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Single and Repeated Snatch Loading of Textile Yarns, and the Influence of Temperature on the Dynamic Mechanical Properties

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Synopsis

Yarns of nylon and polyethylene-terephthalate were subjected to snatch loadings of quarter period 5×10^{-2} sec. and stress amplitudes up to break, by impacting at several known levels of energy. Force developed was measured as a function of time by means of a capacitance gauge, and the extension by photographing the movement of a small torch attached to the yarn. The equivalent linear modulus, calculated from the period of longitudinal oscillation at low energy input, agreed broadly with the initial modulus of the dynamic load-extension curves. In repeated impact at a given energy level, the total deformation increased logarithmically with time, but the extension attributable to individual impacts decreased. There was a corresponding progressive increase in dynamic tension, but the breaking tension was not apparently affected either by the number of previous impacts or by the energy level. Breaking loads of a nylon yarn, reached in 10^{-2}, 10, and 10^3 sec., were compared at temperatures from 20 to 250°C. Tenacity decreased with temperature at a rate depending on the time to break, but the tenacity at a temperature of about 240°C. was substantially independent of rate of loading. Strain-time relationships, obtained at various temperatures using a photoelectric technique, were compared and analysed.

INTRODUCTION

A falling weight provides a direct and versatile method of applying snatch loading to a textile yarn. The method has not been greatly exploited, mainly because high velocity of impact cannot be achieved by the weight except at extravagant heights of fall. Although it is true that the properties of a material near its critical velocity must be examined by other techniques,[1-3] there exists below the critical velocity, a wide and important range of conditions that can be studied with a falling weight. Many uses of parachute lines, ropes, belts, tyres, and sewing threads come within this range. In these applications, elevated temperatures often have to be sustained.

The mechanical properties of a material depend on the time available for the molecular structure to adjust itself to meet an applied force.[4] Using a falling weight, there is no difficulty in breaking a short length of yarn in 10^{-2} sec., and the behaviour reflects that of a longer length impacted at higher velocities. In addition, observation of the characteristics of the harmonic motion when break does not occur during the first quarter cycle can afford interesting data on the viscoelastic properties of the yarn. By containing the specimen in a uniformly heated zone, the effects of temperature on the stress, strain, and harmonic motion can also be studied.

The majority of applications involving snatch loading originate in the need to absorb energy rapidly, and the falling weight method has the advantage that energy input is readily controlled. At moderate snatch velocities, the stress waves in short specimens are reflected many times during a test, so that significant resonance does not occur, and the material can be regarded as homogeneously stressed.

In the experiments described in this paper, a small weight was dropped through a known distance, to impart a quantity of energy to a measured length of yarn. The yarn was tensioned before impact, so that a dynamic stress was superposed on a small static stress. In this respect, the present method is comparable with the resonance method[5] of determining elastic

TABLE I
Samples of Yarns in Tests

Ref. no.	Yarn	Nominal singles count, tex[a]	No. of singles	Twist, turns/meter	Resultant count, tex	Standard deviation of count, tex
1	Nylon type 300[b] high tenacity, untreated	23	4	55Z	96	0.3
2	Nylon type 600[b] super tenacity, untreated	93	1	28Z	94	0.3
3	Nylon type 600[b] super tenacity, heat treated	93	1	28Z	96	0.4
4	Nylon type 900[b] super tenacity, untreated	93	1	24Z	96	0.4
5	Polyester[c] high tenacity, untreated	28	3	150S	88	0.7
6	Polyester[c] high tenacity, 5% stretch	28	3	30Z	80	0.3
7	Polyester[c] high tenacity, 0% stretch	28	3	30Z	84	0.6
8	Polyester[c] high tenacity, 5% relaxed	28	3	30Z	88	0.6

[a] Tex = g./km.
[b] Yarn supplied by British Nylon Spinners Ltd., Pontypool, Great Britain.
[c] "Terylene" yarn supplied by Imperial Chemical Industries Ltd., Harrogate, Great Britain.

moduli, but has the advantage that large dynamic strains are attainable. The following series of tests are reported: (*a*) The weight was dropped from a small height to generate longitudinal vibrations in the yarn. The effect of energy input on the amplitude and periodicity of the stress or strain oscillations at temperatures up to 215°C. were studied; (*b*) the weight was dropped from a height sufficient to break the yarn. The effects on the stress of temperatures up to 240°C. and times to break varying between 10^{-2} and 10^{3} sec. were observed; (*c*) the weight was dropped repeatedly until break occurred. The changes in the dynamic load and extension were measured.

MATERIALS

Samples of the following yarns were included in the tests as shown in Table I.

Yarn no. 3 was heated at a nominal temperature of 210°C. for 40 sec. under a tension which allowed some shrinkage. The heat-setting treatments of yarns nos. 6–8 were performed at nominal temperatures of 220°C. for 30 sec. Yarn no. 6 had been hot-stretched by imposing 5% extension, no. 7 was held at constant length and no. 8 was given 5% overfeed. Yarn no. 4, equivalent to yarn no. 2 but containing antioxidant for high temperature resistance, was used in the tests on the effects of temperature.

Yarns of count values about 100 tex were found convenient. Below 70 tex, creep was likely to occur under the static load, and above 100 tex twist and ply interactions might become important. Most of the yarns tested were of as low a twist as was practicable consistent with ease of handling, so that they behaved essentially as bundles of parallel filaments.

APPARATUS AND METHOD

The falling weight device is illustrated in Figure 1. The upper end of the yarn was attached to a massive steel U-gauge (Fig. 2), and the lower end to a suspended rod and plate assembly. On releasing an annular weight to strike the plate, the tension generated in the yarn was transmitted to the U-gauge and the deflection thereof was converted into a change of capacitance and thence into a change of radio-frequency. This was compared with a constant frequency and the resulting potential was amplified and applied to the Y-plates of an oscilloscope. With the time-base inactive, the vertical trace was photographed with a drum camera operating at 114 cm./sec. (2 rev./sec.) to give a continuous tension-time record. Calibration of the gauge was established by incremental static loading. The validity of such a calibration was dependent on the U-gauge having a high natural frequency (this was 400 cycles/sec. under a load of 5 kg.) and a small deflection (0.0094 mm./kg.). Resonance between the yarn and the U-gauge was thereby avoided, and measurements of tension were made with a range of accuracy of about ± 0.1 kg.

The rod and plate assembly carried, in the earlier experiments, a small torch. The vertical movement of the torch was photographed with a drum camera to give a continuous extension-time record. In later experiments, on the effects of temperature, the torch was replaced by a vertical aluminium plate which partially intercepted a beam of light focused on to a photoelectric cell. Movement of the plate changed the photocell potential, which was displayed on an oscilloscope and photographed. The static tension in the yarn was lower in this method than when a torch was used, and distance calibration lines were readily produced on the films.

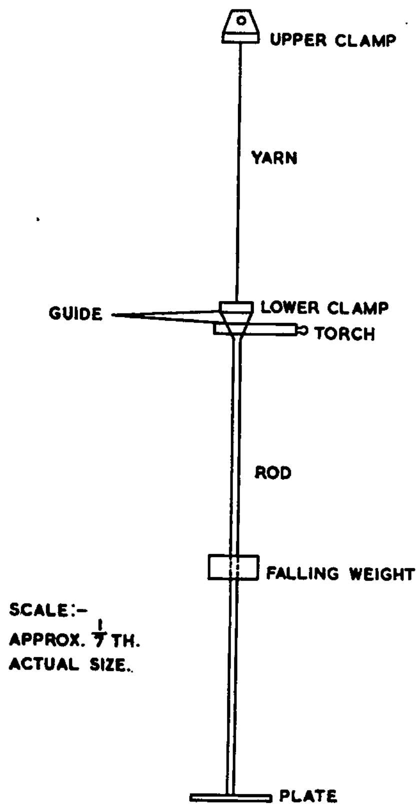

Fig. 1. Falling weight apparatus.

