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REVIEW OF SYNTHETIC FIBER ROPES

by Walter Paul

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REVIEW OF SYNTHETIC FIBER ROPES

BY WALTER PAUL

With an Introduction on the Research Program

Entitled

Investigation of Material Alternatives for Deep Water Mooring Cable

Research and Development Project
United States Coast Guard Academy
New London, Connecticut

National Data Buoy
Development Project
United States Coast Guard
Washington, D.C.

AUGUST 1970

INTRODUCTION

by

Dr. Sherman S. Weidenbaum, Principal Investigator

U.S. Coast Guard Academy Research Project

69X0243 RDCGA 6 Entitled

"Investigation of Material Alternatives for Deep Water Mooring Cable"

The material contained in the Review which follows was prepared by Dr. Walter Paul working in close cooperation with the United States Coast Guard Academy Research and Development Group, and the National Data Buoy Development personnel in Washington, D. C. This work came about when Dr. Paul was contacted in connection with the above mentioned research project.

This research had many purposes. In its own right it was to provide new knowledge concerning the behaviour of rope which is needed as the exploration of the ocean depths gains momentum. In addition, it was to be part of the educational program of the United States Coast Guard Academy. Through association with this project, Coast Guard Academy cadets who wished to do original research projects as "Academy Scholars" or to become aquainted with research techniques through a new course which was being offered had an opportunity to do so.

As the work progressed it became evident from the enthusiastic responses of both the industrial manufacturers of rope, the personnel at oceanographic research institutes, and others at universities and government institutions (including the Navy and NASA) that the areas of technology being studied were of considerable interest and that there was a strong need for this work.

Also, it became apparent that certain steps were necessary to transform the art of rope selection to the science of rope technology. One of these was to collect in an orderly fashion scientific and engineering data pertaining to ropes. This could be done concurrently with the research projects pertaining to rope and both efforts would benefit by interacting with one another. Thus, during the period while Dr. Paul was preparing this Review he was in residence at the Coast Guard Academy several days a week so that the cadet research work and the Review were coordinated through the framework of this Research Project. Summaries of cadet research work are given at the end of this introduction.

It is hoped that this Review of Synthetic Fiber Ropes and the Research Program now in progress at the Coast Guard Academy will contribute towards building the science and technology of synthetic deep water mooring lines.

Throughout this work the sustained support of the Superintendent of the U. S. Coast Guard Academy and his staff has been of great help. In particular, the Dean, the Commandant of Cadets, the Head of the Department of Physical Science and the Director of Research have all been instrumental in making facilities and opportunities available whereby cadets could carry out work and have the opportunity to meet people outside the Academy in industry, at Universities, at government agencies, and in various research organizations. Equally important has been the superb cooperation from the Office of Research and Development of the Coast Guard in Washington, D. C. starting with the warm support of the Chief, Research and Development and extending throughout the Project Manager and staff of the Data Buoy Project in particular. Also special thanks are due to the Commanding officer and staff of the Coast Guard Base, New York at Governor's Island where some of the rope testing machinery mentioned in one of the research reports was built. Finally, there has been a generous outpouring of help and advice from experienced members of the rope industry, researchers at various oceanographic and other research institutes, universities and people in various government agencies. All of these people took the cadets under their wing and made of this research project a unique educational experience. To all of them we would like to express our appreciation.

SUMMARY OF CADET RESEARCH WORK AT U. S. COAST GUARD ACADEMY

Academy Scholars, May, 1970

Theoretical Determination of Fatigue Life
For a Wire Strand in Buoy Moorings

M. D. ALLEN

A simple load model for a wire strand component of a single point buoy mooring is developed. This model is combined with the various wire rope stress theories to define the internal stress state of the strand. Particular attention is paid to the critical areas of wire contact within the strand. Combined stresses within these areas are related to multiaxial fatigue criteria. Two criteria are used to show that the uniaxial stresses equivalent to the combined stresses in the critical areas are under the fatigue limit of the wire. Limitations and ideas for expansion of this work are discussed.

Creep Tests on Synthetic Mooring Lines

M. F. FLESSNER
(Referred to in Sections 2 and 4)

Synthetic ropes are an important part of mooring lines for data buoys in the deep ocean. The tensions produced by the action of the buoy and by the general nature of the moor cause a time-dependent elongation of the rope in addition to the instantaneous elongation which occurs when a new rope is loaded.

Equipment was designed and constructed to measure these elongations quantitatively. The equipment, data collected, and its interpretation are discussed. Included in this are calculated least squares equations which were programed on an IBM 1620 computer, some significant corrleations of the data and what these mean both mathematically and in physical terms.

Recommendations are given concerning equipment modifications, data collection and analysis, dynamic tests, wet tests, and mathematical modeling of creep tests.

Undergraduate Papers in Course entitled Special Topics in Scientific Research, May, 1970

An Investigation of Means of Protecting Deep Sea
Mooring Lines from Fishbite

J. T. ARMSTRONG
(Referred to in Section 2)

The different types of fishbite damage to mooring lines and species of fish responsible for this damage are summarized. Theories as to why fishbite are presented. The effect of geographical location is discussed.

Methods of preventing fishbite damage are summarized, with special attention to the criteria for selecting an effective plastic jacket.

An analytical method is given which can help in selecting a plastic coating best suited for fishbite protection while at the same time allowing a specified flexibility for the coated rope.

Application of Photography to Creep Measurements

K. S. CALLISON

A general overview of the photographic field is given. Specific applications to the creep testing program are presented. A photographic measuring technique which was developed is described and results are given. Recommendations are made on how this method can be further developed as a tool for creep measurements.

Wet Creep Testing of Synthetic Ropes

T. M. GEMMELL

Experimental measurements of creep in Samson Double Braid and Columbian Plimoor ropes in a wet environment are described. Comparison is made with the dry creep testing of similar ropes. The inadequacies of the present wet test system and proposals for an improved wet test system are discussed.

Application of Computer Techniques to the Analysis of Experimental Creep Data

L. H. HAIL

This work involved analysis of experimental creep data by numerical methods. Various equations that might fit the data were programmed for a computer solution. Computer generated graphs were obtained for the results. The bulk of the work was performed on the IBM 1620 computer. Some work was also done on an analog computer. The results of the program are mathematical relationships between variables based on experimental data (i.e., elongation vs time, etc.).

Effect of Braid Angle on Strength and Creep Properties of Braided Rope

W. G. JOHNSON

This is a theoretical approach to analyze what happens to the strength properties, in particular the creep behaviour, of a rope if the angle of the strand axis against rope axis is varied.

These properties depend upon the geometry of the rope, the internal deformation of the rope elements such as fibers, yarns, multi-plies and strands and the load elongation properties of the fiber material. Using these concepts the theoretical results show the influence of the rope construction (here varied by changing the strand angle) and the material properties on the strength, and in particular, the creep behaviour of the rope.

A Study of Synthetic Rope Fibers

J. H. JONES

A study was made of synthetic fibers of Nylon, Dacron, polyester, polypropylene, and polyethelene including a review of the chemical and physical characteristic of the fibers. Experimental measurements were made of breaking strength, breaking length, and creep for individual fibers. Some work was also done to illustrate how individual fibers behave under stress in a controlled environments. The study is part of an overall project concerned with physical properties of synthetic fibers which are used to make rope, with the ultimate aim of finding a relationship between how fibers behave individually and when combined to form rope (i.e., how does the strength of a rope compare with the sum of the strengths of the individual fibers that comprise it?).

A Geometrical Model of Columbian Plaited Rope

J. G. MILO

The key problem in investigating theoretical stress-strain behaviour of a plaited rope, or any other rope, is to establish mathematical relationships between the deformation of the stretched rope and its components.

This is done by setting up the ideal geometry of the unstretched plaited rope in order to get the position of the various rope components such as strands, multi-plies and yarns. Then the change in the rope geometry under rope stretch is defined. The results of the combination of both steps are mathematical laws relating the elongations between strands, multi-plies, yarns and the rope.

A Study of Mooring Line Static Load Models

C. E. SIBRE

A general discussion of static load models and computer simulations for deep sea mooring lines is given. One model is analyzed in detail. The work presented here is a prelude to a planned information matrix for the static case which will be developed next year, and which will take into account all known static models.

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ACKNOWLEDGEMENTS

This report is part of a research project at the U.S. Coast Guard Academy entitled: "Material Alternatives for Deep Water Mooring Cable". It was made possible through joint financial assistance from two groups within the U.S. Coast Guard, namely the Coast Guard Academy in New London, Conn., and the National Data Buoy Development Program, Washington, D.C. The help and support of these groups is gratefully appreciated.

The author received support from so many people, that it would be difficult to adequately mention all of them. However, he would like to thank the Chief of Coast Guard Research and Development and his Data Buoy Project Staff as well as the Superintendant of the U.S. Coast Guard Academy and his Physical Science Department Staff and Director of Research for their generous cooperation and support. The open and positive attitudes and the enthusiasm of many members of both groups have been invaluable.

Cambridge, Mass., August 1970

Walter P a u l

SUMMARY

Though fiber ropes belong to the oldest man made products, little is known about their mechanical behaviour and about factors influencing this. Rope manufacturing and the use of rope in various fields is heavily based on accumulated experience, which was inherited and improved during many centuries of rope use. However, its general use did not involve rigorous scientific and engineering analysis until fairly recently.

With the introduction of synthetic fibers and new rope constructions within the last 30 years and numerous new applications of ropes in engineered systems, scientific methods are required more and more to describe and predict the mechanical behaviour of ropes in general and synthetic fiber ropes, in particular. This Handbook will give up to date information on the work which has been done to establish what may be called rope physics or rope mechanics. The goal is to turn fiber ropes into engineering tools with predictable mechanical response to applied forces and strains and to environmental conditions.

The Handbook starts with an introduction into the basic characteristics of ropes, explaining them as mechanical models and as textile structures. The mechanical properties of rope such as strength, weight, breaking length, are explained next, giving special attention to the fact that fiber ropes stretch considerably under applied loads and thus absorb mechanical energy. Reaction of ropes to loading and stretching in use is covered next. An explanation is given of the often confusing response of the rope to static and cycling loads, shock loads and constant or cycling

strains, along with a discussion of the visco-elastic nature of the synthetic fibers composing the rope. The change of rope properties due to environmental influences is also covered.

The structural mechanics of fiber ropes is introduced in the next section. This includes the textile structure of the rope itself and the structure's reaction to applied stresses or strains. By setting up the rope geometry and definition of deformation assumptions, the stretch of the rope components at any rope stretch can be determined. With the known load-elongation behaviour of the material used, the load reaction of the rope components can be determined and, by summation, the calculated rope load response to the applied stretch is obtained. The theoretical influence of construction changes on the load elongation reaction can be seen. Comparative data on twisted ropes of 5 different materials and 16 different constructions each are given, showing test results and their comparison with the theoretical curves. This method gives much insight into the structure and mechanics of the twisted rope, and should be developed for other rope types.

Finally, some recommendations for measuring and handling in particular oceanographic ropes are given and some terms used frequently in combination with ropes are explained.

The report tries to establish engineering methods to control the structure of fiber ropes and the rope's reaction to external loads and deformations. The reaction of visco-elastic macromolecular synthetic fibers in their complex arrangement in rope structures is a wide-open field for theoretical and experimental studies.

NOTATION SECTION 1 + 2

A	total cross section of a rope
BL	breaking length
BS	breaking strength
C_a	weight constant in air
C_b	strength constant
C_c	value to express load carrying cross section of a rope = A/d^2
C_{wf}	weight constant in fresh water
C_{ws}	weight constant in salt water
d, d_r D	rope diameter
E	Young's modulus
E_{pot}, E_{kin}, E_r	mechanical energy (potential, kinetic, rope)
g	gravity
i	exponent
K_e	elastic constant
l	length of rope
L	load
m	exponent
p	exponent
p_e	constant
P	pretension
s	strain = elongation/original length
s_b S_b	strain at break
$\Delta S/S_o = \mathcal{E}$	elastic strain
$\Delta S_o/S_o = \mathcal{E}_o$	permanent strain
S_o	initial rope length
SG_w	specific gravity water
SG_r	specific gravity rope fibers
t	time
t_r	recoil time
TE	total extension
T, T_e ΔT	tension on a rope
v	speed
w	weight

w_a	weight/unit length of a rope in air
w_r	weight/unit length of a rope general
w_{wf}	weight/unit length of a rope in fresh water
w_{ws}	weight/unit length of a rope in salt water
x	stretch
σ	stress
ε	elastic strain
ε_0	permanent strain
$\dot{\varepsilon}$	deformation speed
$\Delta\xi/S_0$	fractional elastic strain increase

NOTATION SECTION 3

General: All figures describing conditions in the unstretched state have the subscript$_o$, the figures describing the stretched condition have no subscript.

a_o, a	distance rope axis-strand axis
b_c, b_{co}	buckling of the center multi-plies in a strand
d_{so}, d_s	strand diameter = $2r_s$
F_m	axial force in the multi-ply
F_s	axial force in the strand
F_r	axial force in the rope
h_{so}, h_s	helix length of the strand (=helix length of the multi-plies in the strand)
h_{ro}, h_r	helix length of the rope = helix length of the strands in the rope
l_r, l_{ro}	length of a rope
l_s, l_{so}	length of a strand
l_m, l_{mo}	length of a multi-ply
M_s	strand moment
M_r	rope moment
M_t	total resulting rope moment
m	ratio h_r/d_s
m_o, m_i, m_c	number of multi-plies in the outer layer, layer i or center layer
r_{io}, r_i	radial distance of the multi-ply axis of layer i to the strand axis
r_{so}, r_s	strand radius
ε_b	extension by bending in %
ε_{mc}	extension of the multi-plies in the center of the strand
ε_{mi}	extension of the multi-plies in layer i of the strand
ε_{mo}	extension of the multi-plies at the outside layer of the strand
ε_s	extension of the strand
ε_r	extension of the rope
λ_r	length of stretched rope/length of unstretched rope

λ_s	length of stretched strand/length of unstretched strand
λ_m	length of stretched multi-ply/length of unstretched multi-ply
μ	foreturn ratio (additional twist put into the strand on the rope twisting machine to compensate twist loss of the strands by forming a helix opposite to their own twist in the rope)
α_o, α	helix angle of strand axis against rope axis
β_{io}, β_i	helix angle of multi-ply layer i against strand axis before being manufactured into a rope
β_{iro}, β_{ir}	helix angle of multi-ply layer i against strand axis after having formed the rope
β_{oo}, β_o	helix angle of the outer multi-ply layer against the strand axis before forming the rope
β_{oro}, β_{or}	helix angle of the outer multi-ply layer against the strand axis after forming the rope
$\beta_{co}, \beta_{cro}, \beta_c, \beta_{cr}$	as above, but for the center layer of multi-ply
δ	angle of inclination multi-plies against rope axis
γ	angle depending on the number of multi-plies in a strand layer

Section 1

MECHANICAL PROPERTIES OF SYNTHETIC FIBER ROPES

1. INTRODUCTION

1.1 WHAT IS A ROPE?

1.1.1 Basic Characteristics of Ropes

Fiber ropes as well as wire ropes and chains can be described as flexible connecting links used to transfer tensile stresses between two masses. In this book we will deal mainly with ropes made from synthetic fibers, from which we expect the following properties.[1) 2)]

1. The greatest possible tensile strength
2. flexibility, knotability, ease in handling and gripability
3. a compact cross section which retains its form during use
4. elastic behaviour, dampening of shock loads - absorption of mechanical energy
5. stabile load elongation properties in use
6. light weight
7. fatigue resistance
8. abrasion and cutting resistance
9. resistance to chemicals and corrosion, temperature stability
10. ease of splicing or attaching reliable terminations
11. low cost
12. torque balanced or better yet torque free construction

Ropes and chains are bodies, whose symetrical, mostly circular cross sections, are small compared to their lengths. They are able to transfer tensile loads only along their axes. They cannot transfer bending moments or transverse forces of any magnitude and are unstable under compressive loads, they will bend out.

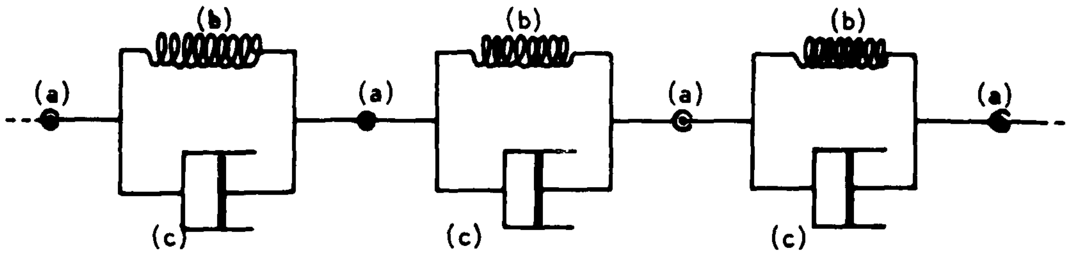
While chains hardly stretch at all and wire ropes very little (under 5%) under applied tensile loads, fiber ropes often show considerable elongation. Some fiber ropes can be stretched over 50% of their original length before they break. Compared with wire ropes, fiber ropes are very flexible. This accounts for their knotability.

1.1.2 Ropes as Mechanical Models

Ideal trusses or cables, with which ropes may be compared in mechanics, are bodies consisting of an infinitely large number of small unextensible solid segments, connected by frictionless joints,[3) lying in a single plane.

These trusses or cables (See Figure 1-1) would be completely flexible, inelastic, and unable to transfer bending moments or transverse forces. This ideal model is nearly correct in explaining the behaviour of a chain.

Real wire ropes, which stretch slightly under tensile loads and have a fairly high resistance to bending, may be described as large number of inflexible, hard (high modulus) springs, connected by joints which develop rapidly increasing friction at growing inclinations of the two adjoining spring axes. To include certain viscous reactions of wire rope under sustained or repeated loadings in the mechanical model, viscous dampeners, socalled dashpot elements, should be included. (See Figure 1-1).



FIGURE(1-1)

Mechanical Model of an ideal cable, a wire rope and a fiber rope.

The model is composed out of small solid bodies connected by joints(a). The solid bodies are composed out of elastic elements (b), here symbolized by an ideal elastic spring; and out of viscous elements (c) here symbolized by a "dashpot". This model can be used to explain the mechanical behaviour of cables and ropes.

(1) ideal cable: The joints (a) are frictionless, the spring (b) and the dashpot (c) are inextensible (Young's modulus $E = \infty$, coefficient of viscosity $\eta = \infty$)

(2) wire rope: The joints (a) have a high coefficient of friction, growing exponentally with increasing inclination of two adjoining solid bodies, since wire ropes have a pronounced bending resistance. The springs (b) are stiff and have a high Young's modulus E of 8 to 13×10^6 psi, also the coefficient of viscosity η is very high.

(3) fiber rope: the joints (a) bend easily. The spring (b) is soft with a Young's modulus of about 5 to 50×10^4 psi; the dashpot is fairly inextensible or η is high, estimated around 5×10^5 psi x sec.

Fiber Ropes, which stretch considerably under tensile loads and have a fairly low resistance to bending, can be described as a large number of soft (low modulus) springs, connected by joints developing only a small amount of resistance against displacements. Viscous dampeners should also be included to explain some yielding or time depending behaviour of fiber ropes under sustained and repeated loadings or strains.

Though these models are not perfect, they do explain ropes and chains as mechanical units with distinct, characteristic response to stresses and strains. The models do not show torque, which is present in some rope structures.

Pronounced elongation to load along the rope axis and great flexibility typify the mechanical behaviour of fiber ropes. It should be mentioned that ropes react differently in directions parallel to and at right angles to their axes. This behaviour is known as mechanical anisotropy. Usually, only their reaction along the rope axis is of interest.

1.1.3 Fiber Ropes as Textile Structures

Ropes are structures made of textile fibers, as are weaves, and knits. Rope structures are designed to obtain the maximum utilization of fiber strength from a compact rope cross sectional area in order to produce certain rope breaking strength and elasticity while using a minimum amount of fibers. Since fibers are very fine elements, sometimes less than 10^{-2} inch but usually around 10^{-3} inch in diameter or width, they have to be set up in large bundles to use their combined strength in a rope. The usual way to obtain strength and compactness in a fiber bundle is to twist the fibers together, that is to wind them around one another. A yarn is formed by this method. Larger structures are obtained by twisting yarns together to form a multi-ply. Again larger structures are formed by twisting multi-plies together to form strands. Finally by twisting strands together a rope is produced.

