ±1 gm accuracy. If a sample ruptured at 60 gms, with no error, the stress would be 10.0 gpd. However, if the same sample rupture was read to be 59 gms and if the den/fil was actually 6.1, the stress would be 9.7 gpd which would result in an error of approximately 3% for the stress.

The displacement signal could be read to within ±0.2 cycles over the 10 cm screen. This means that the beam velocity is accurate to within ±2 inches/sec. Assuming a beam velocity of 432 inches/sec the beam velocity to sweep rate ratio would be 1/9.16 for a beam velocity of 430 inches/sec. Thus, if the sample extended 4 cm on the photograph which could be read to ±0.1 cm, for no error, the elongation, ϵ, would be 17.2% from the following equation:

$$\epsilon = \frac{e \times 100}{R \times L}$$

where

e = extension (cm.)

R = beam/sweep velocity ratio (cm./cm)

L = sample length (cm.)

Using this same equation, let e = 4.1 cm, R = 9.11 cm/cm, and L = 2.40 (allowance for possible error in measurement of sample length), the elongation would be 18.4% which would result in an error of approximately 7% in the indicated strain.

The possible stress and strain errors could compound in the calculations for the modulus and result in an even larger error. Given a 6.0 den/fil sample whose initial slope on the stress-strain curve is extended to 40 gms with a corresponding elongation at that point of 3.0 cm, the modulus, E, with no error would be 51.7 gpd from the following equation:

$$E = \frac{\dfrac{f}{d}}{\dfrac{e_m}{R \times L}}$$

where

f = stress at the extended slope (gms.)

d = denier

e_m = elongation at the extended slope (cm.)

R = beam/sweep velocity ratio (cm./cm.)

L = sample length (cm.)

Using this same equation and assuming f = 39 gms, d = 6.1 denier, e_m = 3.1 cm, R = 9.11 cm/cm, and L = 2.40 cm, the modulus would be 45.8 gpd which would result in an error of approximately 11% for modulus.

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