In tests on repeated snatch loading, the energy input was maintained constant by readjusting the height of fall after each drop. This was necessary because recovery of the yarn from strain in preceding loadings was not complete. The dynamic load and extension at the first quarter cycle were measured in impacts taking place at one minute intervals. The dropped load was removed after 5 sec. and the residual extension was measured after 20 sec. In a further series of tests, 16 hr. periods were allowed for recovery between loadings, the yarn meanwhile being under zero tension.

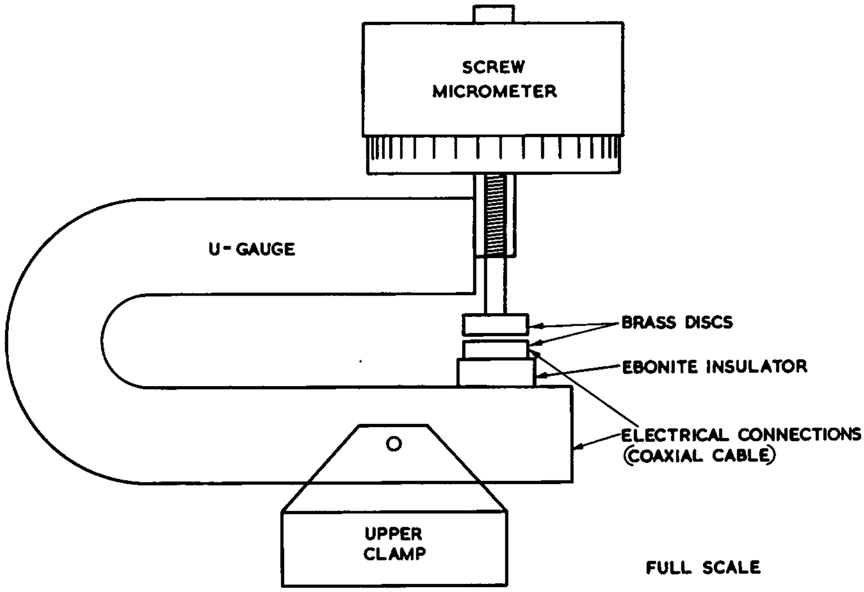

Fig. 2. U-gauge transducer.

In tests at elevated temperatures, an airstream of 2500 l./hr. was passed through an asbestos-covered metal duct containing at one end an electrically heated coil whose output was controlled by a variable transformer. A suitable length of yarn was arranged near the other end of the duct and close to it was fitted an electric fan to ensure a uniform temperature along the length of the yarn.

RESULTS AND DISCUSSION

Single Snatch Loading

A typical force-time trace is shown in Figure 3. The experimental records with different materials, energy inputs, and temperatures are too

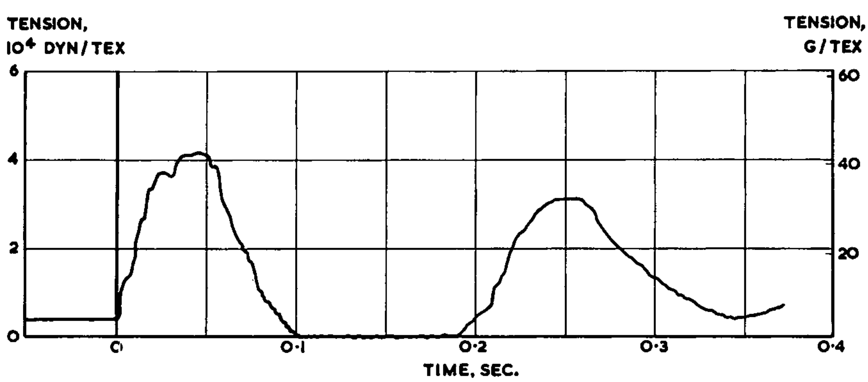

Fig. 3. Typical force-time trace.

numerous to reproduce in detail. The extension-time traces resembled the force records. The yarns sometimes became slack, particularly at the larger heights of fall, so that the tension was zero for a short interval. Similar occurrences have been described by Gimalouski[6] and by Heins[7] in experiments with parachutes.

The motion of the lower clamp approximated to a damped harmonic one. The peaks, especially at the larger heights of fall, were often in double or multiple form. In the extension curves, the negative peaks were also sometimes multiple. This effect might be ascribed to overtones arising from nonlinear elasticity, as, for example, if the motion consisted principally of a moderately damped sine wave together with a highly damped third harmonic, as in eq. (1):

$$F = A\exp\{-a\tau\}\sin\tau + B\exp(-b\tau)\sin 3\tau \qquad (1)$$

where F is the force in the yarn after time τ; A, B, a and b are constants. The relation in Figure 3 is closely represented by inserting into eq. (1) the values $A = B = 1$ (taking the undamped amplitude as unity), $a = 0.07$ and $b = 2$.

It may be remarked that if a increases, the peak force is reduced, when compared with the amplitude in the undamped system. The reverse is true in the case of b in the third harmonic at $\tau = \pi/2$, but if b falls below a certain value and B is large enough, the peak force occurring at $\tau = \pi/6$ may exceed that at $\tau = \pi/2$. The ratios of the exponential terms of the harmonics under different conditions may therefore assume considerable importance.

Multiple rebound of the falling weight on hitting the plate might produce a similar effect although the natural rebound frequency would probably be considerably lower than the modulating frequency observed on the traces. Another modulation, of small amplitude, resulting from natural or somewhat forced oscillations of the U-gauge, was superposed on the force-time curves.

The impacts were characterized by the energy W introduced into the system by the moving body at the instant of impact. For purposes of

TABLE II
Peak Tensions Developed at Various Heights of Fall

		Peak tensions, g./tex, at the following heights of fall, cm.				
Ref. no.	Material	10	20	30	40	50
1	Nylon	34	44	55	67	72
2	Nylon	45	54	70	79	89
3	Nylon	35	47	58	70	73
5	Polyester	39	56	61	74	
6	Polyester	52	64	59		
7	Polyester	43	52	63	74	
8	Polyester	30	45	52	57	58

comparison between yarns, W was expressed as the energy input per tex for unit length of yarn, which was equivalent to the energy input per unit weight. The work done by the combined masses after impact varied with the extensibility of the yarn and this was allowed for in tests at elevated temperatures.

Table II gives values of peak tensions for the nylon and polyester yarns at various heights of fall. The corresponding extensions are given in Table III. Table IV gives the times for attainment of peak tension. Because of their extensibility, heat-relaxed yarns were able to withstand the effects of snatch loading better than heat-stretched yarns.

TABLE III
Percentage Extensions Corresponding to Peak Tensions

		Extensions at heights of fall, cm.				
Ref. no.	Material	10	20	30	40	50
1	Nylon	8.0	10.3	11.5	12.6	13.3
2	Nylon	6.2	8.0	9.4	9.6	10.8
3	Nylon	7.1	9.0	10.6	11.5	12.4
5	Polyester	7.1	8.7	10.5	broken	
6	Polyester	5.7	7.6	broken		
7	Polyester	5.5	7.2	8.6	broken	
8	Polyester	6.9	9.4	11.3	12.9	14.3

TABLE IV
Times, Millisec, to Attain Peak Tensions

		Heights of fall, cm.				
Ref. no.	Material	10	20	30	40	50
1	Nylon	62	56	54	45	48
2	Nylon	50	41	44	37	32
3	Nylon	56	55	47	53	47
5	Polyester	55	55	42	29	
6	Polyester	41	33	19		
7	Polyester	43	41	34	42	
8	Polyester	53	53	53	48	48

Damped Oscillations

For simplification, the following assumptions may be made: (*a*) the motion of the yarn following impact is represented by a damped harmonic wave; (*b*) the falling mass m_2 coalesces perfectly with the impacted end, without rebound, so that the combined masses can be treated as a single mass M at any instant after impact.

The differential equation defining the displacement x of the lower clamp at a time t after the instant of impact is:

$$(MD^2 + GD + E)\,x = 0 \tag{2}$$

where D is the differential operator d/dt, t is the time, G is a viscous damping factor and E is a modulus.