Due to the twisting process, the components of the twisted unit form a fairly compact, mainly cylindrical structure at the sacrifice of some of their tensile strength. The rope itself has to be torquefree or at least torquebalanced. Since the twist can have either a left hand or a right hand turn, torquefree structures can be built up by taking the same number of right and left hand components, arranging and interlacing them symetrically into a cross section. This is the basic construction principle of plaited and braided rope.

Another way to build a rope is to employ three or four equally sized strands having the same twist direction and turn them together to form rope twisted in the opposite direction. This is the principle used to produce a twisted rope.

A third way to combine a larger number of single fibers in a cross section and thus to produce a rope, is to arrange parallel fibers in a circular cross section and to keep them there by extruding a hollow plastic jacket over the fiber bundle. This principle can be used to produce ropes with fairly small diameters which are sold under trade names like nolaro or parafil. Figure 1-2 shows the four basic rope constructions described.

In all cases ropes are slender textile structures whose symetrical, frequently circular cross sections are small compared to their lengths. They are composed of a large number of single fibers.* The fiber bundle has to be arranged to form a torquefree or torque-balanced structure. At the same time the structure has to produce a maximum utilization of the fiber strength and sufficient flexibility and elasticity.

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*A nylon rope of 1 3/8" diameter contains about 1 million fibers of 6 denier.

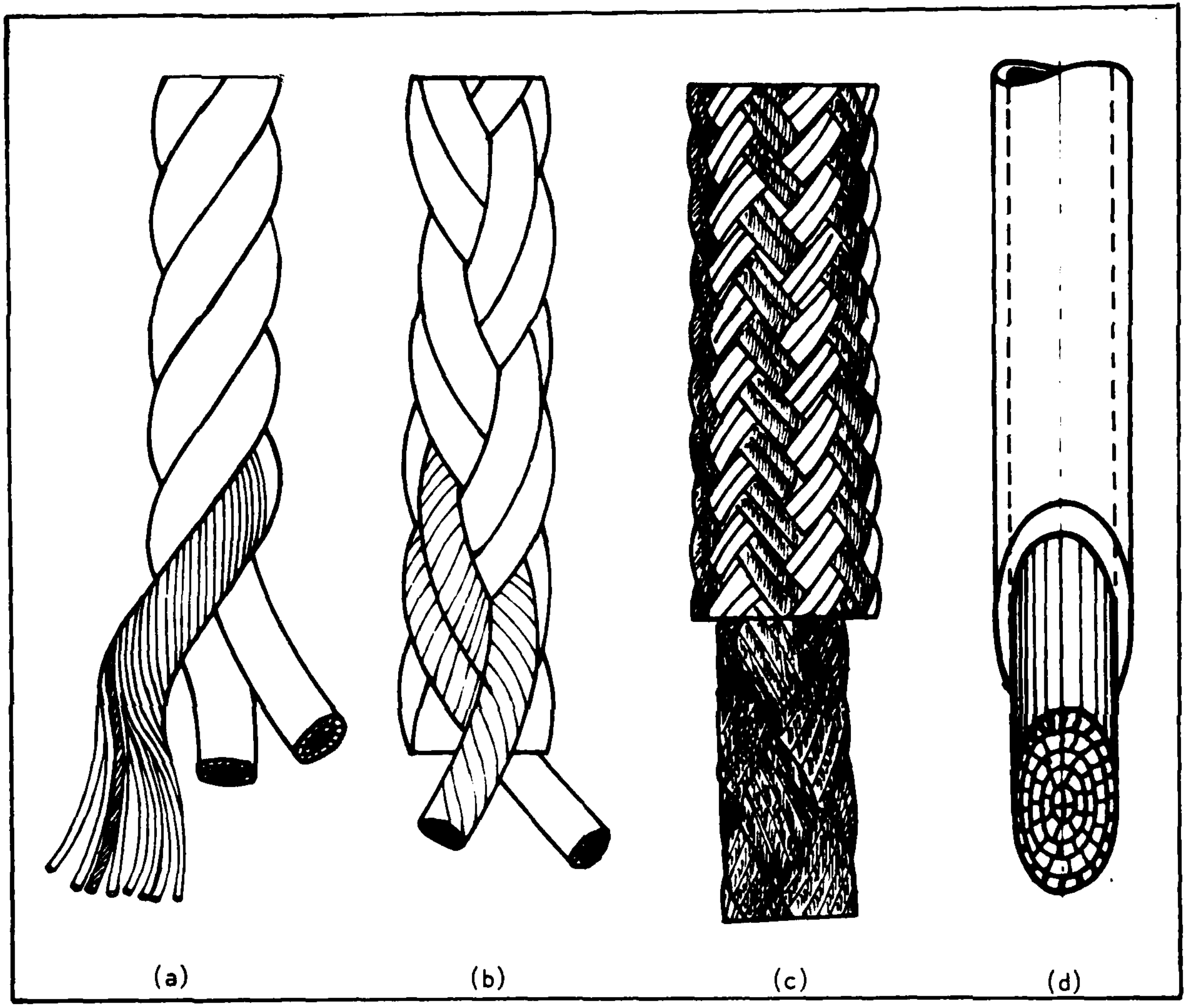

FIGURE 1-2

Standard Rope Types

(a) Twisted - three strand rope
(b) Plaited - eight strand rope
(c) Double braided rope (core - cover braid)
(d) NOLARO or PARAFIL rope

Since fibers are anisotropic, and vary in their properties according to the direction they are measured, ropes also are anisotropic or better orthotropic or transversely isotropic.[4] The later two terms are used to indicate, "that there is no difference in properties between different directions at right angles to the fiber-axis, although these are different from the properties parallel to the fiber axis"[4]. This can be assumed at least for torquefree fiber rope constructions.

References Section 1

1) Smith, J.E.,; Structures in Deep Ocean (Engineering Manual for Underwater Construction), Chapter 7, Buoys and Anchorage Systems. U.S. Naval Civil Engineering Laboratory, Port Hueneme, Cal., Oct. 1965, p. 3-10

2) Himmelfarb, D., in Chapter VII of Man-Made Textile Encyclopedia, F. Press, Editor, New York, abt. 1961 (no year given), p. 291

3) see e.g. McLean, W.G., Nelson, E.W., Engineering Mechanics, 2nd. edition, Statics and Dynamics; Schaum Publishing Co., New York, 1962, p. 57.

4) Morton, W.E., Hearle, J.W.S., Physical Properties of Textile Fibres, Butterworth & Co., The Textile Institute, Manchester & London, 1962, 1965, p. 396

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Section 2

MECHANICAL PROPERTIES OF ROPES

2.1 INTRODUCTION

Fiber ropes change their dimensions and load-elongation properties in use. Therefore, new and used ropes will be described seperately. Available test data from rope manufacturers usually deal with new ropes only, load-elongation curves mainly show the reaction of new ropes under standard test conditions and standard test atmosphere. Little is known about the behaviour of fiber ropes in use, but it is known that with different loading conditions and environments, the reaction of fiber ropes to loads and strains can change considerably. The need for a thorough investigation of rope reaction under typical use should be emphasized. These uses have to be simulated in laboratory tests under carefully defined and controlled conditions. With this procedure the various factors which influence the rope behaviour, like temperature, humidity, load and stretch conditions and energy influences can be determined. Only with this procedure, can reactions of ropes under complex loading situations be predicted, since the influencing factors of rope reactions to detailed situations are controlled. Section 2.2 summarizes the standard information on new rope and its behaviour, while in Section 2.3 rope reactions to different influences in use will be discussed.

2.2 NEW ROPES

2.2.1 Weight, Strength, Breaking Length

2.2.1.1 Weight Properties of Typical Fiber Ropes, Wire Ropes and Chains

The weight of the mooring follows a square power law with regard to the nominal mooring diameter.

Measurements are usually given in weight per unit length such as lbs-wt/ft., or gram-wt/meter. The weight per unit length (in air) can be written as:

$$W_a = C_a d^2 \quad .... \quad (1\text{-}1)^1$$

where W_a is the weight per unit length in air in lbs-wt/ft., or g-wt/meter, d the nominal diameter of the rope or chain steel in inch or mm, and C_a = weight constant for a given rope or chain type and material in air. C_a will be measured in $\frac{\text{lbs-wt}}{\text{in}^2 \times \text{ft}}$ or $\frac{\text{gram-wt}}{\text{mm}^2 \times \text{m}}$. Values of C_a are listed in Table 2-1. Values for rope weight constants in fresh and ocean water are also listed in this table. C_a must be multiplied by $(1\text{-}SG_w/SG_r)$, to obtain rope and chain weight constants C_{wf} and C_{ws} where SG_w is the specific gravity of the water and SG_r the specific gravity of the rope fibers. C_{wf} is the weight constant for fresh water, and C_{ws} for salt water. Table 2-1 shows, that the weight of the synthetic fiber ropes in water is greatly reduced or becomes negative in case of the floating polypropylene. Wire ropes and chains show only a small weight decrease.

2.2.1.2 Breaking Strength of Ropes

Assuming equal breaking stress for all rope sizes, the breaking strength of ropes of the same material and construction will increase

Table 2-1 : Weight constants for computation of weights in lbs per foot of various ropes and chains in air, fresh and salt water

Material	specific gravity of material	weight constants of standard ropes and chains			weight in fresh water as % of dry weight	weight in the ocean as % of dry weight.
		C_a in air*	C_{wf} in fresh water	C_{ws} in salt water		
	[g-wt/cm^3]	[lb-wt/(ft in^2)]	[like C_a]	[like C_a]	[%]	[%]
Nylon	1.14	0.25 - 0.29	.031 - .036	.024 - .028	12.3	9.7
Polyester	1.38	0.30 - 0.35	.082 - .096	.076 - .089	27.5	25.4
Polypro-pylene	0.92	0.20 - 0.24	-.017- -.020 buoyant	-.024 - -.028 buoyant	- 8.7 buoyant	- 12.0 buoyant
Fiberglass (E-glass)	2.5**	abt 0.50**	abt. 0.30**	abt. 0.29	60	59
Wire rope	7.85	1.4 - 1.8	1.2 - 1.6+	1.2 - 1.6+	87.3+	86.9+
Chain	7.85	9.4 - 10.0++	8.2 - 8.7	8.2 - 8.7	87.3	86.9

* tolerances in weight due to different standard constructions and manufacturers' variability.
** construction of glass fiber rope is not yet standarized. Specific gravity of the glass fiber can be lower than indicated due to finish or resin embedment of the fiber.
\+ The values for steel wire rope in water can be up to 25 % lower than indicated due to fiber centers in different wire rope constructions
\+\+ The weight constant is computed for the chain steel diameter itself.

Conversion: If weight constants are given in lb-wt/(ft$\cdot$in^2), metric weight constants in g-wt/(mm$^2\cdot$m) are obtained by multiplying the lbs-wt/(ft in^2) value by 2.3

with the square of the rope diameters. The breaking strength BS of a rope can be expressed as:

$$BS = C_b \times d_r^2 \quad .... \quad (2\text{-}2)$$

where C_b is the strength constant in lbs/in^2 and d_r the rope diameter. Values for C_b are listed in Table 2-2 for various types of ropes and chains.

Actually the breaking strength of a rope does not exactly follow a square power relationship. Small ropes show a higher strength efficiency than large ropes. This was first pointed out by Moseley for manila ropes.[2)] The number of fibers in a rope increases with the square of the diameter. They also exhibit increasingly greater inclinations with respect to the rope axis, and thus suffer a drop in strength efficiency. In chains the dropping strength efficiency with growing diameters is found too and is probably due to less uniform strength carrying capacity of the larger cross sections. Wire ropes also show this tendency. Equation (2-2) may therefore be modified to:

$$BS = C_b \times d^p \quad ... \text{ with } 2 > p > 1.7 \quad .... \quad (2\text{-}3)^7$$

Values of p can be obtained by drawing strength versus rope diameter data on double logarithmic paper. They plot as straight lines having different inclinations and distances from the two axes d and BS. The tangent of the angle of inclination is the exponent p. Values for p are listed in Table 2-2.

As a first assumption in determining the breaking strength of a mooring, the square power relation of Equation (2-2) is sufficient. For more precise calculations Equation (2-3) should be used. The

Table 2-2 : Breaking strength of new mooring cables, equations (2-2) and (2-3)

type of mooring rope or chain: material	construction	strength constant C_b^* for dry strength [$lb\text{-}wt/in^2$]	exponent p
Nylon, multifilament	three strand twisted eight strand plaited	2.5×10^4	1.90
	double braided	2.8×10^4	1.91
	NOLARO	$3.8 - 5.7 \times 10^4$	does not apply
Polyester multifilament	three strand twisted eight strand plaited	$1.85 - 2.1 \times 10^4$	1.85
	NOLARO	$3.6 - 4.0 \times 10^4$	does not apply
Polypropylene multifilament monofilament fiber film	three strand twisted eight strand plaited	1.4×10^4	1.88
Glass fiber	six strand with core	9×10^4 ***	1.7 **
Rocket case steel	1 x 19 wire rope	19×10^4	1.9 **
high grade plow steel	6 x 7 & 6 x 19 wire core galv. plow steel	9×10^4	1.9
galv. wire	6 x 24 with 7 fiber cores	6.5×10^4	1.85
Chain steel	di-lock, stud-link	12.9×10^4	1.9
wrought iron	stud-link	6.05×10^4	1.8
cast steel	stud-link	8.45×10^4	1.9

* computed for rope nominal diameters, not cross-sectional area.

** estimated

*** small sizes only

values of C_b are based, as far as possible, on recent standards or manufacturers' strength data. Individual strength test results are not as uniform. Changes in the construction of a distinct rope can change the strength to a considerable degree. Strength changes up to 30%, due to construction changes, have been reported for twisted ropes of various materials. [4) 5)] In rope standards a minimum breaking strength is specified which can be obtained by manufacture within the dimensional allowances and the properties of the available rope fibers. Some of the strength data are still under discussion. It takes some time until the figures for breaking loads of the newer, synthetic fiber ropes are reliably established. A list of rope standards is given in Section 2.2.3. These laws in general do not apply to Nolaro or Parafil ropes, which are manufactured only up to 1" diameter. At smaller rope diameters, the percent of non load carrying jacket to the strength carrying center fiber bundle is considerably higher. The strength to diameter^2 ratio grows within this diameter range for this type of rope.

Table 2-2 shows a wide variety of strength constants for the different materials. In combination moorings, equal breaking strength of various mooring members is not always the correct criterion for size. The working load limits of fiber and wire ropes are defined as percentage of the breaking strength, while in chains the limit is set as percentage of the proofload. Dynamic conditions, which can be dominant in buoy and ship moorings may dictate mooring combinations based on equal energy absorption, not breaking loads. This concept is discussed in some detail later. Also, the strength to weight ratio of moorings is very important, particular in buoy mooring systems. The ratio of breaking strength to weight per unit length will be discussed in the next section. This ratio in combination with the specific gravity of the mooring material in air and in water will help to get a broader view of the problem. Further attention should also be given to the elongation of various ropes and chains. This is directly related to the energy the rope can absorb.

2.2.1.3 <u>Breaking Length of Moorings</u>

The breaking length is "the length of a specimen, whose weight is equal to the breaking load.[6] This is a term frequently used to describe strength properties of textile structures. The breaking length is obtained by dividing the breaking strength, in lbs-wt (or kilogram-wt), by the weight per unit length in lbs-wt/ft (or gram-wt/meter). The result is the breaking length in ft. (or kilometers), the length of suspended rope or chain which will break under its own weight.* In buoy moorings this term becomes conspicuous. Often, a considerable mooring length is suspended from the buoy. Excessive weight loads may be experienced in wire rope and chain moorings, thus, limiting their use in deep waters. Breaking lengths for ropes of 1" diameter can also be computed by taking the strength constants C_b out of Table 2-2 and dividing them by the weight constants C_a, C_{wf}, or C_{ws} to get the breaking length in air, fresh and salt water. This is done in Table 2-3. A wide variety of values is shown.

*In textile publications the breaking length is often given as gr-wt/denier. It is 9 gram-wt/denier = 1 kilometer. The kilometer is also expressed as gr-wt/tex.

type of mooring		breaking length for 1" diameter ropes and chains					
		in air		in fresh water		in salt water SG=1.03	
material	construction	10^3 ft	kilometer	10^3 ft	kilometer	10^3 ft	kilometer
FIBER ROPES** nylon multifilament	three strand twisted eight strand plaited	90 - 100	27 - 30	590 - 690	180 - 210	760 - 890	230 - 270
	double braided	110	33	770	230	990	300
	NOLARO***	195	59	2,000	600	4,000 - ∞	1,200 - ∞
polyester multifilament	three strand twisted eight strand plaited	53 - 70	16 - 21	190 - 250	58 - 76	210 - 280	64 - 85
	NOLARO***	120	37	600	180	900	270
polypropylene multi- + mono filament+film	three strand twisted eight strand plaited	58 - 70	18 - 21	buoyant	buoyant	buoyant	buoyant
WIRE ROPES galv. wire	6 x 24 + 7fiber core	46	14	54	16	54	16
plow steel hg	6x7 + 6x19 wire core	56	17	64	19	65	20
rocket case s	1 x 19	105	32	118	36	119	36
CHAIN stud-link	Grade 2 ABS	8.8	2.7	10.1	3.1	10.1	3.1
	Grade 3 ABS	12.2	3.7	14.0	4.3	14.0	4.3
	Swedish Oil Rig Chain	12.9	3.9	14.8	4.5	14.9	4.5
GLASS-FIBER ROPE (E-glass)	6-strand twisted with core	180	55	300	91	310	94

Table (2-3) Breaking length of various ropes and chains of 1" diameter in air, fresh and salt water*

*) larger diameters show lower values due to decreasing strength efficiency

**) wet strength of 85 % of dry nylon rope strength considered to compute wet breaking lengths

***) these values for NOLARO ropes with polyethylene coating, with PVC coating lower values

Generally, all fiber ropes used in buoy moorings show such long breaking lengths that their weight can be neglected in the design of a mooring.

Wire rope has a fairly large weight in water. Each 540 to 1180 feet of rope results in a weight load of approximately 1% of the rope's breaking load. Chain weight is a severe handicap in designing deep ocean moorings. Only 100 to 150 ft. suspended chain generates a weight equal to 1% of the chains breaking load. For oil rigs in the ocean, a maximum water depth of 600 to 800 ft. has been reported for chain moorings.[7] The weight limitations of the different moorings types are easily seen with the help of the breaking length computation.

2.2.2 Elastic Properties of Moorings

2.2.2.1 Elongation Properties of New Ropes

Thus far strength and weight properties of moorings have been discussed. Equally as important is the stretch which different moorings exhibit under applied loads. A mooring between two ships could be made of:

a) a chain

b) a wire rope

c) a fiber rope

d) a rubber cord

Assuming equal strengths we can draw the elongation reaction of these moorings (Figure 2-1).

Obviously each type of mooring reacts differently to the applied loads. Fiber rope standards allow for a maximum elongation of the

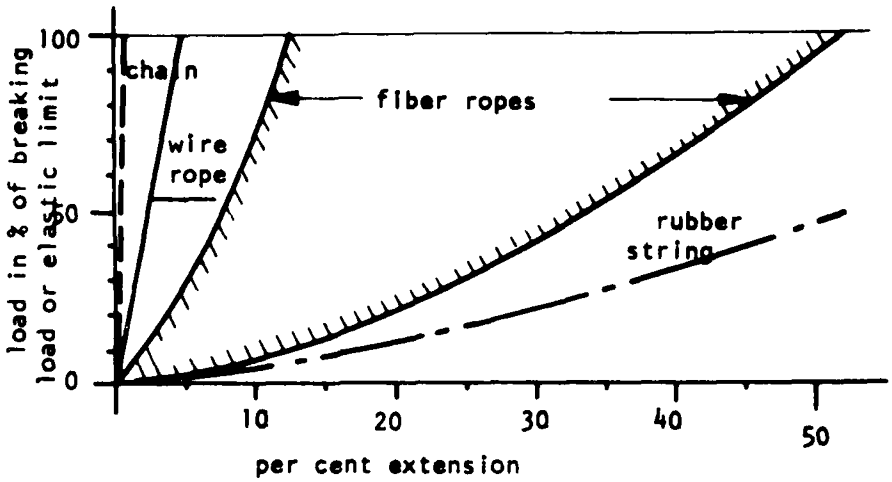

Figure 2-1

Load extension reactions for various new moorings (*for chain and wire rope the reaction is based on the elastic load limit, for all other on the breaking strength.)

new rope tested under standard conditions. The zero load lengths in a fiber rope is unreliable, since fiber ropes without tension can be squished to many different "zerö" lengths. It is common practice now to measure the "zero" length under a slight pretension. The pretension is given as $P = 200D^2$ in [lbs], where D is the diameter of the rope in inches. For most ropes P comes out to be about 1% of the rope strength. Usual breaking elongations, under standard test conditions, for chains are less than 1%, for wire rope 2.5 to 5%, for Nolaro ropes 10-15%, for braided synthetic fiber ropes 15-35%, for plaited and twisted synthetic fiber ropes 30-60%. The fairly wide range is due to the different materials used and tolerance in the construction. Generally, nylon ropes will stretch 1.5 to 2 times as much as ropes from polyester or polypropylene of comparable constructions. Thin ropes will stretch less than thick ropes. Each mooring can be compared, in its reaction to applied loads, to springs with different stiffnesses. Under sudden load increases a straight chain will immediately transfer the load without any dampening effect, all other moorings transfer the loads more or less delayed. The rubber string can be stretched several 100% before noticeable load is built up. Stretch behaviour is a significant factor in the selection of moorings for different applications. Any delayed transfer of stresses, due to stretching, will absorb shock loads. Towing or mooring of ships or buoys in waves would be impossible without the dampening effect of the rope stretch (or the dampening effect of the change of catenary configuration of the moorings).

2.2.2.2 Energy Absorption of Moorings and Snapback

Potential energy is defined as load times the displacement along which this load is working. Moorings which stretch under load therefore absorb mechanical energy which is equal to the work done by the external loads on the mooring. Since $E_{pot} = \int L \, dx$, the absorbed energy can be expressed by the area under of mooring load elongation curve.

The actual length which the rope elongates is important, a rope that is twice as long will stretch twice the distance under the same load and thus will absorb twice the energy.

The energy absorbed by the mooring can thus be expressed by the area under the load elongation curve.

$$E_{pot} = C_e \times L \times l \times s \quad . \ . \ . \ . \qquad (2\text{-}4)$$

Where:

E absorbed energy in [ft x lbs-wt, kilogram-wt x meter]

C_e shape factor of the curve. For a straight line, (Hooke's) as in wire ropes, $C_e = 1/2$. For fiber ropes C_e is approximately 1/3.

L load of the mooring [lbs-wt, kilogram-wt]

l initial length of the mooring [ft, meters]

s strain under load = $\Delta l/l$

A large amount of energy is stored in long lengths of ropes and in highly stretching ropes. If by overstressing ropes break, the stored potential energy is converted into kinetic energy which causes the dangerous snapback. The broken rope parts accelerate to high speeds. The potential energy of a mooring at break is

$$E_{pot} = C_e \, BS \, l \, s_b \quad \text{.....................(2-5)}$$

where BS is the breaking strength and s_b the strain at break. This potential energy is converted to the kinetic energy of the broken rope.

$$E_{kin} = l \, W_r \, v^2 /(2 \, g) \quad \text{.................(2-6)}$$

W_r is the weight of the rope per unit length in lbs-wt/ft or gram-wt/meter; g = gravity and v is the snapback velocity of the rope in ft/sec or meter/sec. Setting $E_{pot} = E_{kin}$ we find the rope snapback speed as

$$v = (g \, C_e \, BS \, s_b \, 2/W_r)^{1/2} \text{...........(2-7)}$$

The snapback speed is independent of the rope length. By substituting BS/W_r by the breaking length BL of the rope, we can write:

$$v = (2 \, g \, C_e \, BL \, s_b)^{1/2} \quad \text{...........(2-8)}$$

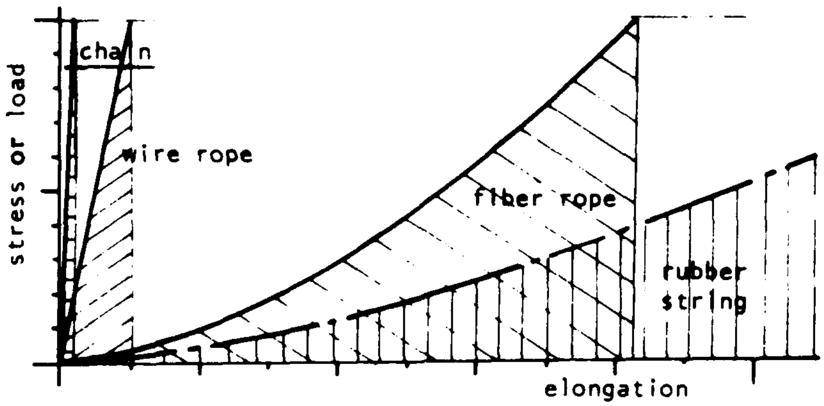

Figure 2-2

Energy absorption of moorings of equal length and strength.

The evaluation of Equation (2-8) shows, that the recoil speeds can approach the sound speed in air. Figure 2-3 shows this for different breaking lengths BL and breaking strains S_b.

After failure during snapback the rope starts to oscillate violently. The recoiling rope will be slowed considerably by the air drag. Air drag on a recoiling and oscillating rope has, to the writers knowledge, not been determined yet.

When long, horizontally used rope lengths fail the time of recoil may be large enough to allow the rope to fall an appreciable distance due to the influence of gravity. If in a towing operation the broken rope end will hit the water, the drag will substantially increase and reduce the recoil speed considerably. The recoil time t_r would be:

$$t_r = \text{failed rope length/recoil velocity} = l/v \ [\text{sec}]$$

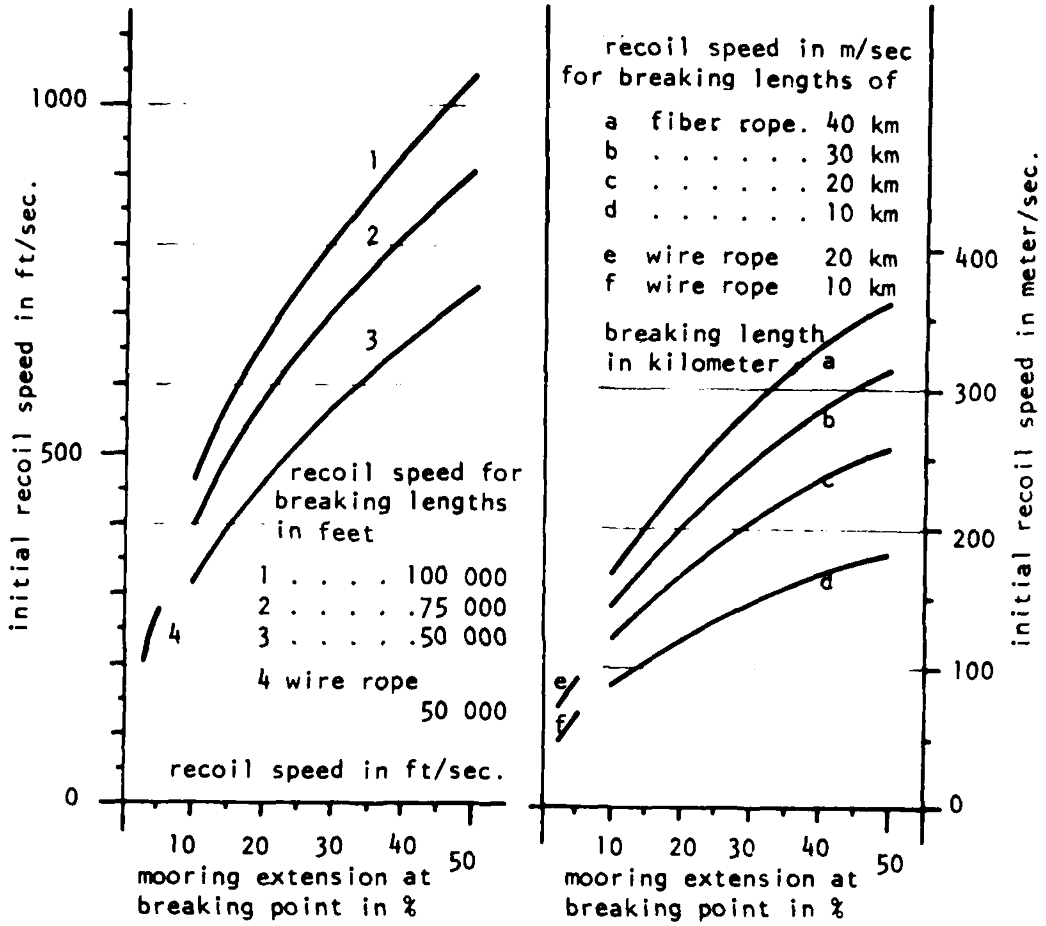

Figure (2-3) Recoil speed for fiber and wire ropes with different breaking lengths and breaking strains.

The drop of the broken rope without air drag will be g $t_r^2/2$ or * $16.1 * l^2/v^2$. Air drag should considerably increase the dropped distance so the rope will touch the water earlier. Additional weights at the rope end, shackles or thimbles, will increase the the rope mass which has to be accelerated at failure. This reduces the recoil speed and increases the dropping rate of the rope.

* with g in ft/sec^2, l in ft and v in ft/sec.

The danger of snapback should be emphasized. The damage which recoiling ropes can do to protective screens and barriers was described by Wesler and Parker[8)], who also studied the snapback in field tests with high speed photography. Numerous often severe or fatal injuries of men have been caused by parting ropes. Protective barriers should be designed to take serious impacts.

The magnitude of the energy released by a breaking rope can be demonstrated by comparing the energy of a moving car and a rope having the length of a car. A car weighing 2,000 lbs. and traveling at 60 mph = 88 ft/sec will have the kinetic energy

$$E_{kin} = m\ v^2/2 = 24 \times 10^4\ [\text{ft-lbs}]\ \ldots\ldots(2\text{-}9)$$

a rope, having the length of this car will have an energy at break of

$$E_{pot} = C_e\ BS\ l\ S_b\ [\text{ft-lbs}]\ \ldots\ldots\ldots\ldots(2\text{-}5)$$

We determine the breaking strength of a rope, which at assumed breaking strains S_b, absorbs the car's energy from Equation (2-5) and Equation (2-9). It is

$$BS = \frac{m\ v^2}{2\ C_e\ l\ S_b} \qquad [\text{lbs}]\ \ldots\ldots\ldots.(2\text{-}10)$$

which with the above values, $C_e = 1/3$ and $l = 20$ ft (car = rope length) will give $BS = 3.6 \times 10^4/S_b$ [lbs]. For an assumed low breaking strain of $S_b = 0.25$ we obtain BS = 144,000 lbs. For a high breaking strain of $S_b = 0.5$ the rope has to hold only 72,000 lbs. For a nylon rope, the latter case would require a rope of about 1 5/8 inch in diameter to stop the car in 10 ft. The lower stretching rope with 25% elongation at break would be 2 3/8" in diameter and should stop the car in 5 ft. In the case of wire rope with a stretch at break of around 2.5% and $C_e = 1/2$, the rope has to hold 960,000 lbs. This would require a 3 1/2" diameter high grade plow steel IWRC rope. These examples illustrate the tremendous impacts which recoiling ropes cause. The importance of proper mooring design, to avoid failures in towing and other marine uses, is more than necessary.

Two Moorings Combined a) For Equal Strength, b) For Equal Energy Absorption

a) Equal Strength

Under static load conditions two moorings should be selected with equal breaking strength. The diameter of the second rope is obtained with Equation (2-2) as:

$$d_2 = d_1 \quad (C_{b_1} / C_{b_2})^{1/2} \quad \ldots\ldots\ldots\ldots (2\text{-}11)$$

b) Equal Energy Absorption

Under dynamic stresses component moorings may be designed so that each component absorbs equal mechanical energy. This is done to avoid overworking of one of the ropes. We can decide to use ropes of the same strength as in a) and adapt the lengths of the components to absorb equal energy or to combine equal long ropes with strength data matched to have equal deformation energies. The practical situation is usually a compromise.

The line (rope) dimensions for each of the three assumptions are obtained as following:

b-1) Moorings 1 and 2 have equal breaking strengths. How long must rope 2 be to have energy absorption equal to rope 1? Equation (2-5) is rewritten as:

$$l_2 = l_1 \frac{C_{e_1} S_{b_1}}{C_{e_2} S_{b_2}} \qquad \text{..........} \quad (2\text{-}11)$$

where $C_{e_{1,2}}$ are the shape factors of the load elongation curves and $C_{b_{1,2}}$ the strains at break.

b-2) *Both moorings have the same length. What diameter of mooring 2 is needed to absorb mechanical energy equal to rope 1?*

Equation (2-5) gives $BS_2 = BS_1 \frac{C_{e_1} S_{b_1}}{C_{e_2} S_{b_2}}$ and with Equation (2-2)

$$d_2 = d_1 \left(\frac{C_{e_1} S_{b_1} C_{b_1}}{C_{e_2} S_{b_2} C_{b_2}} \right)^{1/2}$$

b-3) Given the length of both mooring components l_1 and l_2 and the breaking strength of mooring 1. How strong does mooring 2 have to be to absorb equal energy?

Equation (2-5) will give

$$BS_2 = BS_1 \frac{C_{e_1} S_{b_1} l_1}{C_{e_2} S_{b_2} l_2} \qquad \text{and with Equation (2-2)}$$

it is:

$$d_2 = d_1 \left(\frac{C_{e_1} S_{b_1} C_{b_1} l_1}{C_{e_2} S_{b_2} C_{b_2} l_2} \right)^{1/2} \qquad \text{..........} \quad (2\text{-}14)$$

Comparative data for a), b-1), and b-2) are listed in Table (2-4) for a combination mooring of twisted or plaited nylon rope (1) and a 6 x 7 high plow steel wire rope (2) with the following data:

Nylon rope: $C_{e_1} = 1/3$, $S_{b_1} = .25$, $C_{b_1} = 2.5 \times 10^4$ lbs-wt/in^2

Wire rope: $C_{e_2} = 1/2$, $S_{b_2} = .025$, $C_{b_2} = 9 \times 10^4$ lbs-wt/in^2

Situation	a) equal strength	b) equal energy absorption		
		b-1) equal strong ropes	b-2) equal long ropes	
wanted value	diameter 2	length 2	strength 2	diameter 2
known nylon rope dimension	d_1	l_1	BS_1	d_1
wire rope, asked dimension	$d_2 = 0.53\ d_1$	$l_2 = 6.67\ l_1$	$BS_2 = 6.67\ BS_1$	$d_2 = 1.36\ d_1$

Table (2-4) Comparative dimensions of a combination nylon-wire rope mooring for a) equal strength and b) equal ability to absorb mechanical energy.

It is seen, that a) and b) lead to completely different dimensions, care has to be taken in the choice of design assumptions.

2.2.3. Specifications

The U.S. Government specifications relating to fiber ropes may be classified in two groups as rope standards and test standards. The rope specifications are documenting for each fiber rope type strength, weight and other data for the various rope diameters. The second group is giving the test methods to be used to control the required rope data, given in the rope standards.

Additional regulations and recommendations may be necessary in specialized end uses of a rope, since the rope specifications are fairly general and may not be strict enough for specific applications. These specifications are usually prepared by the Technical Committee of the Cordage Institute in New York City in cooperation with the federal and military standard institutions. In other countries similar organizations are responsible for the set up of national standards on ropes and test procedures. In Western Europe currently all rope standards are combined in international ISO (International Standard Organization) regulations, superseding the previous national standards in various European countries. It would be desirable to agree on the same rope standards worldwide. The U.S. standards are listed in Table (2-5).

TABLE (2-5)*

U.S. - Specifications Concerning Fiber Ropes

Group I. U. S. Government Specifications for Synthetic Fiber Ropes

Specification No.	Date	Product
MIL - R - 17343d	6-2-67	Rope, Nylon
MIL - R - 4398	9-16-52	Rope, Nylon, (Glider Tow)
MIL - R - 1688C	2-16-66	Rope, Climbing, Nylon
MIL - R - 24337	6-17-68	Rope, Nylon, Plaited
MIL - R - 43161	9-20-63	Rope, Nylon (Spun)
MIL - R - 24049	3-28-66	Rope, Polypropylene
MIL - R - 30500 +Amendm.	12-5-62	Rope, Polyester
MIL - R - 24335	6-20-68	Rope, Polyester (film)
TL - 411b	5-26-64	Shot (for) Lines Throwing Guns
MIL - R - 24050A	1-20-67	Rope, Nylon, Double Braid
(TR-605b + Amend.	12-13-63	Rope, Manila and Sisal)

*The assistance of Mr. F. J. Haas of Columbian Rope Company in compiling this list is thankfully appreciated.

TABLE (2-5) Group II: Federal Test Method Standard #191, Textile Test Methods Relating to Cordage Tests

Methods No. 1000 - 1999, Identification - Qualitative Analysis

1240, 41, 50, 51 Identification of various natural fibers

1530; 33, 34, 1600 Identification of various synthetic fibers

Methods No. 2000 - 2999 Quantitative Analysis

Methods hereunder determine the content of fibers, chemicals, moisture, acidity a.s.o. in textiles or fibers themselves.

2050, 51, 60; 2530; 2600, 01

Methods 4000 - 4999 Yarn, Thread, Rope and other Cordage

deal with determination of weight, twist, strength and elongation, abrasion resistance, water absorption, colorfastness; mildew, weathering and leaching resistance of yarns, threads, ropes and other cordage like webbings. Methods used are: 4010, 50, 52, 54; 4100, 02, 04, 06, 08; 4308; 4500, 02, 04; 4800, 04, 30, 32

Methods 5000 - 5999 Cloth

Some of the test methods for cloths may apply to cordage. They are 5010, 41; 5630, 60, 62, 71, 72; 5750, 60, 62

Methods 6000 - 6020

deal with some particular rope tests, which sometimes seem to overlap with the 4000 - 4999 methods. They are mostly additional test methods for synthetic fiber ropes. It is not always obvious at this moment, which method in case of overlapping will be finally agreed upon. The methods are 6000, 01, 02, 03, 04, 10, 11, 15, 16 and 20.

Some of the standards currently are undergoing changes, the tests should be done under the newest standard regulations and at Government authorized laboratories only.

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2.3 ROPES IN USE

2.3.1 Introduction to the Tensile Properties of Ropes

The response of fiber ropes to applied forces, energies, and deformations is their most important technical property. The rope, as a textile structure, reacts to an applied stress or strain with a combination of structural and material deformations. Its reaction thus depends on the structure and fiber material used. A wide variety of mechanical properties can be chosen for a rope, by selection of the rope structure and the fiber material.

The rope structure is a fairly complex arrangement of rope fibers in a multi-helical structure.* The rope fibers are arranged in helical structures whose axes form again helixes in a larger structure. Often the larger structure is again arranged in a larger helical structure. These helical structures stretch fairly easily by becoming longer and thinner, as a spring does under tension. They will snap back if the tension is removed. At the same time the structural deformation causes stresses in the fibers to which they respond by stretch. The fiber stretch reaction depends entirely on the load elongation properties of the fibers used. In a rope composed of material having very low elongation, nearly all the stretch of the rope will be structural. In a rope constructed the same way of highly stretchable fibers, the material stretch will be an important percentage of the rope elongation. It can become up to 50% of the total (See Figure 2-4). Both construction and

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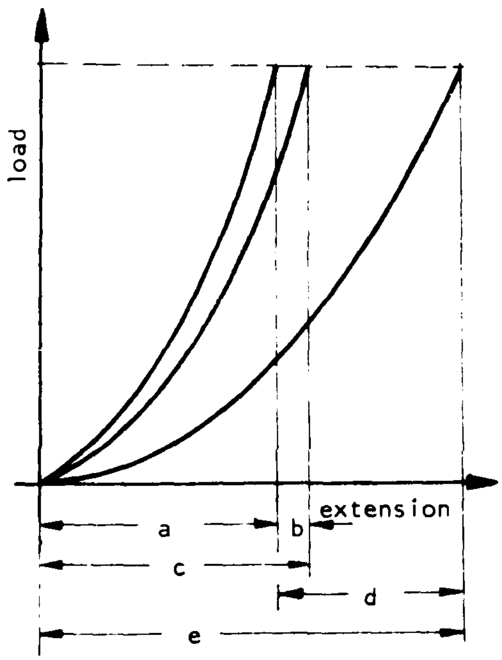
*We deal, if not extra pointed out, with all rope constructions except Nolaro ropes.

material deformation have to be considered in order to understand the rope's reaction to applied tensions. Both structure and material deformation follow their own particular laws and often interfere with each other.



a structural extension
b material extension, fiber 1
c total stretch, rope made of fiber 1
d material stretch, fiber 2
e total stretch, rope made from fiber 2

Figure (2-4) Structural and material stretch in a rope.