If G and E are considered to be independent of displacement, as will be approximately true when the displacement is small, eq. (2) can be integrated analytically. The classical solution is:

$$x = A \exp \{-Gt/2M\} \cdot \sin [t(4EM - G^2)^{1/2}/2M] \tag{3}$$

where A is the theoretical amplitude in the absence of damping, i.e., when $G = 0$.

Oscillations with period $T = 4\pi M/(4EM - G^2)^{1/2}$ occur when the value of the sine is real, that is, when $G^2 < 4EM$. Usefully observable quantities are the period and the ratio of successive amplitudes.

If the ratio of successive amplitudes, positive and negative, is x_{n+1}/x_n, then

$$x_{n+1}/x_n = \exp \{\pi G/(4EM - G^2)^{1/2}\}$$

Since experimental values of ln (x_{n+1}/x_n) tended to be ~ 0.5 or less, G^2 was generally taken to be less than 0.1 EM and the following approximations were used:

$$x = A \exp\{-Gt/2M\} \cdot \sin t\,(E/M)^{1/2} \tag{4}$$

$$x_{n+1}/x_n = \exp\{\pi G/2(EM)^{1/2}\} \tag{5}$$

$$T = 2\,\pi\,(M/E)^{1/2} \tag{6}$$

Thus, E may be evaluated from the period and G from the decrement. Values of E, referred to a given length and count of yarn, are given in Table V. The lowest height of fall was used in these calculations, to reduce the effects of nonlinearity and to avoid the yarn becoming slack. By comparing eqs. (1) and (4), it will be seen that $\tau = t\,(E/M)^{1/2}$.

In addition, if F is the dynamic tension at time t,

$$\begin{aligned} F &= (GD + E)x \\ &= EA \exp\{-Gt/2M\} \cdot \sin [t(E/M)^{1/2} + \delta] \end{aligned} \tag{7}$$

TABLE V
Equivalent Linear Moduli

Ref. no.	Material	Period, sec.	Equivalent linear modulus[a] 10³ dyn./tex/% extension	g./tex/% extension
1	Nylon	0.24	3.2	3.3
2	Nylon	0.22	3.9	4.0
3	Nylon	0.23	3.5	3.6
5	Polyester	0.19	5.5	5.6
6	Polyester	0.21	5.2	5.3
7	Polyester	0.21	5.0	5.1
8	Polyester	0.21	4.8	4.9

[a] This is a specific modulus since g./tex = (Kg./sq. mm.)/fibre density.

where δ, the phase lag, is a measure of the mechanical loss, and

$$\tan\delta = G/(EM)^{1/2} \tag{8}$$

Substituting (8) in eq. (5) gives

$$\pi\tan\delta = 2\ln(x_{n+1}/x_n) \tag{9}$$

Introduction of damping into an undamped system will cause a reduction in the peak force. At the quarter period $t = \pi\ (M/E)^{1/2}/2$, the peak force is $EA\exp\{-Gt/2M\}$ when δ is small. The ratio of the peak force to that in an undamped system of identical modulus is therefore $\exp\{-Gt/2M\}$, which is equal to $\exp\{-(\tan\delta)/4\}$. Using the experimental result $\tan\delta = 0.16$, the reduction in peak force by virtue of damping is 12%, if E is constant. If E increases as the force increases, an even greater reduction in peak force can be expected.

The energy associated with the motion is given by,

$$\begin{aligned} W &= \int F dx = \int F\cdot D(x)\cdot dt \\ &= -\frac{EA^2}{4}\exp\{-Gt/M\}\{1 + \cos[2t(E/M)^{1/2} + \delta]\} \end{aligned} \tag{10}$$

Thus, the energy lost in the first half cycle is given by inserting the limits $\tau = 0$ and $\tau = \pi$, i.e.,

$$\int_{t=0}^{\pi(M/E)^{1/2}} F dx = \frac{EA^2}{4}(1 + \cos\delta)[1 - \exp\{-\pi G/(EM)^{1/2}\}]$$

For small values of δ, this reduces to

$$W = \frac{EA^2}{2}[1 - \exp\{-\pi\tan\delta\}] \tag{11}$$

In the case where $\tan\delta = 0.16$, the energy lost by the yarn during the first half cycle was $0.20\ EA^2$.

When E is not constant, but equal to some function of the extension, eq. (2) may be written:

$$MD^2(x) + GD(x) + f(x) = 0 \tag{12}$$

The solution of eq. (12) can be expressed as a trigonometric series,[8] and the period of the motion will be dependent on the amplitude. The force F can, in principle, be derived by double differentiation of the series, to give a relation consistent with (1).

Dynamic Load-Extension Curves

Taking the value of δ to be 9°, the stress and the strain were out of phase by about 0.006 sec. This difference was considered small enough to justify the combination of the force-time and extension-time data to give the dynamic load-extension curves shown in Figures 4 and 5 for nylon and polyester yarns respectively.

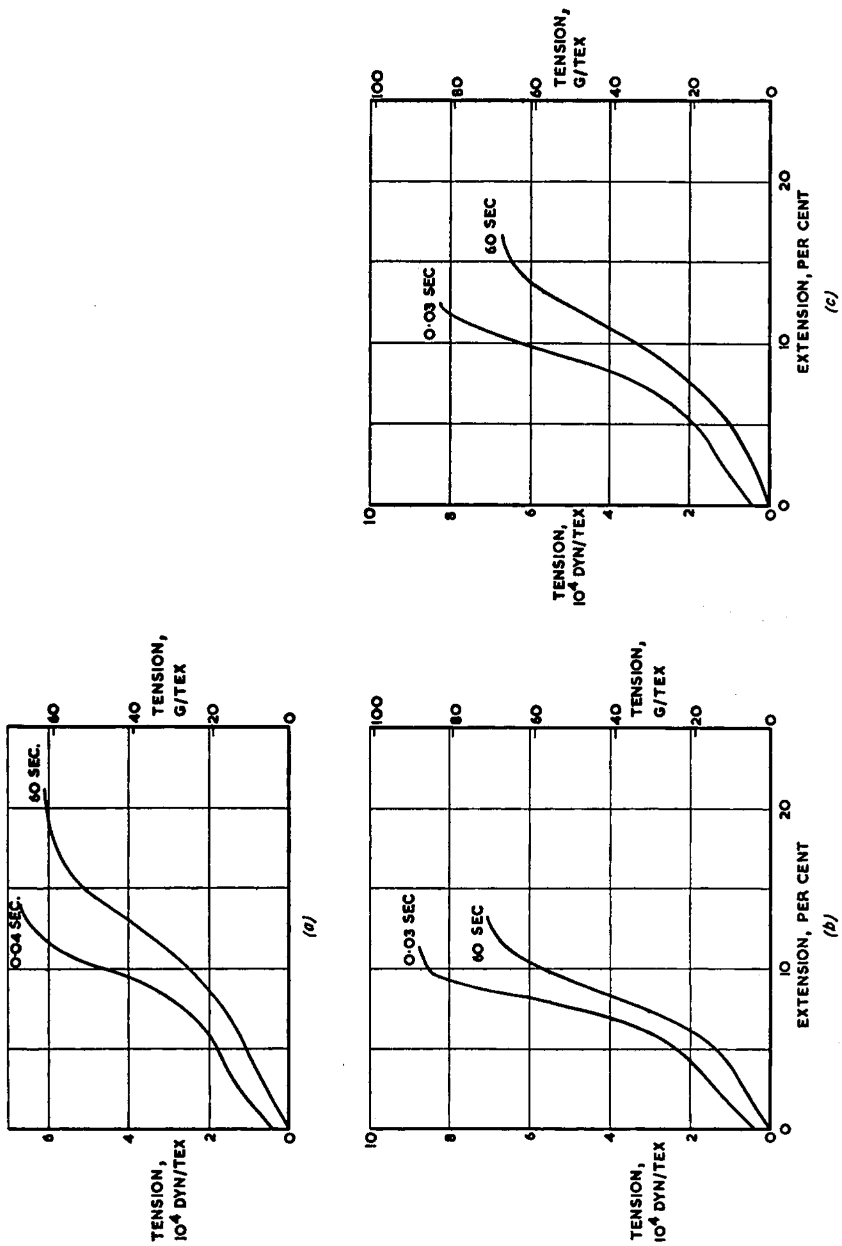

Fig. 4. Force-extension curves for nylon yarns: (*a*) Yarn no. 1; (*b*) yarn no. 2; (*c*) yarn no. 3.

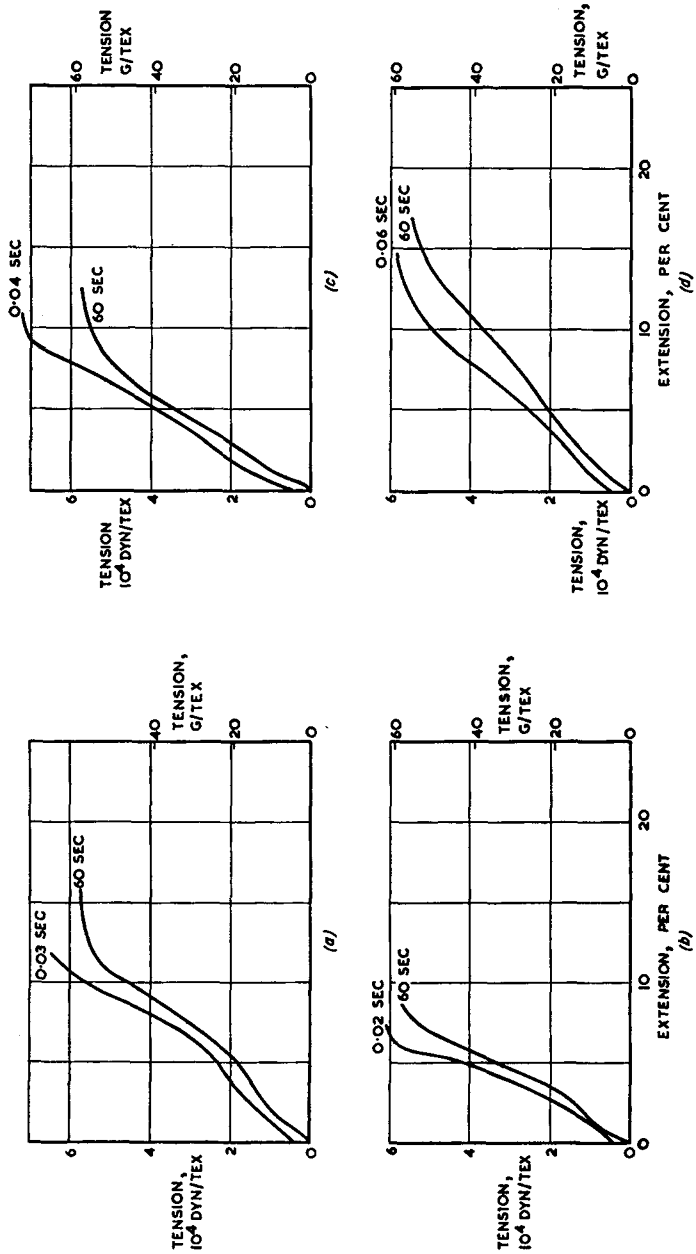

Fig. 5. Force-extension curves for polyester yarns: (*a*) Yarn no. 5; (*b*) yarn no. 6; (*c*) yarn no. 7; and (*d*) yarn no. 8.

Static curves obtained on a conventional Hounsfield rubber testing machine in 60 sec. are shown for comparison. It should be noted that the dynamic curves started from an initial static loading. The dynamic load was greater than the static load at given values of extension, for each yarn.

Harmonic analysis of the load-extension curves in Figures 4 and 5, using a Ferranti "Mercury" digital computer, showed that the Fourier series relating F and x required sine and cosine terms with odd and even harmonics to approach the experimental curves. Tables VI and VII give the values of the coefficients in the series

$$y = qF = b_0 + \sum_{k=1}^{3} (a_k \sin kx + b_k \cos kx)$$

taking the breaking force as unity when the breaking extension was $x = \pi/2$; the parameter q was the ratio between y, the sum of the series, and the observed force at $x = \pi/2$.

Three harmonics are clearly insufficient to characterize the curves. A new computer programme giving much greater numbers of harmonics is

TABLE VI
Fourier Coefficients at Two Rates of Loading for Nylon Yarns

Time to failure, sec.	Nylon 1		Nylon 2		Nylon 3	
	0.04	60	0.03	60	0.03	60
a_1	−7.77	−14.99	−3.70	−11.98	28.50	13.81
a_2	3.99	10.87	1.07	8.07	−18.80	−8.77
a_3	0.04	−2.09	0.57	−1.30	3.22	1.38
b_0	4.48	15.29	−0.02	10.79	−28.05	−13.55
b_1	−1.92	−17.98	3.72	−11.41	33.41	16.28
b_2	−4.33	1.40	−5.29	−0.89	−3.77	−2.13
b_3	1.83	1.29	1.63	1.51	−1.55	−0.60

TABLE VII
Fourier Coefficients at Two Rates of Loading for Polyester Yarns

Time to failure, sec.	Polyester 5		Polyester 6		Polyester 7		Polyester 8	
	0.03	60	0.02	60	0.04	60	0.06	60
a_1	35.51	−23.14	24.00	54.90	59.32	30.86	−39.19	2.16
a_2	−20.54	17.89	−16.32	−34.22	−37.09	−16.31	26.64	0.09
a_3	2.47	−3.87	3.02	5.00	5.53	1.24	−4.54	−0.37
b_0	−31.46	25.49	−24.69	−51.73	−55.60	−24.02	39.14	−0.46
b_1	33.53	−32.12	30.54	58.44	62.75	22.69	45.51	−0.54
b_2	0.58	5.21	−4.71	−2.84	−2.81	4.60	3.50	1.07
b_3	−2.58	1.42	−1.07	−3.87	−4.29	−3.27	2.94	−0.07

being arranged, and it is hoped that some physical significance can then be attached to the values of the Fourier coefficients.

Repeated Snatch Loading

The dynamic load and extension progressed with repeated snatch loadings as shown in Tables VIII–XIV. The peak of the load rose with the number of drops, while the time to reach the maximum decreased. The total extension increased with each drop, but the extension attributable to each successive loading became less, when based on the length of the yarn immediately before that loading. The difference could be accounted for by delayed recovery (creep) in the yarns. Extension at break is not given in the tables, because of difficulty in deciding the point of rupture on the traces.

The amount of creep was approximately a logarithmic function of the number of impacts. This is illustrated in Figure 6, plotted from the data

TABLE VIII
Repeated Impact of Nylon 1—Mean Dynamic Breaking Strength 73 g./tex

Energy input/cm. length of yarn, 10^8 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total residual extension 20 sec. after each impact, % original length
1.18	1	0.062	34	8.0	8.0	2.2
	2	0.046	35	6.7	8.7	2.6
	5	0.045	35	6.6	9.0	3.0
	10	0.054	37	6.2	9.0	3.0
	20	0.047	38	6.2	9.2	3.4
	50	0.040	39	6.2	9.6	3.8
	100	0.042	40	6.0	9.6	4.0
7.08	101	0.021	73	broken	—	—
2.36	1	0.056	44	10.3	10.3	3.0
	2	0.047	48	8.8	11.3	3.2
	5	0.043	49	8.3	11.7	3.8
	10	0.040	50	8.3	11.9	4.2
	20	0.042	54	8.3	12.2	4.4
	50	0.039	55	7.8	12.4	5.0
	100	0.047	57	7.4	12.9	5.4
5.90	101	0.019	75	broken	—	—
3.54	1	0.054	55	11.5	11.5	3.6
	2	0.037	60	9.4	12.4	4.4
	5	0.043	65	9.2	13.5	5.2
	10	0.041	65	9.4	14.7	6.0
	15	0.038	66	9.4	15.1	6.6
	19	—	—	broken	—	—
4.72	1	0.045	67	12.6	12.6	3.8
	2	0.040	73	10.4	14.0	4.6
	3	0.041	76	10.4	14.7	5.2
	4	0.037	76	broken	—	—
5.90	1	0.048	72	13.3	13.3	5.0
	2	0.036	78	broken	—	—
7.08	1	0.040	69	14.3	14.3	5.8
	2	0.022	69	broken	—	—

of Table VIII. There appeared to be a certain residual deformation, calculable from such data, which would mean failure if it were exceeded in the next impact. This property might be used to forecast breakage at a given energy level if the amount of set tolerable were known from previous tests.