Structures usually tighten in use after several loadings, but they may be opened by action of the material used, for example by swelling or shrinking processes after immersion in water or exposure to heat. The fiber material itself is viscoelastic and thus changes dimensions and load elongation behaviour due to loading processes and environmental influences. At the same time these changes may interact with the arrangement of the fibers in the rope structure.

Each of the different fiber types show their own particular reaction towards applied tensions, strains, and different environmental conditions. Higher stretching fibers will much more interact on the rope structure - which correspondingly has to stretch more than low stretching fibers. Any fiber could be taken to make a rope, but since ropes are mainly strength carrying, energy absorbing "connection links", high-tenacity fibers with various degrees of low stretch are used. The high tenacity synthetic fibers used for cordage manufacturing are nylon, polyester, polypropylene, polyethylene and for some applications glass fibers. These fibers are described in Section 2.3.2.5.

Knowing both the material load elongation characteristics and modification of these characteristics possible with various rope constructions, the proper combination of structure and material can be chosen to build a rope which best fits a known end use. Similar rope behaviour can be obtained by arranging highly stretchable fibers in a low stretching structure or low stretching fibers in a high stretching rope structure.

Since the load-elongation behaviour of both structure and material undergoes considerable change in use, the final goal is to predict with sufficient accuracy the long term behaviour of the rope under known loading and environmental conditions. The various factors which influence the load elongation behaviour of fiber ropes in use will be discussed in the next section. We will start with a look at the rope fibers themselves. The factors which change the characteristics of constructions, such as different twists of the rope components, will be considered in some detail later.

2.3.2 Synthetic Rope Fibers in Use, An Introduction

2.3.2.1 The Viscoelastic Nature of Fibers

Synthetic and natural fibers are viscoelastic. They react to loads or strains with spring-elastic recoverable deformation and viscous non recoverable stretch. Part of the fiber reaction follows the elastic performance of a spring. Part of it follows the behaviour of a viscous fluid. The term elastic describes "that property of a body by virtue of which it tends to recover its original size and shape after deformation".[9] The opposite performance, retaining a deformed size and shape after stretching, is called plasticity.

All fibers consist of large macromolecules, which by drawing processes become oriented parallel to the fiber axis. The viscoelastic behaviour of macromolecules under stress and strain is very complex. It depends on the type of polymer, the degree of polymerisation, the attracting forces between molecules and the degree of orientation. It is impossible, within the limits of this report, to go into the details of the nature of the macromolecules in fibers. Their deformation behaviour has been described in depth by numerous authors.[10] The response of a fiber to applied stress and strain is time dependent, since all position changes within the macromolecular fiber substance need time to take place. Temperature, humidity and previous load history also influence the load elongation behaviour of the fibers.

2.3.2.2 Typical Viscoelastic Fiber Reactions

Viscoelastic reactions of fibers modified in rope reactions under constant loads, constant extensions, cycling loads and extensions will be described in Section (2.3.3). The different fiber reactions themselves are listed here.

1) Under constant load, a fiber will show an immediate extension and a delayed, time depending extension called creep. After removal of the load, there will be an immediate length recovery, some delayed recovery and some permanent deformation. See Figure (2-12).

2) Under constant deformation, the initial load response of the strained fiber will gradually decrease with time (load relaxation). After removing the deformation, the fiber recovers from part of the elongation instantaneously and from some after a delay. It will also show permanent deformation. See Figure (2-14).

3) Under cycling loads, the fiber will show hysteresis loops between the loading and unloading stress-strain curves. It will quickly proceed to a continuously repeated "master-hysteresis", loop. See Figure (2-15). The "master-hysteresis" loop has a considerably higher Young's modulus than at the first cycles. The recovery of the fiber between cycles depends on the cycle frequency.

4) Under cycling strains, the load response of the fiber will taper off similar to load relaxation under constant deformation, thereby forming hysteresis loops in the load-elongation curves. The loops are highly dependant on the cycle frequency.

Under cycling loads or strains, the hysteresis loops will generate heat. In some instances this heat may be large enough to melt the fiber. In each of these loading conditions the viscoelastic behaviour of the fibers will allow for more stretch if more time under load is available. It will also show more stretch recovery, if more time after load removal can be used. The position changes in macromolecules need time to take place. Immediate deformation response to an applied load is mainly elastic and recoverable, while delayed response is to a considerable degree plastic and unrecoverable. If loads are applied quickly and shortly only elastic deformation occurs. If load last longer, viscous deformation has time to develop and thus permanent stretch takes place. At prolonged cycle tests under high loads the elastic elongation and recovery tends to decrease and the permanent elongation continues to increase even further. Similar considerations apply to the time dependant influence of strain on the load response.

5) In tensile tests, the deformation rate will influence the test result considerably. At slow test speeds the fiber will show more deformation under comparable loads than in tests with faster deformation speeds. The viscous deformation has time to react. The fiber also will break at lower loads than under faster deformation speeds, as shown in Figure (2-5). A distince time until break or a constant speed of deformation has to be met,[11] * in order to be able to compare textile data. The influence of the test speed in nylon fibers on the rate of extension is shown in Figure (2-6).

6) Often fibers are subjected to other than tensile loads or strains. In particular bending, torsion and shear is often

stressing fibers[12], frequently in combination with tensile loads. For rope applications this can become important, seen by the low knot strengths which ropes and fibers show. The fibers will also show viscoelastic reactions to these non-tensile stresses, e.g. as bending recovery and permanent bending deformation. The shear resistance of fibers is usually very low, caused by the high degree of anisotropy of the oriented fiber structure.

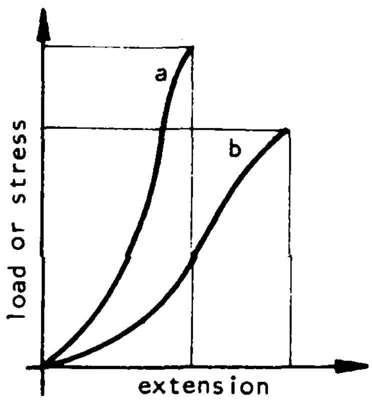


Figure (2-5)

Schematic stress strain curves of a synthetic fiber at various test speeds.
a) high test speed
b) low test speed

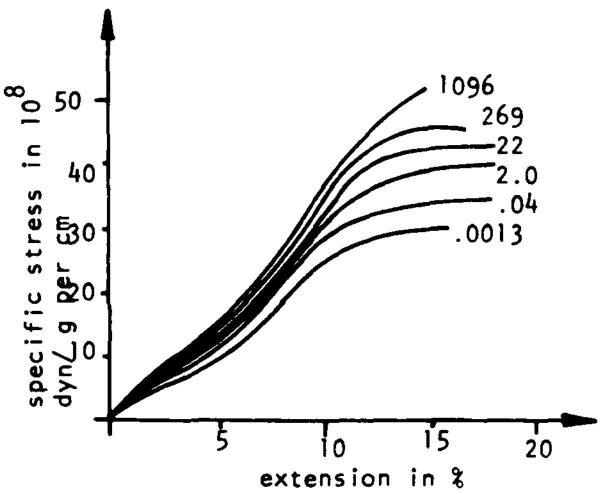


Figure (2-6)[11]

Stress strain curves of nylon at various test speeds, the figures refer to the rates of extension in per cent of the sample length per second

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*There are also instruments using a constant rate of loading to test the strength of fibers, which can show considerable difference in the test results. The most widely used and recommended method is to strain the fibers with a constant speed of deformation and to measure the resulting load response, see[11].

2.3.2.3 Mechanical Models to Describe Viscoelasticity

A convenient, though imperfect way to describe the deformation behaviour of viscoelastic fibers is to construct a model composed of elastic springs and viscous dampers. These simple models combine elastic springs following Hooke's law, stress = E x $\hat{s}$, and viscous dashpots following Newton's law, stress = η ds/dt, where E is the Young's modulus and η the coefficient of viscosity. The components can be arranged in series shown in Figure (2-7). They show permanent deformation which equals secondary creep, after instantaneous extension under sustained load. Spring and dashpot may also be arranged parallel as in Figure (2-8).

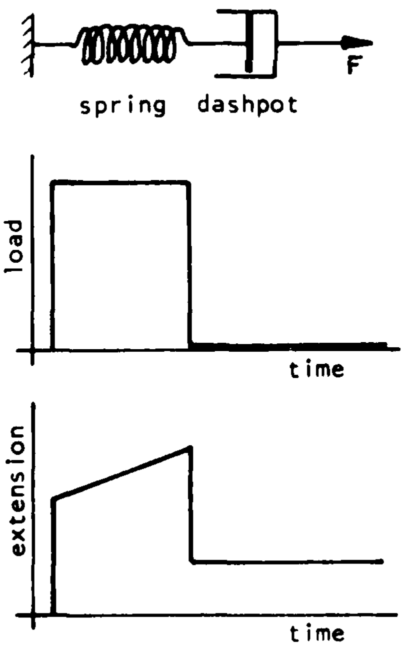

Figure (2-7)
Spring and dashpot in series; reaction under load and after load removal.

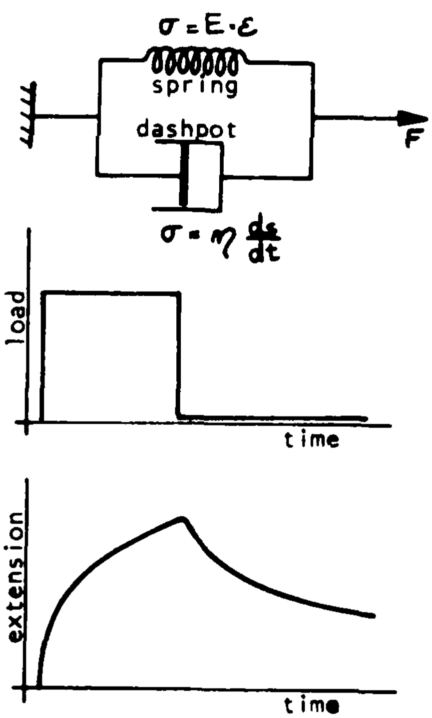

Figure (2-8)
Spring and dashpot parallel; reaction under load and after load removal.

Then they will show delayed deformation and recovery. But even a combination of numerous spring-dashpot models together will not describe the typical viscoelastic behaviour of macromolecules under strain. Therefore, Eyring, in his three element model, (Figure 2-9) uses a dashpot with a hyperbolic sine law for viscous deformation.[13] In the Poynting Thomson model, described by Juilfs,[14] the dashpot and springs, Figure (2-9), are non linear. Viscosity and elastic moduli are "modulus functions". "They exhibit a complex dependance on the test conditions."[14]

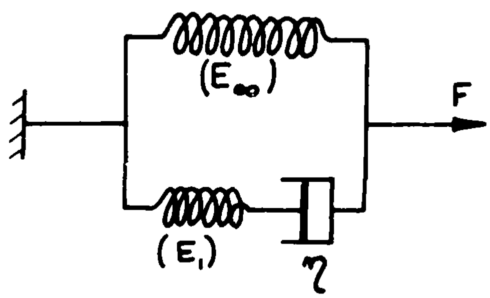

Figure (2-9)

Eyring's three element model, using Hooke's springs and a dashpot with a hyperbolic sine law for viscous deformation. Also: Poynting Thomson model, with both springs and dashpot non-linear.

2.3.2.4 <u>Modulus Functions For a Non-Linear Poynting-Thomson Model</u>

Modulus functions for the non-linear viscous and elastic elements have been developed by Juilfs and Zidan.[14] They studied a test situation combining a tensile loading up to a certain point and relaxation after reaching this load. The functions Young's moduli of the two springs and the function of the viscous modulus are given as curves for various deformation speeds depending on the elongation value. See Figure (2-10) for a nylon material, and

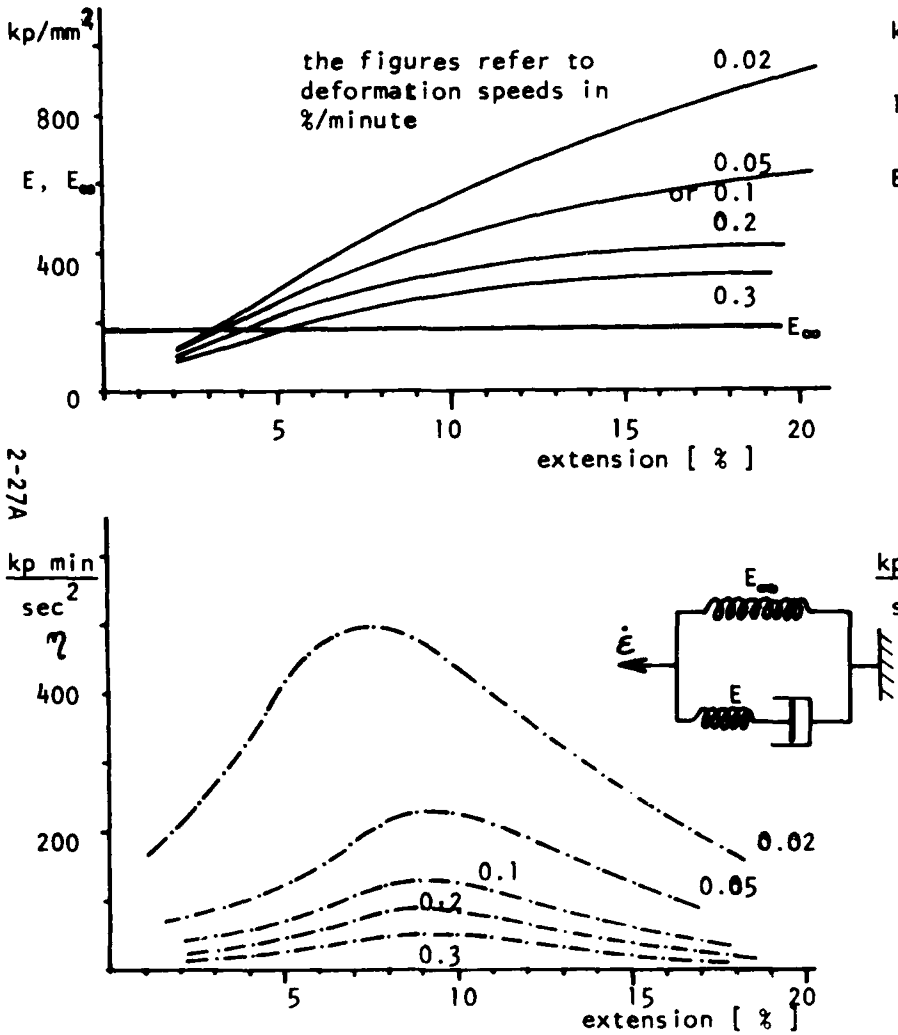

Figure (2-10) Dependency of the modulus functions for E, E and on the deformation speed for nylon.

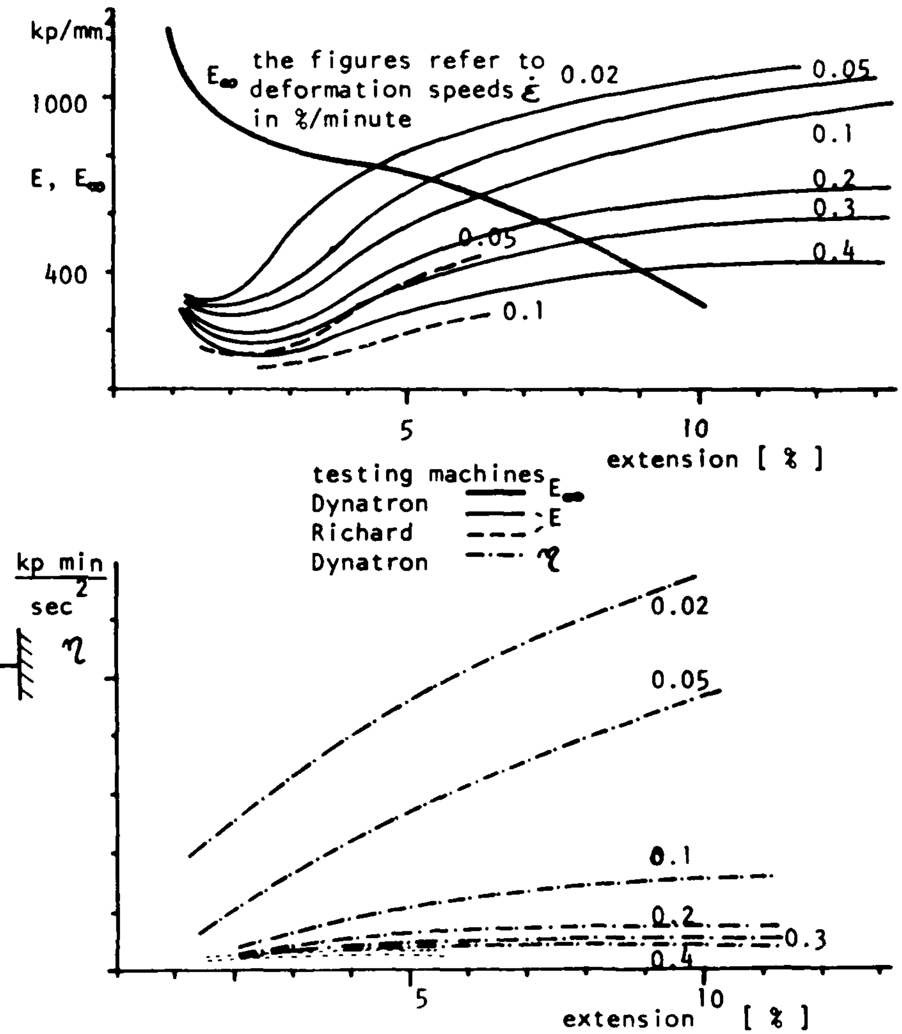

Figure (2-11) Dependency of the modulus functions for E, E and on the deformation speed for polyester.

Figure (2-11) for a Polyester fiber, showing the non-linearity and the pronounced changes obtained for the modular functions. These curves are presented to show the reaction of these fibers when only the deformation speed is changed. Or, as Julifs writes[14] "The complex deformation behaviour of highpolymer fiber substances can, in its reaction to stress, only be described by a careful analysis of suitable test results. Individual data like breaking strength, breaking elongation can give in this connection only indicative, roughly comparative information." (translated)

2.3.2.5 The Main Synthetic Cordage Fibers

Only high tenacity fibers with fairly low stretch behaviour are used to manufacture regular ropes. The fibers have to be highly elastic and have to show minimum viscous deformation behaviour. Fibers with small viscous influences, or a high modulus of viscosity, will have a high degree of instantaneous and delayed elastic recovery. Therefore, they will show fairly small hystersis loops under cycling loads or strains. This will reduce the tendency to heat up the fibers due to frictional energy loss. Since all high tenacity fibers are produced by giving them a fairly high degree of orientation, these fibers also show a pronounced mechanical anisotropy which results in knot strengths of these fibers in ropes of 45-60% of the breaking load. The main synthetic cordage fibers are nylon 6.6, nylon 6, polyester, polypropylene, for uncritical uses polyethylene, and for special applications sometimes glass fibers. Typical properties of these fibers are listed in Table (2-6).

General information has been published about these fibers in such a braod scale, that only some references are given for further interst in this matter.[15) 16) 17) 18) 19)]

It is difficult to conclude from these data the optimum fiber for a given rope use. The stress strain properties are widely modified due to the rope structure, and change considerably in use. Generally, it could be recommended to use nylon fibers whenever high strength, high stretch and stretch recovery and high shock absorption is required for the rope. Polyester should be used, where low stretch, high strength and a maximum prediction in the long term load elongation behaviour is required. Polypropylene should be used where the main goal is floatability of the rope and where strength and elongation behaviour is not critically. Glass fibers, after improvement of their properties, should be used only where dynamic loads are negligible and low stretch and high strength is required. Polyethylene should be used only in uncritical applications.

INFLUENCE OF WATER

Though none of the fibers mentioned above is deteriorated by water, nylon shows a significant strength loss of about 15% when wet and tends to shrink when immersed or exposed to heat. Water splits up hydrogen bonds, which are formed between some CONH groups of the nylon molecules. These hydrogen bonds are weaker than the inter-atom valency bonds but stronger than the attracting van der Waals forces between molecules. They contribute to the

Table (2-6) Typical mechanical properties of synthetic cordage fibers [15)-19)]

material	nylon 6.6	nylon 6	polyester	polypropylene	polyethylene	glass fiber
tenacity or breaking length in gram/denier and (kilometer)	7.5-9.0 (67.5-81.0)	7.5-9.0 (67.5-81.0)	6.4 - 8.0 (57.6-72.0)	5.0 - 7.5 (45 - 67.5)	3 - 6 (27 - 54)	5.3 - 8.9 (48 - 80)
tenacity wet in per cent of dry	85	85	100	100	100	100
breaking stress in lb-wt/sq.inch x 10^4	9 - 13	9 - 13	10.5 - 12.5	5 - 7	3 - 6	20 - 30
breaking extension dry in per cent	19 - 24	16 - 19	8 - 11	10 - 20	10 - 25	2.5 - 5.0
specific gravity in gram-wt/centimeter^3	1.14	1.14	1.38	0.92	0.95	2.5
elastic recovery	excellent, 100 % up to 4% extension.	excellent, better fatigue life than nylon 6	excellent from low previous extensions	fair	poor	excellent
melting point in degrees F	sticks at 445°, melts at abt.500°	melts at 414° to 428°	melts at 480 to 550°	melts at 325 to 335°	melts at 240°	sticks over 940°
dimensional change in water	shrinks up to 12 %	shrinks up to 14 %	does not shrink permanently	no change	no change	no change
sunlight resistance	fair	fair	good	if unstabilized poor		
moisture regain at 70° F, 65% rel.hum.	4.0 - 4.5	4.0	0.4	0	0	0
fiber knot strength per cent of tensile	80	80	70	75	80	15 - 30

strength of the nylon material in dry conditions, but since they are split by water due to their hydrophilic nature, do not respond to strains on the wet fiber. Because of this, the wet strength of nylon is only 85 - 90 per cent of the dry strength at 65% relative humidity. At the same time the wet nylon molecules have less resistance to stress, which results in more stretch under comparable loads at higher humidities. This is to some degree caused by previous shrinkage in this condition, which can be compared with folding and thus shortening of the structure. If the shrunk structure is put under tension, the "folded" regions have to be stretched out thus increasing the elongation of wet nylon fibers. The folding can be avoided by putting a tension higher than the shrinkage tension (as high as 10% of its breaking strength) on the fiber while exposing it to the shrinkage causing environment.

No other cordage fiber discussed here is affected this way by water. Care has to be taken when using nylon, to consider the changes in length, elongation, and strength between wet and dry usage. Despite these disadvantages nylon still is a superb fiber for cordage use.

Temperature stability: All synthetic fibers consist of thermoplastic materials, so there is a natural tendency of strength decrease and elongation increase at growing temperatures. Within the range of 32°F to 100°F there is a fairly small change in all fibers discussed here, except polytheylene, which, due to its low melting point shows considerable strength changes. The strength drop

Material	temperature [°C]	tenacity [g-wt/tex = km]	breaking extension [%]	work of rupture* [g-wt/tex]	initial modulus** [g-wt/tex]	yield*** stress [g-wt/tex]	yield**** strain [%]
nylon, 210 den.	- 57	79	11	4.2	1010	15	1.9
	21	65	13	4.0	450	7	1.5
	99	46	14	2.2	226	5	2.0
	177	26	29	4.7	108		
Dacron 70 den.	- 57	78	8	3.3	1370	27	1.1
	21	56	8	2.8	1070	17	1.7
	99	41	10	1.4	261	5	2.5
	177	26	19	2.3	45	4	5.8

* work of rupture = area under the load-elongation curve for unity length

** tangent of the stress strain curve at the origin

, * the yield point as defined by Coplan is the crossing point of the initial modulus tangent with the tangent on the curve having the least slope - *which will not lead to a realistic point at all* fiber load elongation curves. The stress at this point is the yield stress, the strain the yield strain.

TABLE (2-7) Effect of temperature on tensile properties [20]

and extension increase for nylon and Dacron polyester over a wider temperature range is shown in the above Table (2-7)[20]. The changes should be more pronounced for polypropylene - which at 177° C is molten already - and less pronounced for glass fibers. Temperature changes due to hysteresis deformations may alter the fiber reactions considerably.

Light stability: All synthetic cordage fibers suffer strength losses when exposed over a period of time to sunlight, in particular the ultra-violet and infra-red radiation of it. Polyethylene and polypropylene fibers deteriorate so rapidly, that they can be used only when they contain reliable ultra-violet light stabilizers.[21) 22)] Much testing has been done. The results depend on factors like fiber diameter, fiber material, stabilizers, dyes, geographical location of the test site (sunshine hours and sunshine intensity). The strength loss decreases with increasing fiber diameter, in ropes the loss is much less pronounced since only the surface fibers are effected by radiation. A Dacron polyester rope of 1/2" diameter lost after 1 1/2 years exposure 10 %, a Dacron yarn during the same period 85 % of its original strength.[23)] If possible, fibers and ropes should not be exposed unnecessarily to the sun. Cordage made from fibers with light stabilizers should be prefered for use in outdoor applications.

2.3.3. Rope Response to Standard Loading and Unloading Conditions

The typical performance of ropes under in-use conditions in laboratory tests will be discussed first. In the laboratory, the test speeds are usually slow and the rope samples are conditioned in a standard atmosphere. Later we will deal with the change in performance from standard reactions due to change in test conditions, test speeds and environmental conditions.

As do the fibers described in the previous section, the rope reacts to stresses and strains as a viscoelastic body. The deformations are largely modified by the arrangement of the fibers in the rope structure. Both plastic and elastic deformations can be measured under defined testing conditions. There are six basic loading and deformation conditions under which ropes can be used and under which deformations can be measured. These conditions are:

1) constant load

2) constant deformation

3) cycling load

4) cycling between different stretch conditions

5) stressing or straining in other than rope axis directions

6) shock loads

The test method used to predict rope behaviour has to be chosen according to the end use of the rope.

Method 1) may be applied in buoy moorings, where a taut connection between an anchor and a subsurface buoy is planned. The reaction under zero or known current conditions has to be investigated.

Method 2) may be chosen, where a taut mooring between anchor or subsurface buoy and surface buoy shall be used and the reaction under zero or known current conditions and neglectable wave and tidal influences have to be predicted.

Method 3) may be chosen where the rope is used to hoist distinct loads at known time intervals like in standard cargo handling operations.

Method 4) may be applied, where a ship or buoy moored to a fixed point will cycle with known excursions in a sea state.

Method 5) has to be used to study rope reaction e.g. on bollards, sheaves or in splices or other end terminations.

Method 6) should be applied where ropes are subjected to sudden load pickups like in mountaineering, at the upper end of a buoy mooring, or in some cargo handling and salvage uses. The shock load may also be transverse to the rope axis like in aircraft arrestor systems.

Each of these loading or deformation conditions of a rope can exist either for itself or combined. A typical combination would be (1) plus (4) for a moored ship or buoy which is exposed to a constant current or wind drag and known cycling excursions in waves. In addition environmental conditions - in particular humidity and temperature - may have to be simulated in the test in order to predict actual reactions of the ropes under the various loading and deformation conditions.

Much work was done on the reaction of various textile fibers under possible loading and elongation conditions. Little has been published on similar performances of ropes. As a general rule however it can be stated, that there is a remarkable difference between the load elongation reaction when the rope is new and when it has been taken into use. The setting or tightening of the rope structure under the first loads will lead to a pronounced permanent elongation and some diameter reduction of the rope. This in combination with the fiber reaction to stresses and strains gives a rope behaviour with considerably higher Young's modulus in use than when new. As a rule of thumb under standard test atmosphere fiber ropes in use will only stretch 1/2 the amount of a new rope under the same load. Similar behaviour is observed with wire rope. The different loading and elongation conditions which can simulate actual rope behaviour in use, will be discussed in some detail in the following chapters.

2.3.3.1 Ropes Under Constant Load

If a constant load is applied to a rope and maintained, the rope will show an instantaneous elongation, but will also continue to stretch as time goes on. This time dependant extension under an applied load is called creep after removing the load, the rope will show an immediate recovery and some delayed recovery. It will maintain some non recoverable stretch or permanent deformation. This behaviour is **illustrated** in Figure (2-12).

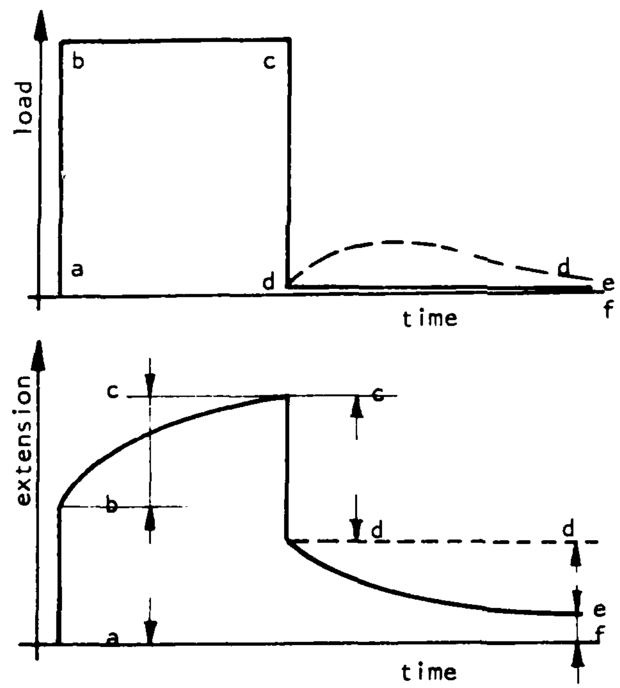

Figure (2-12)

Ropes under constant load and recovery under zero load; showing instantaneous extension a-b, total creep b-c, instantaneous recovery c-d, delayed recovery or or primary creep d-e, permanent deformation or secondary creep e-f. Dotted lines: If the rope is held after load release in d, the load will build up and relax along the dotted line.

It is seen, that the instantaneous extension is followed by creep and that after removing the load there is an instantaneous recovery and a time delayed recovery. The latter is also called primary creep. Secondary creep is the unrecoverable deformation which is left over. Total creep and primary creep slow down with time. The creep-time behaviour follows a logarithmic law. Flessner[24] has shown the logarithmic creep-time behaviour of double-braided and plaited nylon ropes under various loads in standard test atmosphere. He found that at least 80% of the creep has taken place in the first 72 hours of the test and that the creep was mainly fiber reaction and independent of the rope construction within the measuring tolerances. The two rope types tested showed remarkable differences in the instantaneous elongation. The total extension TE under 30% of the rated breaking strength after a time t is given by Flessner for 2 in 1 nylon double braided rope* as

$$TE = 0.1689 \log_e (\text{time}) + 16.50 \quad \ldots\ldots\ldots\ldots \quad (2\text{-}15)$$

and for 8 strand plaited rope**

$$TE = 0.2210 \log_e (\text{time}) + 24.30 \quad \ldots\ldots\ldots\ldots \quad (2\text{-}16)$$ [24]

where the instantaneous extension at a slow extension rate of 3"/min is 16.50% for the double braided rope and 24.30% for the plaited rope. Flessner's creep curves are given in Figure (2-13). The total amount of creep was also found to be independent of the load height, as found by Leaderman[25] for high loads in nylon fibers. The delayed recovery of the rope also follows a logarithmic law. Once the final permanent deformation or secondary creep for a given test load has nearly been reached, a rope will recover almost completely from any subsequent loading below this test load. Its reaction will be completely elastic. This situation is also known as mechanical conditioning in fiber technology.[26] For information on the behaviour of various synthetic fibers under constant loads see Morton and Hearle.[27]

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*manufactured by Samson Cordage Works, Boston, Mass.
**manufactured by Columbian Rope Company, Auburn, N.Y.

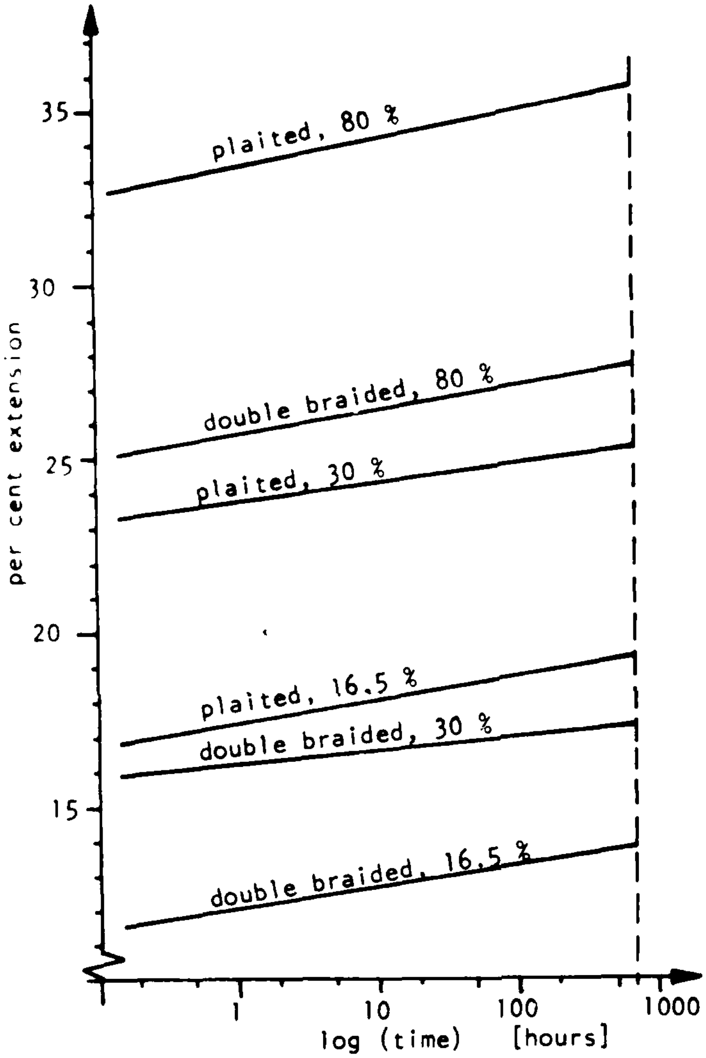

Figure (2-13)

Creep curves, taken from Flessner's Figure 33; showing extension versus log. (time) behaviour of Columbian Rope's 8-strand plaited and Samson double braided nylon ropes of 7/16" diameter, tested under constant loads of 16.5; 30 and 80 % of their rated breaking strength in standard climate. The curves were obtained by the least square method from at least three tests.

The practical results of these creep tests should give information about how great a constant load can be held by various rope types without failure. Flessner[24] showed that properly spliced nylon ropes will hold 80% of their advertised breaking strengths over prolonged periods of time in undisturbed lab tests but are very sensitive to any changes in test conditions under this load and never should be subjected to these high loads in use. It is known that polyethylene ropes will "flow away" much earlier.

Polyethylene fibers of the best quality (Ziegler and Philips Type) will flow away at room temperature under 40% of their breaking load after 10 to 12 days.[28] This is due to very pronounced secondary creep, sometimes called "cold flow".

The measurement of instantaneous elongation, total creep, instantaneous recovery, delayed recovery and permanent deformation is no basic problem. Since creep and creep recovery are very pronounced at the beginning of the loading or unloading operation, frequent measurements, on the order of fractions of a minute, have to be made during the initial period of creep or creep recovery measurements. Later in the test, measurements can be reduced to daily intervals.

If the rope would be held at the extension d in Figure (2-12) showing zero tension immediately after load release, it will be observed that tension will build up to a distinct value again with time. This load build up is caused by the energy still retained in the rope fibers, which otherwise would cause the delayed creep recovery or primary creep, if the rope would be allowed to contract freely. This effect is often noticed, when a rope is hauled in under tension over a capstan and then, after load release by the capstan, is wound loosely on a drum. Since the rope can not contract on the drum, it will build up tension with time. This tension leads to jamming and wedging of the rope layers on the spool. It can be high enough to cause crushing or flange popping of the drum.

2.3.3.2 Condition 2: Ropes Under Constant Strain

This condition of a permanently stretched rope can be used to predict the rope tension in a taut mooring, with a scope less than 1, in calm water. Whenever a rope, textile fiber or any viscoelastic material is held prestretched over a period of time, the tension experienced by the material will gradually decrease, and may under certain conditions disappear completely. This reaction is known as relaxation and is schematically illustrated in Figure (2-14). The reaction shows a diminishing strength drop rate with increasing test time. Ultimately a nearly constant load will be experienced by most materials used in this test. If the load relaxation is plotted versus a logarithmic time scale, many fibers and fiber ropes show linear load reductions similar to creep.

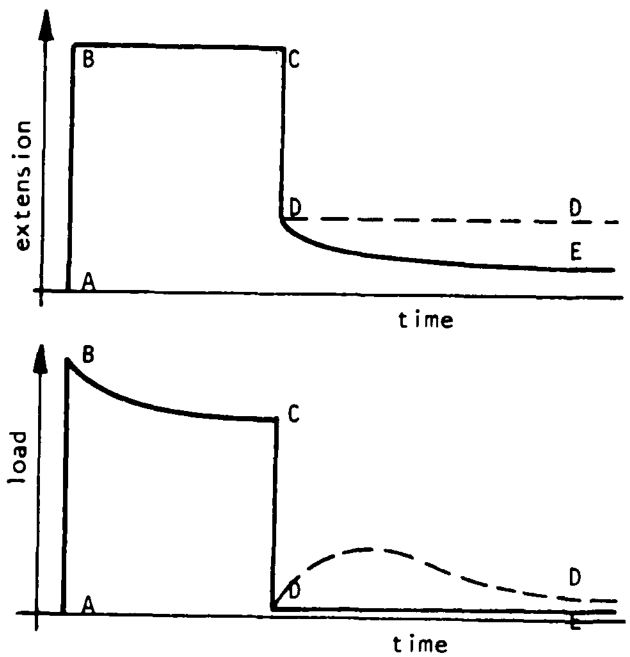

Figure (2-14)

Load relaxation of a rope of fiber held at a constant elongation over a period of time; and recovery after removal of the elongation. If the rope is held at D, where after stretch release the load is first 0, a load will build up and relax along the dotted line.

Relaxation tests are apparently not as common, as creep tests with fibers.[29] For ropes, no relaxation tests have come to the attention of the author. These tests could be used to obtain permanent deformation and delayed recovery data on ropes after constant elongation tests. If we measure the elongation when the rope load first becomes zero in D of Figure (2-14), we obtain the instantaneous relaxation from load C. The rope is then allowed to recover under zero load or pretension, until at E, no noticeable further length decrease is observed. Then the permanent deformation or secondary creep E-F of the rope after relaxation tests can be measured as well as the delayed recovery D-E. EF and DE may differ from the corresponding results of a creep and creep recovery test. The "load build-up after release" effect becomes apparent when the rope is held at deformation D (temporary no-load condition). The recovery D-E would then be impossible and a load buildup, as indicated by the dotted line, would become effective. The test results would be modified for most fibers and fiber ropes, due to changes in the environmental conditions, in particular immersion.

2.3.3.3 Condition 3: Ropes Under Cycling Loads

Wire ropes, fiber ropes, textile fibers and yarns show a characteristic behaviour under cycling loads. If a new rope is put into use and cycled between zero and a distinct working load, it is observed, that the initial load elongation curve is never reached again in subsequent loadings.

A typical set of load elongation curves under cycling loads is given in Figure (2-15).