If the superposition principle of Boltzmann is taken as applicable,[9] the total deformation of the yarn will be given by summing the effects of all previous changes in load. Creep curves may be constructed giving the total yarn deformation x as a continuous function of time t (Fig. 7). The creep is seen to conform for the period of the tests to the empirical linear equation

$$x = x_0 + k\log t \tag{13}$$

where k is a constant and x_0 is the deformation at time $t = 1$.

TABLE IX
Repeated Impact of Nylon 2—Mean Dynamic Breaking Strength 91 g./tex

Energy input/ cm. length of yarn, 10^3 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total residual extension 20 sec. after each impact, % original length
1.21	1	0.050	45	6.2	6.2	0.8
	2	0.046	48	5.9	6.4	1.0
	5	0.044	49	5.8	6.5	1.2
	10	0.038	49	5.6	6.7	1.2
	20	0.038	50	5.7	6.7	1.4
	50	0.037	53	5.5	6.7	1.6
	100	0.042	55	5.5	6.9	1.8
7.26	101	0.029	110	broken	—	—
2.42	1	0.041	54	8.0	8.0	1.2
	2	0.034	57	7.4	8.7	1.4
	5	0.039	58	7.1	8.7	1.6
	10	0.034	60	7.3	9.0	1.6
	20	0.040	61	7.1	9.0	1.8
	50	0.041	62	6.9	9.0	2.0
	100	0.040	64	6.9	9.2	2.0
7.26	101	0.027	87	broken	—	—
3.63	1	0.044	70	9.4	9.4	1.2
	2	0.042	74	8.5	9.4	1.6
	5	0.024	76	8.3	9.9	2.0
	10	0.031	77	7.8	9.6	2.2
	20	0.044	79	8.1	10.1	2.6
	30	—	—	8.5	10.3	2.8
	34	—	—	broken	—	—
4.84	1	0.037	79	9.6	9.6	1.4
	2	0.033	82	9.0	10.4	2.0
	3	0.036	84	9.2	11.0	2.6
	4	0.036	86	broken	—	—
6.05	1	0.032	89	10.8	10.8	1.8
	2	0.035	98	broken	—	—
7.26	1	0.031	83	broken	—	—

TABLE X
Repeated Impact of Nylon 3—Mean Dynamic Breaking Strength 84 g./tex

Energy input/ cm. length of yarn, 10^8 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total residual extension 20 sec. after each impact, % original length
1.18	1	0.056	35	7.1	7.1	1.6
	2	0.050	39	6.2	7.6	1.8
	5	0.045	40	5.8	8.0	2.2
	10	0.049	41	6.0	8.1	2.6
	20	0.047	44	6.0	8.1	2.6
	50	0.046	45	6.1	8.6	2.8
	100	0.046	45	5.5	8.3	3.0
7.08	101	0.026	75	broken	—	—
2.36	1	0.055	47	9.0	9.0	2.2
	2	0.043	50	7.4	9.1	2.8
	5	0.048	53	6.9	9.2	3.0
	10	0.042	54	7.8	9.7	3.2
	20	0.037	55	7.8	9.7	3.6
	50	0.046	57	7.6	9.7	3.8
	100	0.046	60	7.8	10.1	4.0
7.08	101	0.030	82	broken	—	—
3.54	1	0.047	58	10.6	10.6	3.0
	2	0.036	66	8.9	11.3	3.4
	5	0.034	68	8.5	11.9	4.2
	10	0.037	69	9.0	12.4	4.6
	20	0.033	70	8.6	12.4	5.0
	50	0.040	73	—	—	6.0
	53	—	—	broken	—	—
4.72	1	0.053	70	11.5	11.5	3.6
	2	0.033	80	9.2	12.0	4.2
	5	0.042	82	9.5	12.2	5.0
	10	0.042	85	9.2	12.7	6.0
	11	0.034	88	broken	—	—
5.90	1	0.047	73	12.4	12.4	4.0
	2	0.030	81	10.1	13.8	4.8
	3	0.033	91	—	—	5.4
	4	0.035	90	broken	—	—
7.08	1	0.040	90	12.4	12.4	4.0
	2	0.031	99	broken	—	—
8.26	1	0.032	84	broken	—	—

In experiments where 16 hr. rest periods under zero load were allowed between impacts, recovery was more complete than after one minute, and the same repeated energy input would be expected to give a slower progression of peak force. The detailed results are not presented, but broadly this expectation was confirmed, though with considerable scatter. Conversely, it might be supposed that recovery times of less than one minute would reduce the number of impacts sustainable by the materials, but it was not possible to test this supposition with the present apparatus.

There was no significant indication in the experiments that the dynamic breaking strength was altered by preceding impacts, or by the level of energy input. This result need not necessarily apply in the event of a large number of impacts at a very low energy level.

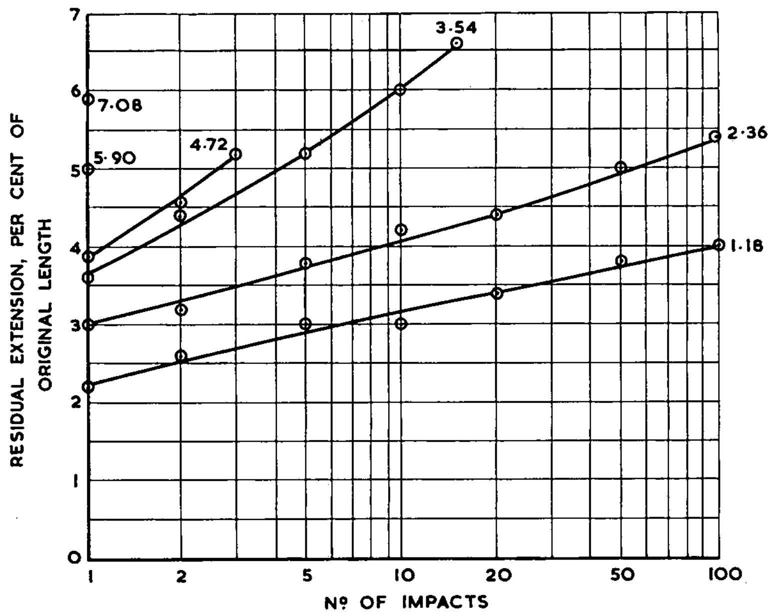

Fig. 6. Dependence of residual extension of nylon on number of impacts. The number against each curve indicates the energy input in units of 10^3 erg/tex cm. length of yarn. The curves relate to a particular nylon yarn (yarn no. 1).

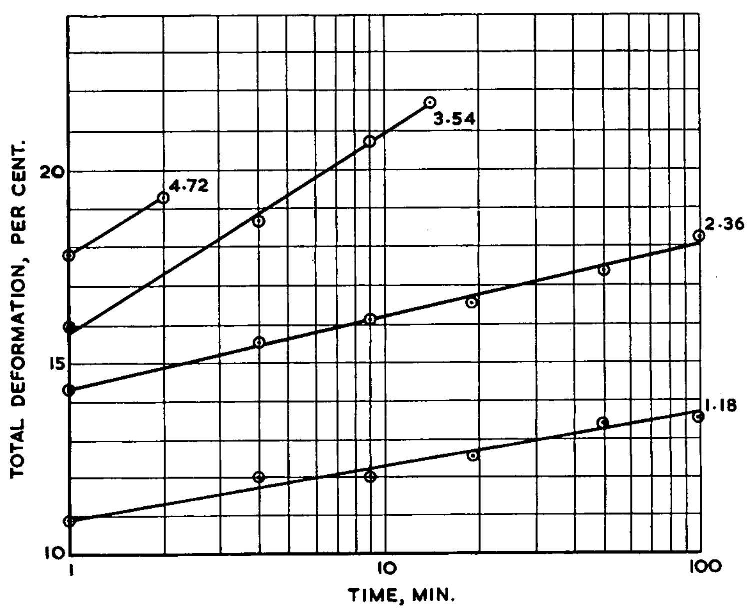

Fig. 7. Dependence of total deformation of nylon on time. The number against each curve indicates the energy input in units of 10^3 erg/tex cm. length of yarn. The curves relate to nylon yarn no. 1.