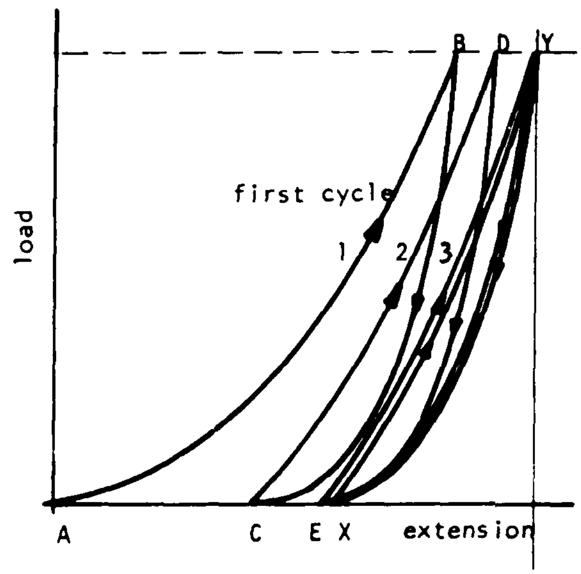

Figure (2-15)

Rope under cycling loads

After a few cycles the rope will follow its "master" or "conditioned" hysteresis loop X - Y

After the work load has been reached at the first loading, (point B) is released, the unloading curve BC follows a much steeper downward slope than the loading curve AB. The curve will not return to its original starting point. Repeating the cycle, the rope will start at C and move to D on a much steeper curve than the initial loading. It will return, after load release to a point E. Repeating these cycles several times will quickly show the curves following the same cycle XY. This cycle may have a slight drift towards higher elongations, particularly for materials with high creep values and at large number of cycles. At each of the load cycles a hysteresis loop has been formed, indicating conversion of some part of the mechanical energy necessary to stretch the rope into internal friction. The final or semifinal hysteresis loop X-Y may be called the conditioned or master hysteresis loop.

The master hysteresis loop is phenomenon found at all cordage fibers, at all different rope types tested so far, as well in fiber ropes as wire ropes. There are differences of course in the stretch behaviour of wire and fiber ropes. Fiber ropes will stretch much more. They do not follow Hooke's law, but shape and tendency of the hysteresis curves are similar.

For cycling tests on new twisted nylon ropes of 8 and 9 inch circumference, it was found that the ropes followed their "master" hysteresis curve after three load cycles,[30] when loaded up to 75% of their breaking strength. Under the same loading conditions ropes from multifilament polypropylene (Ulstron) needed about five cycles. From cycle number five to 120, slight drift of about 2% to the right of the elongation axis was observed.[31]

Nylon double braided ropes of 7/16" and 2 1/4" diameter were tested intensively in load cycles with four deformation speeds between 1.67 and 16.7 per cent of sample length per minute wet and dry to obtain more data for this report*. The ropes were cycled between a pretension of $200D^2$ and 10%, 20%, 40% and 80% of the rope's breaking strength. They cycling was started with the highest test speed till a 'master hysteresis loop' was well established, then the tests were repeated with the next slower speed till the master hysteresis loop stayed constant and so on. It was found that there was no complete mechanical conditioning of the ropes at these tests, though the change was small. The total elongation

*The cooperation of Mr. K. Fogden and Mr. A. Thomas Jr. of Samson Cordage Works Shirley Laboratory, who ran and evatuated these test series, is thankfully appreciated.

with increasing number of cycles stayed about constant, but the portion of the elastic elongation decreased, while the permanent and semipermanent deformation is growing accordingly. This means, that the upper portion of the hysteresis loops stays constant, but the starting point is moving slowly to the right - like from E to X in Figure (2-15). The ability to absorb shock loads of the rope in use will thus decrease, since the elastic stretch becomes smaller. The different test speeds showed no noticeable effect on the test results, but the wet rope - which had been shrunk before the start of the test - showed after subtraction of the shrinkage always more stretch than the dry rope under the same load.

Since the rope will generate heat at each cycle due to the frictional loss of mechanical energy equivalent to the area of the hysteresis loop, the cycle speed and the environment of the rope become important. If the energy generated during one cycle can not dissipate completely into the environment, the rope will heat up more and more at subsequent cycles. This will change its load-elongation behaviour. The rope may become so hot that it starts to melt. Ropes which are cycled frequently in use are often subject to work hardening caused by melting of some of the inner parts of the rope. Some part of the work hardening may be caused in nylon ropes by shrinkage. The 2 in 1 nylon ropes just mentioned only showed work hardening after being cycled to 80% of their breaking strength in the dry condition for at least 40 cycles. No other cycle situation within the range of test speeds affected these ropes. For some barge towing operations in England, work hardening has caused rejection of nylon and polyester ropes.[32] Immersed use of ropes under cycling stresses, possible in ocean towing and mooring, will greatly reduce the danger of overheating. Systematic cycling tests of ropes using different cycle speeds and loads should show results similar to the cycling tests on nylon yarns done by Kelly.[33] It was shown, that at loads in excess of 71 to 76% of the breaking stress the yarn samples failed in less than 1000 cycles at fairly low frequencies between 2 and 11 cycles per minute.

It is obvious that only rope fibers which show fairly "thin" master hysteresis loops will be useable for cycling rope applications, particularly at "higher" frequencies and loads. Cordage fibers must therefore be highly 'spring-elastic', with very little viscous reaction to load.

2.3.3.4 Generalized Stress Strain Behaviour of Ropes Under Cycling Loads

The pattern of the "master" hysteresis loop formation and its shape have led Wilson[30] to develop formulas describing the elastic reactions of ropes under cycling loads. He first obtained generalized stress strain behaviour for various rope types by separating the elastic and permanent deformation of the ropes tested. The limitation is that each set of load-cycle curves is only valid for a given, constant cycling load situation. In particular, the relaxation time which is available between cycles will greatly influence the starting point, inclination and size of the hysteresis loop.[34] The more time between cycles, the greater the delayed recovery of the test sample and vice versa. Different rope diameters in a given construction and material have to be tested, since the elongation tends to become larger with increasing rope sizes. In addition, environmental influences have to be considered, particularly immersion in water. So a large series of generalized stress strain curves have to be measured in order to cover the many different combinations of cycle speeds and stress acting on various types of ropes, of various materials, working in different environments.

Wilson's curves[35] were taken from undefined cycling tests run by British Ropes Ltd., Plymouth Cordage Co., and a South African test facility. Wire ropes, three strand coir* and nylon ropes, which are redrawn here in Figure (2-16) and (2-17), were tested. They show the same tendency as the schematic Figure (2-15).

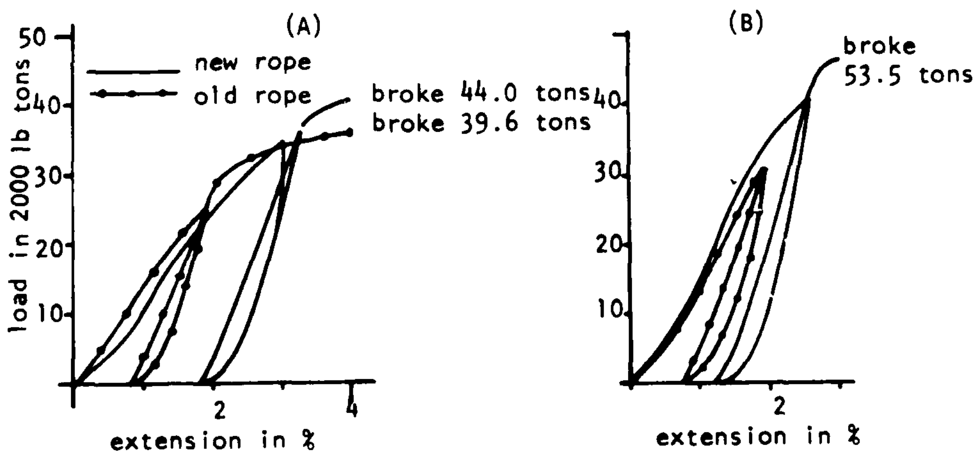

Figure (2-16) Repeated load-extension tests for wire ropes[35].
(A) 3 1/2" circumference steel wire mooring rope, 9 ft long
(B) 4" circumference steel wire mooring rope, 9 ft long

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*Since coir rope (made from coconut fibers) has only 10% of the strength of nylon rope, and is little used, it is omitted here. It generally follows the same deformation tendency as nylon ropes except poorer recovery.

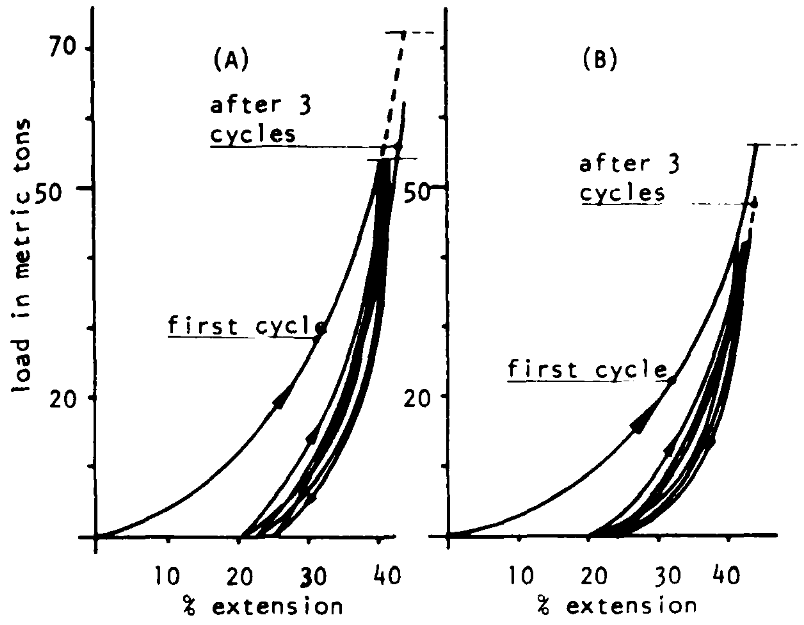

Figure (2-17) Repeated load extension tests for twisted nylon ropes. (A) 3" diameter (9" circumference) [35]
(B) 2 5/8" diameter (8" circumference)

The values of permanent and elastic elongation at various stress levels were taken by Wilson to draw separate curves for the permanent and elastic elongation under a specific cycling situation. In Figure (2-15) for the hysteresis cycle load the elongation AX would be permanent, the elongation XY would be elastic. Curves for wire and nylon rope are redrawn in Figures (2-18) and (2-19). In Figure (2-19) the curves for double braided nylon are added.

As seen in the wire rope curves in Figure (2-18), the permanent elongation tends to grow indefinitely near the breaking point, expressing the yielding of the rope wires. The elastic elongation

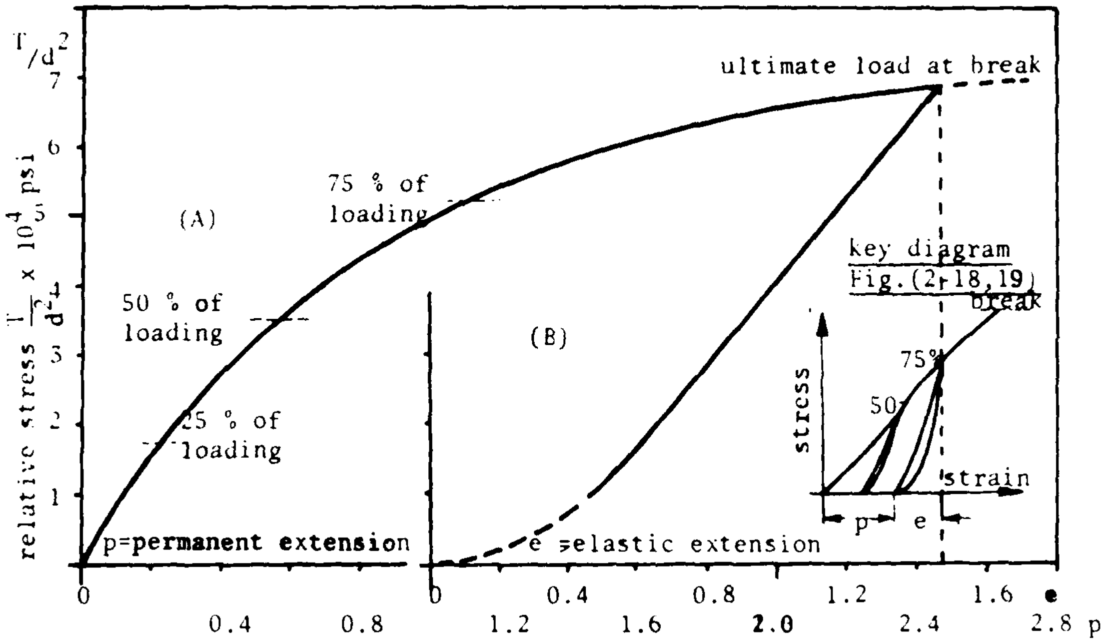

Figure (2-18) Generalized stress-strain curves for wire ropes
A) permanent strain; B) elastic strain

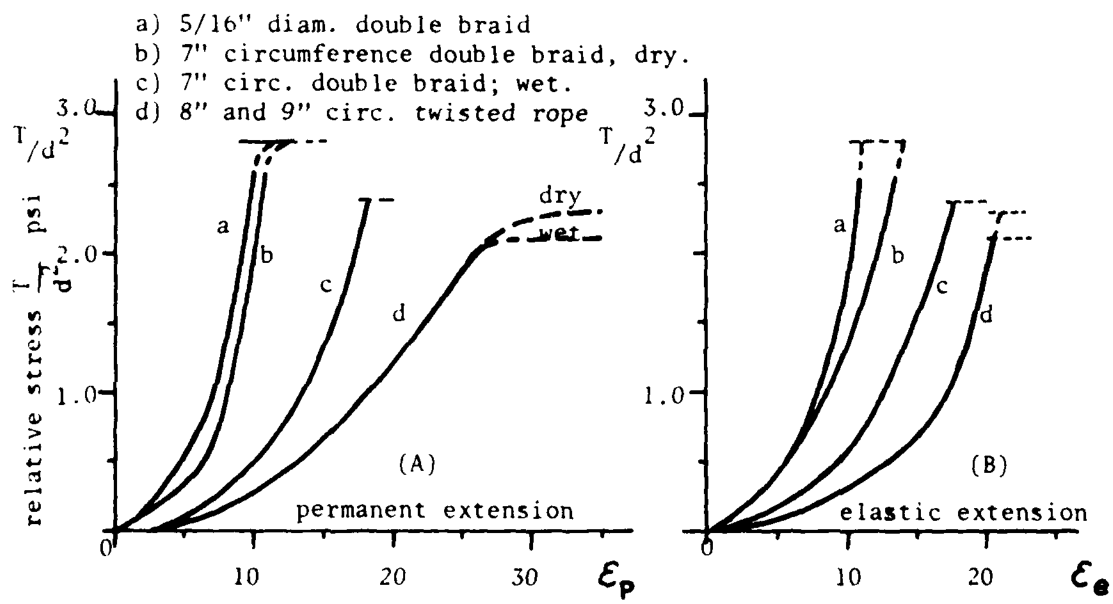

Figure (2-19) Generalized stress-strain curves for various nylon ropes
A)permanent strain; B) elastic strain
see key diagram in Figure (2-18)

follows a straight Hooke's line in the upper region. At the beginning of the elastic curve geometric influences are probably responsible for the lack of linear behaviour. In the nylon rope (Figure 2-19) the tendency of the permanent elongation to grow indefinitely near the breaking point, is much less pronounced. Yielding is not that pronounced in the nylon fibers. They react more rubber like or spring elastic, even at high loads. The elastic elongation nearly follows Hooke's law at the upper end of the load region.

These results led Wilson[35] to the schematic relationship between stresses and strains under cycling loads in Figure (2-20). It is approximated here, that the axes of different hysteresis loops, a'g and c'h, run parallel, and thus have the same Young's modulus, though c'h applys at a higher load. At the stress bg the elastic strain is a'b, the plastic strain Oa'. At the higher stress of the elastic strain is c'e and the plastic strain OC'. Wilson's Figure 10 (our Figure 2-21) compares the elastic elongation for nylon and wire rope in double logarithmic scale. (valid only for cycle tests according to Figure (2-16) and (2-17).

From Figure (2-20) and (2-21) Wilson approximates the elastic elongation $\Delta S/S_o$ under the tension T by the general equation

$$T/d_r^{\,2} = K_e \, (\Delta S/S_o)^m \quad . \; . \; . \; . \; . \; . (2\text{-}17)$$

where K_e is an elastic constant of proportionality and m a numerical exponent. The relation between the load carrying cross sectional area A and the rope diameter d can be introduced with $C_c = A/d^2$ to compare stresses, not T/d^2 values. In combination with Equation (2-17) this gives

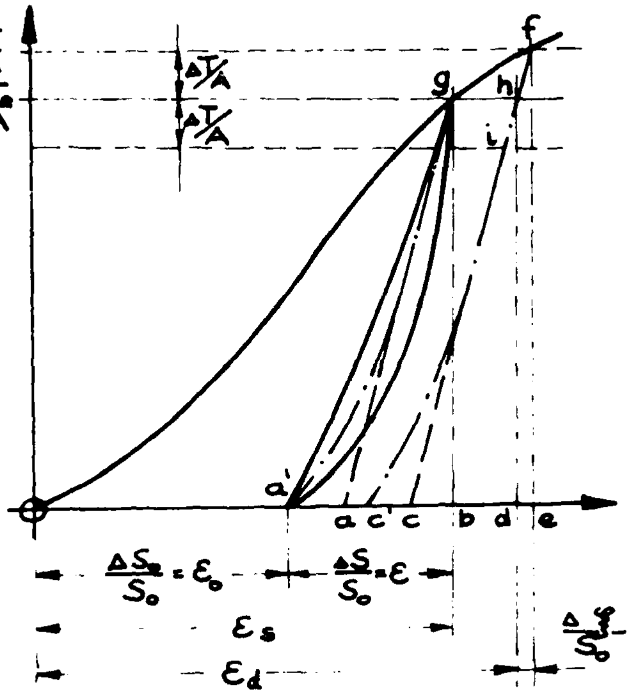

Figure (2-20)
Schematic diagram of stress-strain relationships for a typical mooring rope

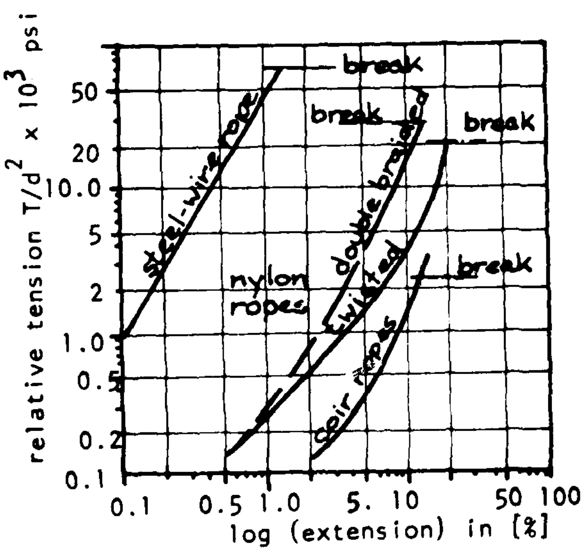

Figure (2-21)
Comparative stress-elastic strain relationships for steel wire, nylon and coir ropes.

$$T/A = K_e/C_c \ (\Delta S/S_o)^m \quad \ldots\ldots \quad (2\text{-}18)$$

Typical values of C_c and K_e/C_c for wire and nylon ropes

... sted according to Wilson's figures in Table (2-8) with values

... braided nylon ropes added.

type of mooring rope	elastic constant K_e [lbs-wt/sq.inch]	eponent m	area constant C_c	modified elastic constant K_e/C_c [lb-wt/sq.inch]
steel wire	3.9×10^7	1.5	0.405	9.63×10^7
nylon twisted	2.2×10^6	3	0.630	3.53×10^6
dito, altern.	4.0×10^5	2	0.630	6.35×10^5
nylon 2 in 1 dry	1.45×10^6	2	0.75	1.94×10^6
dito, wet	4.3×10^6	3	0.75	5.7×10^6

Table (2-8) 'Constants' for mooring ropes, Equations (2-17);(2-18)

The values of K_e and m are fairly flexible, since the curves don't follow with sufficient accuracy logarithmic laws. The values of K_e and m given here are for the upper part of the load-elastic elongation curves. The area constants C_c are not precise either. But for approximate calculations K_e, C_c and m may be sufficient. It is suggested that the breaking lengths or tenacities are introduced in these equations instead of the stresses to obtain more precise values to express the ropes' mechanical properties.

Under cycling loads the conditions change slightly. Following Wilson's example we try to find the stress-strain ratio. As in Figure (2-20), the rope is under a constant stress g-b or T_e/A and cycles with an amplitude $\Delta T/A$ around T_e/A. This means that the rope will stretch under the peak stress $(T_e + \Delta T)/A$ along its original load elongation curve from g to f. According to the general performance, the relaxation will now occur along a hysteresis loop with the axis i-h-f. This axis coincides with the Young's modulus E of the rope at the stress T_e/d^2 under cycling loads. Based on the original rope length S_o and a strain increase between T_e/A and $(T_e + \Delta T)/A$ of $\Delta\xi/S_o$, the Young's modulus of the loop axis i-h-f is:

$$E = \Delta T/A \cdot S_o/\Delta\xi \quad . \ . \ . \ . \ . \ . \ . \ (2\text{-}19)$$

Differentiating Equation (2-18) will give

$$\Delta T/A = \frac{m\,K_e}{C_c}\,(\Delta S/S_o)^{m-1}\,\Delta\xi/\Delta S_o \quad . \ . \ (2\text{-}20)$$

which combined with Equation (2-19) will finally give:

$$E = \frac{m\,K_e}{C_c}\,(\Delta S/S_o)^{m-1} \quad . \ . \ . \ . \ (2\text{-}21)$$

Taking this equation it is possible to draw Young's moduli for the various degrees of loading of the different rope types. This is done in figure (2-22), *redrawn from* Wilson's Figure 11 [30].

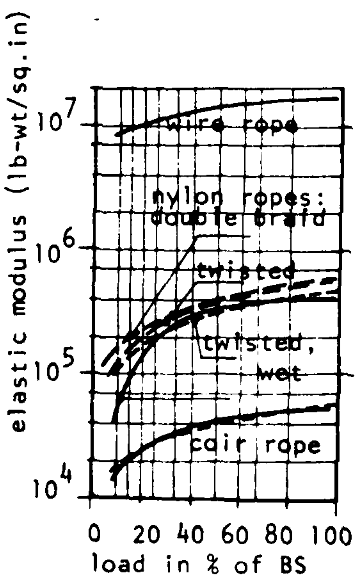

Figure (2-22): Dependence of elastic modulus for mooring ropes on extent of loading.

By combination of Equations (2-2) and (2-17) and introducing $\Delta S/S_o = \mathcal{E}$ = elastic strain, we obtain

$$T_e/BS = K_e/C_b\,\mathcal{E}^m \quad . \ . \ . \ . \ . \ . \ . \ (2\text{-}22)$$

Wilson then eliminates $\mathcal{E} = \Delta S/S_o$ in Equations (2-21) and (2-22), to get the most general expression for the Young's modulus under dynamic loads, as

$$E = p_e \, (T_e/BS)^i \quad \ldots\ldots\ldots\ldots \quad (2\text{-}23)$$

with

$$p_e = \frac{m\,K_e}{C_c} \, (C_b/K_e)^{\frac{m-1}{m}} \quad \ldots\ldots \quad (2\text{-}24)$$

and

$$i = (m - 1)/m \quad \ldots\ldots\ldots\ldots \quad (2\text{-}25)$$

In Equation (2-23) the Young's modulus is depending on the ratio applied tension T_e to breaking strength BS, a constant p_e and an exponent i. Based on the previously given values m, C_b, C_c and K_e values for i, p_e and Young's moduli at 25 % and 50 % of the moorings breaking strength are listed in Table (2-9).

type of mooring rope	numerical exponent i	elastic constant p_e [lb-wt/sq.inch]	Young's modulus in [lb-wt/sq.inch] at 25 % of BS	50 % of BS
steel wire	1/3	1.76×10^7	1.1×10^7	1.4×10^7
nylon twisted	a) 2/3 (Wilson)	5.3×10^5 dry	2.1×10^5	3.3×10^5
		4.75×10^5 wet	1.9×10^5	3.0×10^5
	b) 1/2	3.2×10^5 dry	1.6×10^5	2.2×10^5
		2.9×10^5 wet	1.5×10^5	2.1×10^5
nylon 2 in 1 double braided	1/2 (dry)	5.4×10^5 dry	2.7×10^5	3.8×10^5
	2/3 (wet)	5.4×10^5 wet	2.1×10^5	3.4×10^5

Table (2-9) <u>Constants for elastic moduli of moorings, Equation (2-23)</u>

Taking the more precise strength to diameter ratio of Equation (2-3) instead of Equation (2-2), would change slightly the preceding

Equations (2-17) through (2-25) except (2-22). Ultimately this would yield smaller values of p_e for increasing rope diameters. (For the modified formulas see [36]).

These generalized formulas of Wilson for the stress-strain behaviour of ropes under cycling loads which seem to give Young's moduli up to 30% too high - were given here in some detail, since it is the first attempt (to the writer's knowledge) to describe these reactions mathematically. More work in this field would put this procedure on a broader and more precise base. In particular, the dependency of these results on cycle speed, amount of load, rope type, fiber material and environmental conditions has to be investigated. Before test series have derived general stress train behaviour rules, it is suggested that the mooring application be simulated as closely as possible on a testing machine to get the reaction of a specific rope under specific environmental conditions. This is the only way seen at this moment to obtain reliable data for rope performance in a specific use. The complex viscoelastic behaviour of the rope fibers modified by a complicated rope structure, precludes general predictions at this time.

2.3.3.5 <u>Condition 4: Ropes Under Cycling Extensions</u>

Frequently ropes have to sustain cycling extensions within their working elasticity. Typical examples of this are ships surging back and forth in seiches moored in a ports open to the ocean,or a ship moored to a buoy, surging in waves,or a large buoy cycling in a seastate. In each of these cases it would be impossible to hold the ship or buoy on a spot, since forces generated in an attempt to do so would exceed by far any holding power of existing ropes. So the moorings have to allow the ships' or buoys' motions within their elastic limits, which in some cases are broadened by configuration changes of catenary systems. If surge excursions of a ship in a sea state exceed the elastic stretch of the rope, the mooring will fail due to overextension. This problem has been investigated in some detail by various authors.[37]

The "rope-question" in this subject: What stresses will be generated within a mooring under known cycling extensions? Or how has a mooring to be designed to allow distinct cycling extensions within its working limit? The latter problem is mainly a question of rope length, since rope stretch is s times rope length, where s is the allowable strain for a particular rope type within its working limits. The first question is similar to that of cycling loads. Taking Figure (2-15) under cycling extensions will show that there is a relaxation process with time, since in particular new ropes will develop permanent extension, thus becoming longer and less taut. Depending on the type of mooring this should have different results. If a ship is moored to a pier in the usual way, with bow and stern lines and various springs - and will be subjected to cycling motions due to waves, the whole system will tend to become looser, since the ropes become longer and thus slacker. If however, the ship is connected to a fixed point by a single point mooring and subject to a cycling extension, assuming that current or wind will keep the rope taut, the rope also becomes longer in use and will have less percent elastic elongation. In the usual elongation ranges of rope

elasticity, in this special case the difference between total new rope stretch and used rope stretch is neglectable. The rope will allow about the same amount of total stretch if new or used.*
Only when the rope creeps considerably the total stretchable rope length will become larger. As a rule of thumb in regular ship to pier moorings, the load response to given excursion cycles becomes less while for a single point mooring the load response will either stay constant or decrease. This excludes catenary influences, and rope stretch due to the environment. As in previous conditions it is to recommend that sample tests be run for a given application. Simulate field conditions as closely as possible.

2.3.3.6 Ropes Stressed in Directions Different from the Rope Axis

Ropes are frequently stressed in directions different from the rope axis. Typical situations are ropes stressed around capstans, chocks and bollards, ropes forming splices, loops and knots.

In all these cases additional stresses are put on the rope by bending it. Some of the total rope stretch is used to take the bending stretch, which accordingly reduces the ability of the rope to take tensile loads. The sharper the bend and the smaller the stretch of a rope, the larger will be the drop in tensile strength.

*According to Figure (2-15) a rope stretches $(1 + \varepsilon)$ new, where ε is the extension of the new rope. Used it will get a total permanent stretch of $\ell_o (1 + \varepsilon_o)$ and will stretch elastically along the axis a'g and will thus become $\ell_o (1 + \varepsilon_o + \varepsilon) = \ell_o (1 + \varepsilon_s)$ or the total stretch stays constant. Only if the used curve would have a higher stretch than the new curve, then the stretch of the used rope would be higher, provided nobody shortened the rope to keep the same distance to the anchoring point.

In knots of fiber ropes a load of only 40 to 60% of the rope strength is necessary to break them, the smaller value applies to low stretching polyester ropes. Similar drops are found in the loop strength of ropes. Eye splice strength of a rope is 85 to 90% of its breaking strength. A bending radius of a rope of at least nine times the **fiber rope radius** is necessary to maintain full rope strength. For wire ropes sheaves or drums should have diameters of 31 to 72 times the rope diameter[38] or under certain conditions minimums of 18 to 42 times the rope diameter[39] depending on the wire rope construction. In a spliced eye the minimum bending radius of the splice loop around a bollard or hook or thimble can be about 4 times the rope diameter only, since the load on each "arm" of the eye splice is only 50% of the rope load.

The stressed bent rope causes contact pressure on the drum, sheave etc., which was discussed recently in some detail by Heller.[40] Occasionally torsional effects can reduce the life of ropes, in particular if two ropes with different torsional characteristics are shackled together without a swivel.

Generally, it can be said that all stresses of ropes not reacting along the rope axis cause reduction in the tensile strength of a rope which often can be very dangerous. A proper design of hardware used for rope is necessary and will avoid the often dangerous overbending.

2.3.3.7 Ropes Under Shock Loads

Ropes in use may be subjected to impact loads along their axis or transverse to it. Ropes used in mountaineering, in some load hoisting procedures and as upper part of a buoy mooring cable[41] may suffer often severe impacts along the rope axis. A typical situation where transverse impacts hit ropes is the use of nylon pendants in aircraft arrestor gears. In both impact directions critical oscillations and strain waves may occur.

The example of a mountain climber, falling into his rope, may show, that his allowable weight w compared to the ropes' breaking strength is only a fraction of the static safety figures. In Figure (2-23) the worst condition of a shock load is shown. The rope is fixed at M to the mountain. The climber is standing the total rope length l above point M, looses control and falls down the distance 2xl. The potential energy of the man is

$$E_{pot} = W \times 2xl \;.......... \;(2\text{-}26)$$

The energy the rope absorbs is

$$E_r = 1/3\ BS\ l\ s_b \;........ \;(2\text{-}5)$$

The rope will break if $E_{pot} \geq E_r$. For $E_{pot} = E_r$

$$W = 1/6\ BS \times s_b \;..........(2\text{-}27)$$

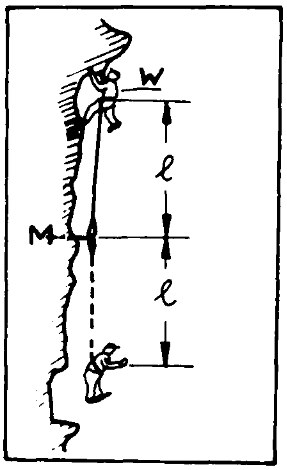

Figure (2-23)
Maximum drop of a mountaineer, held by a rope.

For different values of the rope's breaking extension, the weight W is determined in Table (2-10), which will just break the rope. The weight is independant of the rope's length.

The use of wire rope - which may extend at break 3% - is not feasible, since a weight of only 1/2% of its breaking strength can destroy it. Usual mountaineering ropes are made of nylon and stretch at break 20 to 30%. With a safety figure of 4 this would

rope extension at break in %	3	10	20	30	50
weight W in % of rope strength that will break the rope	0.5	1.7	3.3	5.0	8.3

Table (2-10) Mountaineer's weight, able to break climbing rope in case shown in Figure (2-23)

this would mean, that the weight of the mountaineer shall be 1 % of the rope's breaking strength, giving for average climber weights nylon ropes of 5/8" to 3/4" diameter.

Under high impact speeds the elongation of a rope decreases, while the strength increases, - see Figure (2-5). The frequency of the impacts can become critical in particular in the upper part of a buoy mooring rope[41, 42]. Further investigation in this field is necessary.

2.3.4. The Influence of the Environment on the Load - Elongation Properties of Ropes

2.3.4.1. Water and Humidity

The influence of water on the rope behaviour in naturally similar to its influence on fiber behaviour - see Section 2.3.2.5. It has its most pronounced influence in nylon ropes, where the strength loss of the nylon fibers and their shrinkage due to prolonged exposure to humidity or immersion may cause pronounced differences in the load elongation behaviour of these ropes. The strength drop of about 15 % in the wet rope is equal to the loss in the fibers. Any elongation changes due to the wet fiber are magnified due to the arrangement of the fibers in the rope structure. In conventional rope constructions the fiber stretch will result in a rope stretch of 1.5

to 3 times the fiber stretch, depending on the material and construction used. A rope will contract due to shrinkage which is much more pronounced than fiber shrinkage. This will often lead to the hardening of the nylon rope structure to a degree that the rope becomes too stiff to be handled properly. This is also observed when the rope is stored in humid climate for some time. The nylon rope therefore is often stabilized. Stabilization is done by exposing the rope to shrinkage causing conditions under tensions larger than the shrinkage tension. This process will result in a nylon rope much more stable to changes in the humidity in use. European rope standards now require stabilization of nylon ropes, while in the corresponding U. S. standards stabilization is expressly prohibited.[43] The shrinkage and stabilizing process is a complex molecular reaction.[44]

Cycling tests with 2 in 1 nylon ropes of Samson Cordage Works have shown, that rope samples which were shrunk by boiling them in water for 5 minutes* and then cycled to 30% of their breaking load exhibit the same load elongation curve as the new rope. The dry rope cycled to the same load limit shows about half the stretch of the new dry or cycled preshrunk rope under equal loads.

As mentioned earlier no other cordage fiber shows noticeable water influence at room temperature, though higher water temperatures may change their properties considerably, caused by thermal effects. Synthetic fiber ropes other than nylon ropes do not noticeably change their properties with humidity since these fibers absorb little or

*boiling of a nylon rope will shrink it down to its probable long term maximum shrinkage in use.

no water. Polypropylene ropes may show 2 to 5% higher breaking loads when wet due to the reduction of fiber friction in the rope by the water around the fiber itself. It shows no change in stretch.

2.3.4.2 Effect of Sunlight

As mentioned before all synthetic cordage fibers suffer often severe strength losses when exposed to sunlight, particularly to ultra-violet and intra-red radiation. This effect is considerably weaker in ropes specifically at large rope diameters, since only the surface fibers are affected by the radiations.[23] Comparative weather resistance data for nylon and polyester ropes of 1/2" diameter exposed in Florida are given by DuPont.[45] They show strength drops after 18 months exposure of 5% for Dacron polyester ropes; 40% for other polyester ropes, 37.5% for DuPont nylon 6.6 type 707 ropes (15% for dyed ropes) and 55% for nylon 6 ropes. In polypropylene ropes ultra-violet stabilizers should make their performance comparable to those of nylon and polyester.

Whenever possible ropes should not be stored over longer periods of time in direct sunlight. Thin exposed ropes like flaglines or halyards, particularly under tropical sun, should be made out of fibers with built in additions to protect against deterioration by ultra-violet rays. In ropes of polypropylene and polyethylene this is most desirable, otherwise radiation quickly starts to crack the chain molecules. This becomes visible by a pronounced embrittlement of the surface fibers leading to a condition where they can be ground between two fingers into dust. Exposed thin polypropylene ropes may reach this condition after less than six months, but if proper stabilizers are added, don't show visible deterioration after several years.

2.3.4.3 Temperature

The strength decrease and elongation increase with rising temperatures is found in the ropes as well as the fibers covered in Section 2.3.2.5. Dangerous heat build up can easily start to melt ropes with low melting points, particularly ropes made of polyethylene and polypropylene (melting or sticking points 240° and 300°F). A rope slipping under tension while wound around a capstan may quickly build up enough heat to melt the rope. Polyethylene and polypropylene ropes should not be used where frequent handling on winches is unavoidable. The danger of overheating under cycling loads or strains caused by hystersis effects was mentioned previously. The pronounced influence of immersion into hot fluids should be remembered. Boiling water will cause greater reaction than hot air at the same temperature. At cold temperatures all fibers increase their strength and reduce their elongation in tensile tests to a degree that brittleness is observed in some fibers below a distinct temperature. Polyester and nylon fibers tested at -57°C by Coplan[20] do not show embrittlement, the probable limit should be much lower. Cook[16] reports that polypropylene remains flexible until -70°C, while polyethylene becomes brittle (reference ASTM Method D 746-55T) at less than -114°C. Since ropes may be used under cold conditions such as mountain climbing or in parachute ropes, it is important to know this limit. In a cold temperature test, a wet 7" circumference nylon rope was frozen in a zig zag form at -70°C, the bonestiff zig zag rope was cycled under load on a tensile testing machine.* The rope straightened out under load, but returned to the zig zag form after load release. After a longer cycling time the ice started to melt and the rope began to straighten out. Otherwise, no detrimental effect of the ice in the rope was observed in particular no cutting of ice particles and the rope behaviour under cycling load was normal. With some caution one can recommend the use of the conventional synthetic fiber ropes at a temperature range between -70°C (-94F) and +90°C (+194F)** without expecting any difficulties.

2.3.4.4 Effect of Chemicals, Rust, Rot and Mildew, Marine Microorganisms, Fishbite

Synthetic cordage fibers and ropes made out of them are remarkably resistant to agressive chemicals, they are stable to most acids and alkaline substances. For special information see.[46,47,48]

However, it should be noted that rusting iron or steel degrades ropes rapidly, "Sometimes in a period as short as one or two weeks."[49] Proper design and material selection for rope hardware, thimbles, shackles, blocks can avoid this hazard. Synthetic fiber ropes do not rot. Mildew, which may grow on the ropes, is not harmful. Synthetic fiber ropes were not attacked by marine microorganisms in deep oceans, while cotton and manila ropes suffered severe damage by them in parallel exposure tests.[50] Fishbite, in some areas, has seriously limited the use of thin synthetic fiber ropes in deep sea

*done by Samson Cordage Works in 1969.

**90°C for polyethylene ropes is too high already and critical for polypropylene ropes.

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buoy moorings. A small group of fish, among them one species of sharks, attack the ropes in geographically limited areas and in the upper 1500 meters water depth. The danger is obviously much larger for thin ropes. Some protective coating and armouring for synthetic fiber ropes has been developed and much is still under development. For further information in this area see.[51,52,53,41]

References Section 2

1) Wilson, B.W.; "Elastic Characteristics of Moorings", Journal of the Waterways and Harbors Division, Proceedings American Society of Civil Engineers; Vol. 93, No. WW4, Nov. 1967, p. 30

2) Moseley, O.H.; "Tensile Strength of Manila Rope", Selected Engineering Paper No. 88, Institution of Civil Engineering, London, 1930

3) Paul, W., Discussion of "Elastic Characteristics of Moorings" by B.W. Wilson, - ref. 1) - Journal of the Waterways and Harbor Division; Proc. A.S.C.E., Vol. 94, No. WW3, Aug. 1968, p.373.

4) Weindling, L., "Relations between Twist per Foot in the Ready and in the Rope and the Character of the Rope", Doctor's Thesis, Cornell University, Ithaca, N.Y., 1918.

5) Paul, W., "Untersuchungen ueber das Kraft-Dehnungsverhalten dreilitziger Seile aus synthetischen Fasern. (Load-Extension Properties of Three Strand Ropes Made from Synthetic Fibers)" Doctor's Thesis, Technical University Hannover, Germany, 1967, p. 3, p. 98.

6) The Textile Institute; "Textile Terms and Definitions", 5th edition, Manchester, England, 1963.