TABLE XI
Repeated Impact of Polyester 5—Mean Dynamic Breaking Strength 70 g./tex

Energy input/ cm. length of yarn, 10^3 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total residual extension 20 sec. after each impact, % original length
1.29	1	0.055	39	7.1	7.1	2.8
	2	0.040	44	5.3	7.9	3.4
	5	0.033	45	5.1	8.1	3.8
	10	0.031	48	5.1	8.5	4.0
	20	0.039	48	4.8	8.3	4.0
	50	0.036	49	4.6	8.3	4.2
	100	0.033	51	5.0	8.8	4.4
5.16	101	—	72	broken	—	—
2.58	1	0.055	56	8.7	8.7	3.2
	2	0.041	61	7.1	9.7	3.8
	5	0.038	65	6.9	10.4	4.2
	10	0.038	66	6.4	10.4	4.8
	12	—	—	broken	—	—
3.87	1	0.042	61	10.5	10.5	4.0
	2	0.033	69	broken	—	—
5.16	1	0.029	74	broken	—	—

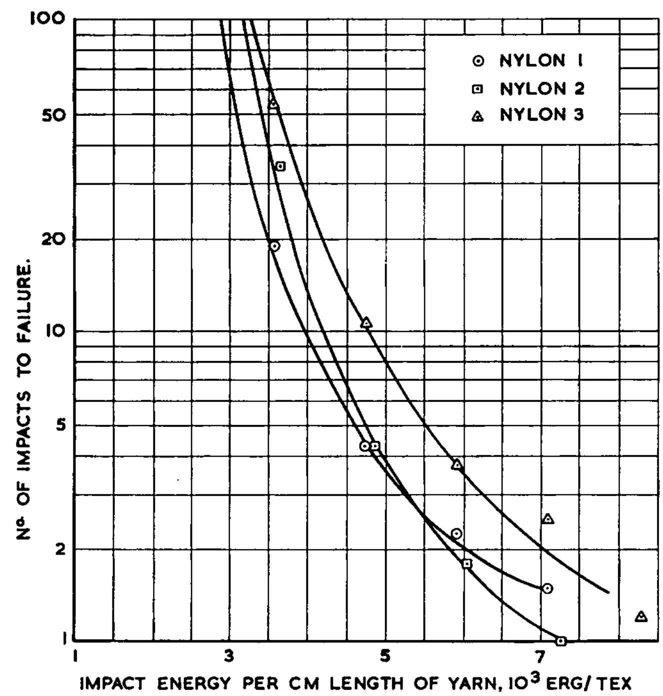

Fig. 8. Relationship between energy input and number of impacts to failure for nylon.

TABLE XII
Repeated Impact of Polyester 6—Mean Dynamic Breaking Strength 66 g./tex

Energy input/ cm. length of yarn, 10^3 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total residual extension 20 sec. after each impact, % original length
1.42	1	0.041	52	5.7	5.7	0.8
	2	0.040	54	4.8	6.0	1.0
	5	0.038	55	4.4	6.2	1.2
	10	0.032	56	4.4	6.2	1.2
	20	0.033	57	4.4	6.2	1.2
	50	0.030	56	4.4	6.2	1.4
	100	—	—	4.4	6.2	1.6
4.26	101	0.025	68	broken	—	—
2.84	1	0.033	64	7.6	7.6	1.2
	2	0.033	70	—	—	1.8
	3	—	—	broken	—	—
4.26	1	0.019	59	broken	—	—

The number of drops which the yarns could sustain at the given energy levels are shown in Figures 8 and 9. Each point plotted is the mean of six replicates, with a mean coefficient of variation of 23%. The scatter is

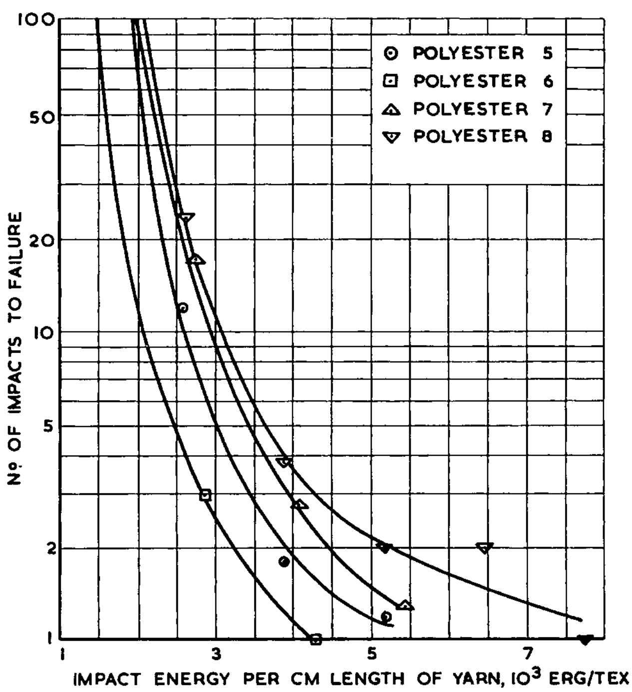

Fig. 9. Relationship between energy input and number of impacts to failure for polyester yarns.

attributable to the slow rise in stress on repeated impact, with the consequence that breakage was imminent over a range of drops.

At lower levels of energy, the number of sustainable impacts was greater for all the yarns. For any particular energy, the nylon yarns were able to withstand more than the polyester, while the heat-relaxed polyester yarns could sustain a greater number than the heat-stretched polyester.

TABLE XIII

Repeated Impact of Polyester 7—Mean Dynamic Breaking Strength 67 g./tex

Energy input/ cm. length of yarn, 10^3 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total extension 20 sec. after each impact, % original length
1.35	1	0.043	43	5.5	5.5	0.6
	2	0.033	44	5.3	6.0	0.8
	5	0.033	44	5.0	6.2	1.0
	10	—	—	5.0	6.2	1.2
	20	0.031	45	5.5	6.7	1.4
	50	0.032	45	5.5	6.7	1.6
	100	0.034	48	4.8	6.7	2.0
5.40	101	0.028	61	broken	—	—
2.70	1	0.041	52	7.2	7.2	1.2
	2	0.033	57	6.5	7.8	1.8
	5	0.033	60	6.5	8.8	2.6
	10	0.042	61	6.5	9.8	3.8
	17	—	—	broken	—	—
4.05	1	0.034	63	8.6	8.6	2.2
	2	0.033	69	—	—	3.8
	3	0.031	70	broken	—	—
5.40	1	0.042	74	broken	—	—

Influence of Temperature on Dynamic Mechanical Properties

Increases in temperature caused a reduction in the breaking strength of the heat-resistant yarn no. 4, as shown in Figure 10. The rate of reduction was dependent on the time in which failure occurred, the experimental data covering the range from 10^{-2} to 1.4×10^3 sec. If the breaking load F at the temperature θ and different times t to failure is represented by the family of equations

$$F = -l\theta + m \tag{14}$$

where l and m are different constants for each value of t, evaluation of l, m and r by the method of least squares from the experimental data up to 220°C. gives the results in Table XIV, where r is the linear correlation coefficient and N is the number of tests.

There was some tendency for the results at temperatures higher than 220°C. for times $t = 1.4 \times 10^3$ seconds to be lower than indicated by the relation (14), probably because of chemical (oxidative), rather than physical, effects. The four lines approximately intersect if extrapolated

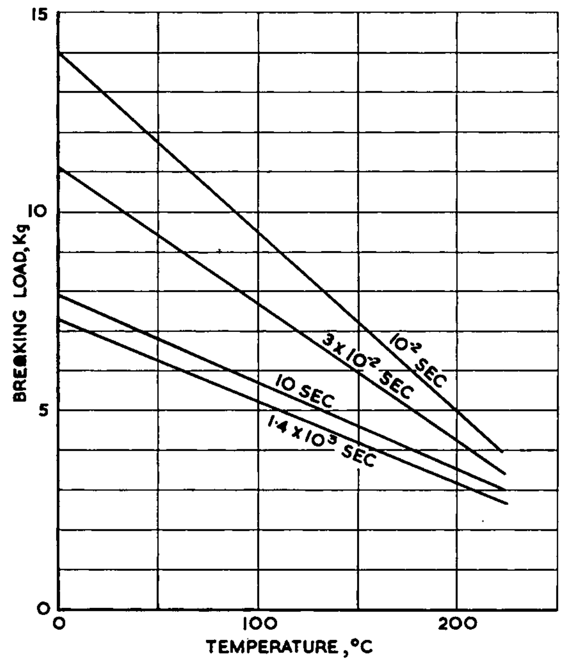

Fig. 10. Variation of breaking load with temperature at different times to break.

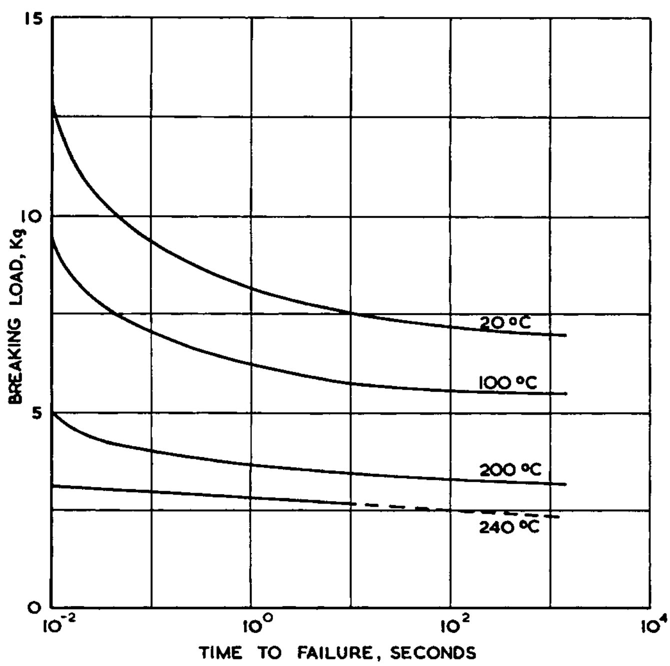

Fig. 11. Relationship between breaking load and time to failure at different temperatures.

TABLE XIV
Repeated Impact of Polyester[8]—Mean Dynamic Breaking Strength 64 g./tex

Energy input/ cm. length of yarn, 10^3 erg/tex	No. of impact	Time to reach maximum force, sec.	Maximum force, g./tex	Maximum extension in each impact: % Length before that impact	Maximum extension in each impact: % Original length	Total residual extension 20 sec. after each impact, % original length
1.29	1	0.053	30	6.9	6.9	2.6
	2	0.033	33	5.8	8.2	3.2
	5	0.035	37	5.5	9.3	4.0
	10	0.035	37	5.1	9.6	4.6
	20	0.038	39	5.3	10.1	5.0
	50	0.035	41	5.0	10.2	5.6
	100	0.033	42	5.1	10.4	5.6
5.16	101	0.026	59	broken	—	—
2.58	1	0.053	45	9.4	9.4	3.6
	2	0.039	53	7.6	11.3	4.6
	5	0.040	59	6.6	12.0	5.8
	10	0.041	61	7.2	13.4	6.8
	15	0.033	61	6.8	13.8	7.6
	20	—	—	7.1	14.5	8.0
	23	—	—	broken	—	—
3.87	1	0.053	52	11.3	11.3	5.2
	2	0.031	62	8.5	13.6	6.8
	3	0.035	67	8.3	14.5	8.2
	4	0.036	66	—	—	—
5.16	1	0.048	57	12.9	12.9	6.4
	2	0.028	68	broken	—	—
6.45	1	0.048	58	14.3	14.3	7.6
	2	0.020	66	broken	—	—
7.74	1	0.057	60	broken	—	—

TABLE XV
Lines of Best Fit for Variation of Strength with Temperature at Different Times to Break

t, sec.	N	$10^2 l$, kg./°C.	m, kg.	r
10^{-2}	32	4.53	14.1	−0.89
3×10^{-2}	25	3.45	11.2	−0.88
10	104	2.18	7.9	−0.98
1.4×10^3	31	2.13	7.35	−0.98

linearly to about 240°C. Above 240°C., the rate of reduction in strength increased sharply, and no variations were noted between the results at different times to failure.

Consideration of the theoretical eq. (15),[10] relating θ, t, and breaking stress σ(kg./mm.²) at constant load:

$$t = t_0 \exp\{u_0 - \gamma\sigma)/k\theta\} \tag{15}$$

where t_0 is a constant having the dimensions of time; γ is a parameter having the dimensions (cal./mole)(cm.²/g.); u_0 is the activation energy of breakdown, corresponding to bond energy; k is the Boltzmann constant, leads to the following conclusions: (*1*) if γ is constant at given times to break, the stress should be proportional to temperature, which is in agreement with the experimental data; and (*2*) if γ is constant at given temperatures, the stress should be proportional to the logarithm of the time to

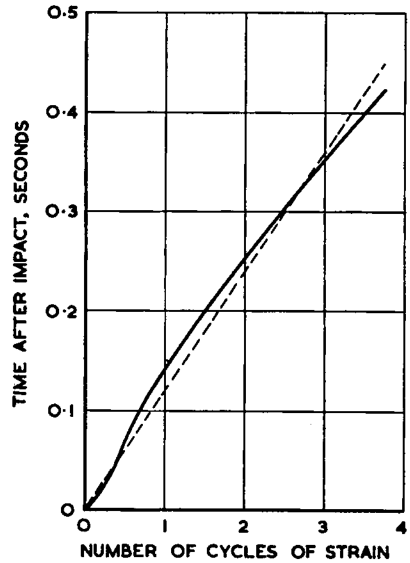

Fig. 12. Relationship between strain cycles and time.

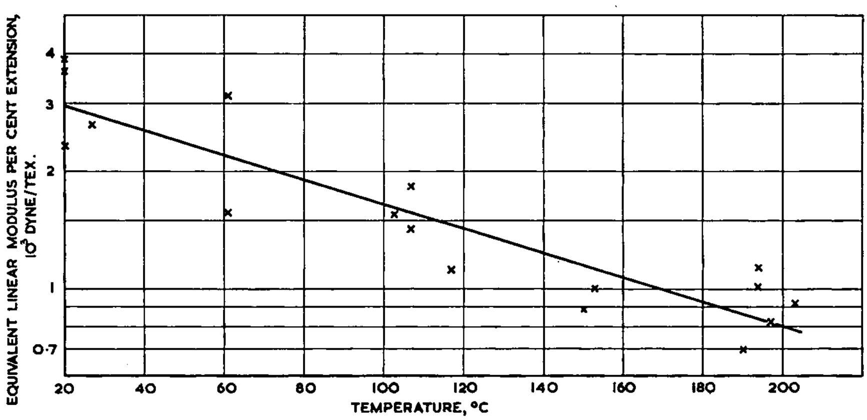

Fig. 13. Variation of calculated dynamic modulus with temperature.

break. Meredith[11] arrived at a similar conclusion in tests covering the range from 1 sec. to 1 hr., although at high rates of extension ($\sim 10^3$%/sec.), a plot of tenacity against log (rate of extension) was slightly concave to the tenacity axis. The results obtained in the present experiments are shown in Figure 11. At short time to break, the relation between strength and the logarithm of the time to break was not linear, particularly near room temperature. This might be interpreted as an indication that γ in eq. (15) was not constant in these conditions.

Figure 12 is an example illustrating the time required for successive half-periods in the oscillations of the yarn following impact at elevated temperatures. For energy inputs up to 5000 erg/cm. tex, the number of cycles at all the temperatures studied was approximately proportional to time (dashes in Fig. 12), though with a small perturbation soon after impact and often with a slightly increased frequency as the vibration proceeded (continuous line in Fig. 12). The average periods, taken from data similar to that shown in Figure 12, were used in calculations of the equivalent linear

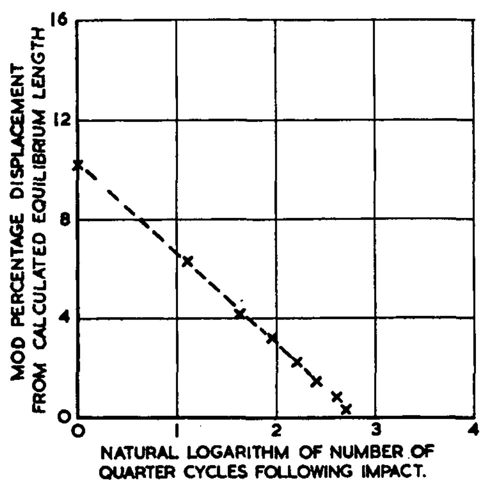

Fig. 14. Displacement from equilibrium length as a function of the number of cycles following impact.

modulus, according to eq. (6). The use of eq. (6) at different constant temperatures was considered justified in the circumstances studied, since E did not show any significant dependence on the energy input. Similar remarks apply to the calculation of G. The modulus, related to the linear density of the yarn at the temperature concerned, is shown as a function of the temperature in Figure 13. Taking the function to be linear, the correlation coefficient was found to be -0.91.

The amplitude of the vibrations decayed to zero after a few cycles, the yarn oscillating about an increasing equilibrium length. Positive and negative antinodes x^+ and x^- were proportional to the logarithm of the number of cycles, as would be expected from eq. (4), i.e.,

$$x^+ = \rho_1 \ln n$$

$$x^- = \rho_2 \ln n$$

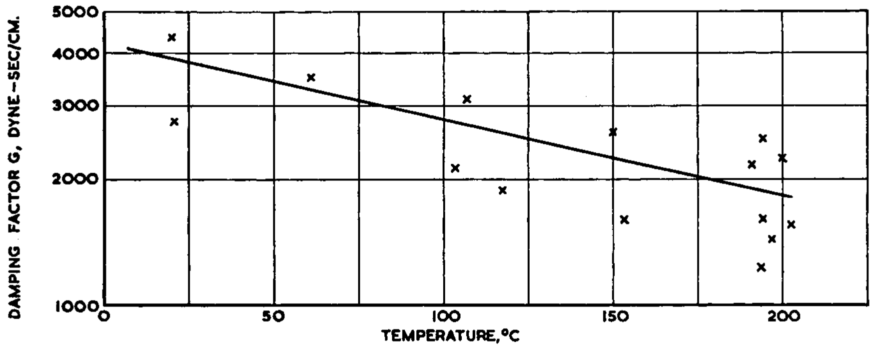

Fig. 15. Variation of calculated damping factor with temperature.

where ρ_1 and ρ_2 are experimental constants. The increase x_0 in equilibrium length is then given by

$$x_0 = \frac{\rho_1 + \rho_2}{2} \ln n.$$

The antinodal displacements may be related to this increase in length, and plotted without reference to sign in Figure 14.

Tan δ was found to be independent of temperature, and had the value 0.29, with standard deviation 0.09 in 16 readings. G was thus proportional to the square root of the modulus, and varied with temperature accordingly (Fig. 15). Equation (4) can therefore be written

$$x = A\exp\{-0.145\tau\}\sin\tau,$$

where $\tau = t(E/M)^{1/2}$, for the motion of yarn no. 4 in the conditions studied.

Equation (2) may be written more generally, taking into account the effects of nonlinearity in the force-extension relationship and the influence of temperature:

$$M\frac{\partial^2 x}{\partial t^2} + G\frac{\partial x}{\partial t} + f(x) = 0 \tag{16}$$

where G is dependent principally on temperature, and $f(x)$ is a Fourier series whose coefficients vary with temperature, extension and strain rate. Certain simplifying assumptions concerning G and $f(x)$ must be made in order to solve eq. (16), and the solution will usually be obtainable only by computer.

SUMMARY

(*1*) By using a falling weight, the behaviour of yarns broken in times down to 10^{-2} sec. and temperatures from 20 to 250 °C. was studied.

(*2*) The relationships between energy input and the changes in mechanical properties on repeated snatch loading were examined.

(3) The harmonic motions following snatch at low energy levels and temperatures from 20 to 200°C. were analyzed. Dynamic moduli were calculated and the contribution of damping was assessed.

The authors wish to acknowledge the work of their late colleague, Arthur Baker, in these investigations.

Mr. J. H. Cadwell and other members of Mathematics Department, R. A. E., are thanked for preparing the computer programme.

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Résumé

Des fibres de nylon et de téréphtalate de polyéthylène ont été soumises à des charges de rupture et de quatre périodes de 5×10^{-2} sec et à des amplitudes de tension allant jusqu'à la rupture, au moyen d'impacts à différents niveaux connus d'énergie. La'force développée a été mesurée en fonction du temps au moyen d'une jauge capacitive et l'extension a été mesurée en photographiant le mouvement d'une petite torche attachée à la fibre. Le module linéaire équivalent calculé à partir de la période d'oscillation longitudinale à faible énergie d'entrée, s'accorde largement avec le module initial des courbes d'extension de change dynamiques. Lors d'un impact répété à un niveau d'énergie donné, la déformation totale augmente d'une façon logarithmique avec le temps mais l'extension attribuable aux impacts individuels diminue. Il y a une augmentation progressive correspondante dans la tension dynamique, mais la tension de rupture n'est apparemment affectée, ni par par le nombre d'impacts antérieurs, ni par le niveau d'énergie. Les changes de rupture d'une fibre de nylon, atteinte en 10^{-2}, 10 et 10^3 sec sont comparées à des températures variant de 20 à 250°C. La ténacité diminue avec la température à une vitesse dépendant du temps à la rupture, mais la ténacité à une température d'environ 240°C est essentiellement indépendante de la vitesse de charge. Les relations élongation-temps, obtenues à différentes températures en employant la technique photoélectrique sont comparées et analysées.

Zusammenfassung

Nylon- und Polyäthylenterephthalatgarne wurden ruckweisen Beanspruchungen von Viertelperioden von 5×10^{-2} sec und Spannungsamplituden bis zum Bruch durch Stösse bei einigen bekannte Energiestufen unterzogen. Die entwickelte Kraft wurde als Funktion der Zeit durch Kapazitätsmessungen und die Dehnung durch photographische

Aufnahme der Bewegung einer kleinen am Garn befestigten Lichtquelle bestimmt. Der aus der gionitudinalen Schwingungsperiode bei kleiner Energiezufuhr berechnete äquivalente lineare Modul stimmte in grossen Zügen mit dem Anfangswert der dynamischen Belastungs-Dehnungskurve überein. Bei wiederholten Stössen bei einer gegebenen Energiestufe nahm die Gesamtdeformation logarithmisch mit der Zeit zu; die Dehnung pro individuellem Stoss nahm jedoch ab. Es bestand eine entsprechende progressive Zunahme der dynamischen Spannung, die Bruchspannung wurde aber weder durch die Zahl der vorhergehenden Stösse noch durch die Energiestufe merklich beeinflusst. Die nach 10^{-2}, 10 und 10^3 sec erreichten Bruchbeanspruchungen von Nylongarn wurden bei Temperaturen von 20 bis 250°C verglichen. Die Zähigkeit nahm mit der Temperatur mit einer von der Bruchdauer abhängigen Geschwindigkeit ab; bei einer Temperatur von etwa 240°C war aber die Zähigkeit im wesentlichen von der Belastungsgeschwindigkeit unabhängig. Die bei verschiedenen Temperaturen nach einem lichtelektrischen Verfahren erhaltenen Beziehungen für die Zeitabhängigkeit der Dehnung wurden verglichen und einer Analyse unterzogen.