7) Watts, J.S.; Faulkner, R.E.; "Designing of a Drill Rig for Severe Seas"; Ocean Industry, Vol. 3, No. 11, 1968, p. 28

8) Wesler, J.E.; Parker, E.L.; "Recoil Properties of Ropes", U.S. Coast Guard Field Testing & Development Center Test Report No 449; Proj. 3973/01/01, Washington, D.C., 1966

9) American Society for Testing and Materials definition, quoted by Morton, W.E.; Hearle, J.W.S.; "Physical Properties of Textile Fibres, The Textile Institute, Manchester & London, 1965, p. 332.

References Section 2, cont.

10) For example see: Morton, W.E., Hearle, J.W.S., loc. cit., chapter 18, p. 407

11) ibid., chapter 13.4, p. 274; chapter 16.4, p. 350; Figure (2-6) is taken from chapter 16.4, Figure 16.25d, p. 356.

12) ibid., chapter 17.

13) ibid., p. 414.

14) Juilfs, J., "Zur praktischen Analyse des Dehnungsverhaltens von hochpolymeren Faserstoffen, (Practical Investigation of the Deformation Behaviour of Highpolymer Fibers), Schweizer Archiv fuer Angewandte Wissenschaft und Technik; Vol. 32, Nov. 1966, p. 352

15) A good short summary of the fiber properties is found in the Fiber List, edited annually by the magazine Textile Industries

16) Cook, J.G.; "Handbook of Textile Fibres"; Vol II, Man-Made Fibres, 4th edition, Altrincham, England, 1968

17) Mark, H.F.; Gaylord, N.G.; Bikales, N.M.; editors, "Encyclopedia of Polymer Science and Technology", keywords: 'polypropylene', vol. 9; 'polyamide fibers', vol. 10; 'polyester fibers' vol. 11, Interscience Publishers, New York, London, Sydney, Toronto; 1968/69.

18) Galanti, A.V.; Mantell, Ch.L.; "Polypropylene Fibers and Films"; Plenum Press, New York, 1965

19) Du Pont de Nemours, E.I. & Co.; Textile Fibers Dept.; "Tensile Stress Strain Properties of Fibers", Technical Information Bulletin X 82; Wilmington, Del.; May 1958.

20) Values taken from Coplan, M.J.; quoted at Morton, W.E., Hearle, J.W.S.; loc. cit.; Table 13.5, p. 298

21) Erlich, V.L.; "Polyolefin Fibers and Polymer Structure", Textile Research Journal, 29, 1959, p. 679

22) Klust, G.; "Bewetterungsversuche mit Zwirnene und Schnueren aus Polyolefinfasern, (Weathering Tests with Twines and Cords Made of Polyolefin Fibers)"; Textil Praxis, 1965, 1, p.4.

23) Bringgardner, D. J.; McCarty, J.W.; Pitrulsky, P.P.; "Light and Weather Resistance of Fibers", Textile Industries; 130, No. 4, 1966, p. 125-

24) Flessner, M.F.; "Creep Tests on Synthetic Mooring Lines"; Academy Scholars Project Report, U.S. Coast Guard Academy, New London, Conn.; 1970. Figure (2-13) is plotted from values of Figure 30.

References, Section 2, cont.

25) Leaderman, H., "Elastic and Creep Properties of Textile Materials and other High Polymers", The Textile Foundation, Washington, D.C. 1943, quoted by Morton, W.E., Hearle, J.W.S., loc. cit., p. 340, 341.

26) Morton, Hearle, loc. cit., pp. 328, 336.

27) *ibid.* chapter 16.2, p. 334

28) Erlich, V.L.; "Polyolefin Fibers in Textiles", Modern Textiles Magazine; 58, Nov. 1958, p. 65.

29) Morton, W.E., Hearle, J.W.S.; loc. cit.; chapter 16.3, p. 347

30) Wilson, B.W., "Elastic Characteristics of Moorings", loc. cit.; p. 37

31) West, K., "The Properties of Textile Fibres Made form Polypropylene", Journal Textile Institute, Proceedings, Vol. 53, No 8, 1962, Figure 6, p. 472

32) Goy, R.S.; Jenkins, J.A.; "Industrial Applications of Textiles", Textile Progress; Vol. 2, No. 1, Mar. 1970, p. 47.

33) Kelly, W.T.; "Some Effects of Repeated Loading on Filament Yarns", Textile Research Journal; Vol. 35, No. 9, Sep. 1965, p. 852.

34) Du Pont de Nemours, E.I. & Co.; Textile Fibers Dept., "Extension and Recovery of Ropes of Nylon and Dacron", Technical Information Bulletin X-92, Oct. 1958; pp. 6.

35) Wilson, B.W., "Elastic Characteristics of Moorimgs", loc. cit., p. 27 - 56

36) Paul, W., Discussion to "Elastic Characteristics of Moorings"; loc. cit., p. 374.

37) see Wilson, B.W., loc. cit.; p. 45 - 51 inclusive references.

38) Marks' Standard Handbook for Mechanical Engineers, 7th. ed.; 1966, p. 8-114.

39) MACWHYTE Wire Rope Catalog G 17, 7th ed.; Kenosha, Wis., 1969, p. 158.

40) Heller, Jr., S.R.; "The Contact Pressure between Rope and Sheave", Naval Engineers Journal, Feb. 1970, p. 49.

41) Isaacs, J.D.; Faughn, J.L.; Schick, G.B.; Sargent, M.C.; "Deep Sea Moorings Design and Use with Unmanned Instrument Stations", Bulletins of Scripps Institution of Oceanography Vol. VIII, 1962 - 64, University of California Press, Berkeley and Los Angeles, 1964, p. 271.

References, Section 2, cont.

42) Goeller, J.E., Laura, P.A.; "Analytical and Experimental Study of the Dynamic Response of Cable Systems", Report 70-3, Department of Mechanical Engineering, The Catholic University of America, Washington, D.C., April 1970.

43) e.g. German Standard DIN 83 330; for U.S. Standards see Section 2.2.3., pp. 2-15 of this report.

44) Du Pont de Nemours, E.I. & Co., Textile Fibers Dept.,"Shrinkage of Du Pont Nylon Fibers", Technical Bulletin N-200, Wilmington, Del., Sept. 1966.

45) Du Pont de Nemours, E.I. & Co., Textile Fibers Department, "Properties of Ropes of Dacron and Du Pont Nylon", Bulletin X-226, Wilmington, Del., Feb. 1969.

46) Cook, J.G., "Handbook of Textile Fibres, Vol. II, Man-Made Fibres", loc. cit., for nylon 6.6: p. 263; for nylon 6: p. 301.

47) Du Pont de Nemours, E.I. & Co., Textile Fibers Dept.; "Comparative Chemical Resistance of Fibers", Bulletin X-48, Wilmington, Del., Mar. 1956;
dito: "Chemical Resistance of Dacron Polyester"; Bulletin D-235, Feb. 1970;
dito: "Properties of Ropes of Dacron and Du Pont Nylon", loc. cit., Table II, Feb. 1969

48) Hercules Inc.; Fibers and Film Dept.; "Resistance to Chemicals of Polypropylene"; Bulletin FH 701, Wilmington, Del., Jan. 1969

49) Du Pont de Nemours, E.I. & Co., Bulletin X 226, loc. cit., p. 5.

50) Muraoka, J.S.; "Deep Ocean Biodeterioration of Materials - Part VI, One Year at 2,370 feet"., U.S. Naval Civil Engineering Lab., Report TR-525, Port Hueneme, Cal., May 1967.

51) Stimson, P.B., "Synthetic Fiber Deep Sea Mooring Cables: Their Life Expectancy and Suspectibility to Biological Attack"; Deep Sea Research, 1965, Vol. 12, pp. 1

52) Turner, H.I., Prindle, B.; "Some Characteristics of Fishbite Damage on Deep Sea Mooring Lines", Woods Hole Oceanographic Institution Ref. 65-22, 1965.

53) Armstrong, J.T.; "An Investigation of Means of Protecting Deep Sea Mooring Lines from Fishbite", U.S. Coast Guard Academy, Dept. of Physical Science; Report in Course on "Special Topics in Scientific Research", New London, Conn., May 1970

SECTION 3

STRUCTURAL MECHANICS OF ROPES

3.1 GOALS AND BASIC PROCEDURE

Rope load elongation behaviour depends on the fibers used and their arrangement in the rope, the rope construction. Changes in material and construction can greatly change the load elongation behaviour of the rope itself. Prediction of load elongation behaviour is possible with the help of a series of tensile tests but the method is slow and expensive. The tests only supply the external load reaction to external applied elongations or elongation reactions to applied rope loads. Usually, the only comparative figures available are the load elongation curves of the fibers, yarns or multi-plies, from which the rope is made. The influence of the rope construction can not be detected with the experimental procedure. This does not give much insight. Since changes in rope construction may change the rope strength by more than 30% for one fiber and show hardly any change for another fiber, more should be known about the apparently important structural influence. This is done with the help of structural rope mechanics. Structural rope theories are yet incomplete.

The structural mechanics analyze the influence of the structure under deformation. The theories define deformation of the components of the rope under known external deformation of the structure itself. The theoretical procedure then enables us to calculate stress response of the components of the rope fibers, yarns, multi-plies strands. Finally the stress or load reaction of the rope itself can be computed. Thus we can analyze the effect of different materials or construction changes on the final rope reaction. The actual tensile test will be an important proof of the validity of the theoretical assumptions. Only the reaction of the rope structure to simple axial strains is described here, but the procedure may be expanded to compute reactions of stretched ropes in a bent configuration, or under the influence of tension plus torque.

Since fiber ropes are textile structures, the basic methods established for textile structures like yarns and fabrics can be used to compute theoretical load elongation reactions of fiber ropes. The basic methods have been developed mainly at the University of Manchester in England since about 1955. They can be adapted for the theoretical load-elongation mechanics of rope as follows:

1. Model the geometry of the rope in the unstretched condition.

2. Compute, with assumed deformation laws, the deformation of the geometry of the rope structure under external stretch to obtain the stretch of the rope components or the internal deformation.

3. Introduce the load reaction of fibers to their stretch as rope component to obtain internal loads under internal deformation.

4. Sum up the internal loads to obtain their resulting external load reaction as rope load under stretch.

With these four steps, the theoretical load reactions of a rope are obtained. The reactions to applied stretch depend on the rope's structure, step 1, 2, 4; and its material, step 3 and 4. By repeating these steps for a large enough number of strain values, enough load or stress reactions can be computed to be able to draw theoretical load elongation curves. These curves have to be verified by tests. The dependence between the theoretical and the experimental method is shown in Figure (3-1).

Though the basic procedure looks simple, a number of detailed problems have to be solved to make it workable. The difficulties and limitations of the general procedure can be seen by the problems which were encountered in developing the structural mechanics for one of the simplest textile structures, the yarn, as summarized by Hearle.[1]

More information on the four steps is given in the following sections.

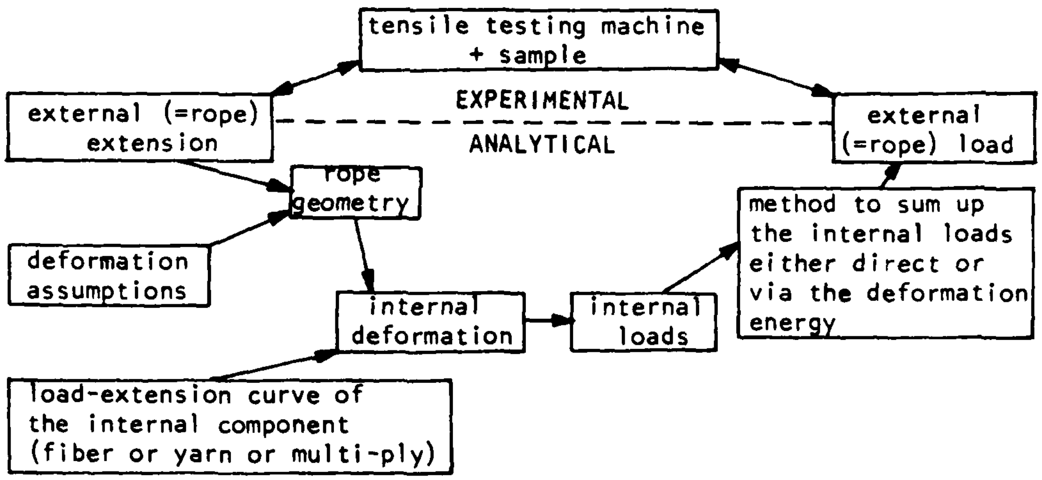


Figure (3-1): Experimental and analytical procedure to obtain load-elongation reactions of fiber ropes. (instead of loads stresses or specific stresses can be used).

3.2 SET UP OF THE ROPE GEOMETRY

3.2.1 Basic Procedure

To be able to look into the rope mechanics, it is necessary to model the geometry of the rope in the unstretched condition in order to obtain a reference or starting point.

The geometry will give us the positions and thus the angles of the axes of the rope components with reference to the rope axis. To ease the mathematics, the procedure is set up to describe the various components as seperate geometric units. Then one will take the subordinate unit and arrange it, usually as a helix, in the next higher structural element. So for example, one will take multi-plies with known dimensions and properties and arrange them in a strand structure with a straight strand axis. The next step will be to arrange strands with known dimensions in the rope. The knowledge of the basic rope construction and the strand dimension is used to determine the radial positions and the helix angles of the strands in the rope.

Ropes are composed of flexible elements. Compressive forces can easily cause small deformations and thus change the geometrical set up. So flattening is possible, particularly at zero load and low twist. The flattening usually disappears under load, due to solidifying of the cross sections. Rope geometry has to use the idealizing assumption of neglecting the deformation by flattening. This because these deformations are fairly unpredictable and usually dissapear after loading.

Since we deal with fibers, yarns, multi-plies, strands and ropes, it is necessary to consider the geometry of each of these units in order to build the rope structure. It may be advantageous to restrict the geometry to strands and rope itself, since it is possible to get sufficient data and dimensions as well from fibers as from yarns and multi-plies either by own tests or from the fiber manufacturer. So the largest known unit is taken to build the rope geometry, for twisted and plaited rope it is the multi-ply, for braided ropes the yarn and the fiber for nolaro ropes.

This will simplify the operation since it reduces the total number of steps to be taken to set up the rope geometry to two operations. The first step would then be to set up the strand geometry composed of multi-plies with known dimensions for twisted and plaited rope, and yarns for braided ropes, and fibers for nolaro rope. The second step then will be to establish the geometry of the strand in the rope, which is the rope geometry. The second step is obsolete for the nolaro rope.

At this time the mechanics of the twisted rope has been put together and proofed by tests[2], and more recently a similar study on plaited rope was done by Milo[3], which still needs broader proof. Braided rope mechanics have not yet been worked out. Nolaro rope mechanics would be oversimple, since its structure is just a bundle of parallel fibers. Without going into much detail some of the mechanics of the twisted rope will be given in the following sections. The geometry of the twisted rope is described first.

3.2.2 Geometry of the Twisted Rope

3.2.2.1 Geometry of the Rope Strand

The rope strand is constructed from multi-plies arranged in annular patterns around the strand axis. It's construction is the same for strands of twisted, plaited ropes, and braided ropes except that braided rope strands are composed of yarns, not of multi-plies.

A rope strand is a textile structure. It is a smooth "macroyarn" with zero migration[4] where the fibers are replaced by multiplies. The strand is formed by twisting a given number of multi-plies of known, usually equal, dimensions and properties around one another. The multi-plies are arranged against their own twist direction in concentric layers around the strand axis. The strand twist helix length is constant. So the strand is a system of multi-plies, arranged in coaxial helixes of equal helix length but different radial distance from the strand axis.

Therefore, the angle of inclination of the multi-plies, with respect to the strand axis, decreases the closer the plies are located to the strand axis. In the strand center the angle of inclination is zero. The angle of inclination, β_{io} = helix angle of the multi-plies of the layer i in the strand in the unstretched condition is:

$$\tan\beta_{io} = 2\pi r_{io}/h_{so} \quad \text{..........} \quad (3\text{-}1)$$

where r_{io} is the distance multi-ply axis - strand axis and h_{so} the helix length of the multi-plies along the strand axis, both for the unstretched condition, indicated by the subsctipt $_o$. For the stretched condition no subscript is used. A schematic view of the rope strand is shown in Figure (3-2)

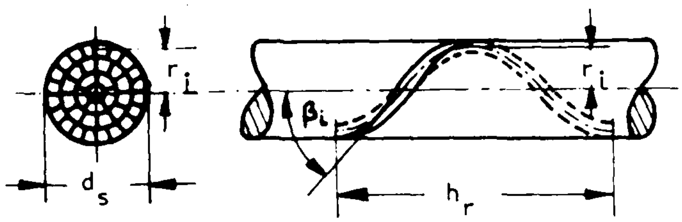


Figure (3-2) Schematic view of a rope strand

To avoid overtwisted or too loosely twisted strands, the strand helix length for the flexible textile multi-plies should be within 4.2 to 7.4 times the diameter of the strand. The stiffer the material becomes, the looser the strand can be twisted without having a sloppy, saggy structure. The multi-plies form layers of annualar cross sections around the circular center. Each layer has about eight plies more than the next inner one, so that the outer layer always completely includes and covers the next inner layer.

The number of multi-plies for a given strand diameter is known or can be approximately calculated. The arrangement is known and therefore the distance r_i of the multi-ply layers in the strand cross section. The geometry of the rope strand is defined.[5]
With a first approximation of the distance of the different layer centers from the strand axis, the preliminary helix angles β_i are computed, along with the area, which the multi-plies need in the strand cross section. With the known area of the annular layers, more precise distances of the multi-ply layers from the strand axis

can be calculated. With these more precise radii, the improved helix angles of the multi-ply layers in the strand are finally obtained for use in the further calculation.

After forming the rope, the strand looses twist due to the formation of a helix in the strand axis opposite to its own twist direction. At the same time the strand gains twist due to the so called foreturn, which is applied to the strand at the moment the rope is formed to maintain the firmness of the strand structure. Without foreturn the strand would form soft, sloppy structures in the rope. With afterturn the strands stay firm, springy and maintain surface hardness and torsional balance in the rope[6]. Due to this change of twist the helix length of the multi-plies in the strand usually decreases and causes the center multi-plies to form small buckles due to the shortening of the strand helix length. For a foreturn ratio of μ the angle β_{io} changes to β_{ir_o} as

$$\tan\beta_{ir_o} = \tan\beta_{io} \; [\; 1 + h_{so} \cos\alpha_o (\mu - \cos\alpha_o)/h_{ro}] \; . \; . \; . (3\text{-}2)$$ [7]

where β_{ir_o} is the multi-ply helix angle of layer i after having formed the rope, h_{ro} is the rope helix length and α_o the rope helix angle. All values are for the unstretched condition. With foreturns over abt. 0.8 $\beta_{io} < \beta_{ir_o}$. The buckling of the center multi-plies due to the shortening of the helix axis for a foreturn ratio of 1 : 1 is:

$$b_{co} = [\; 1 - \frac{\cos\beta_{or_o} \quad \cos\beta_{co}}{\cos\beta_{o_o} \quad \cos\beta_{cr_o}} \;] \times 100 \; . \; . \; . \; . \; . \; . \; . \; . \; (3\text{-}3)$$ [8]

where b_{co} is the buckling of the center multi-plies in percent, β_{o_o}, β_{or_o} the helix angle of the outer layer of multi-plies with respect to the strand axis before and after forming the rope and β_{c_o}, β_{cr_o} the corresponding helix angle for the center multi-ply layer. β_{co} and β_{cr_o} may be zero, if the center layer is just a parallel multi-ply. The buckling can be 5 % or more, the degree of buckling has to be known, since at the beginning of the rope stretch the center multi-plies will first not contribute to the stress response of the strand for they will stretch by unfolding.

The geometry of the strand before and after forming the rope is thus known.

3.2.2.2. <u>Geometry of the Twisted Rope Itself</u>

The twisted rope is constructed of three strands of equal, circular, cross sectional area. The strand axes describe helixes around the rope axis with equal distance a from the rope axis. In the rope cross section - shown in Figure (3-3) - the strands form ellipses with a small axis equal to strand radius r_s and a large axis equal to $r_s/\cos\alpha$.

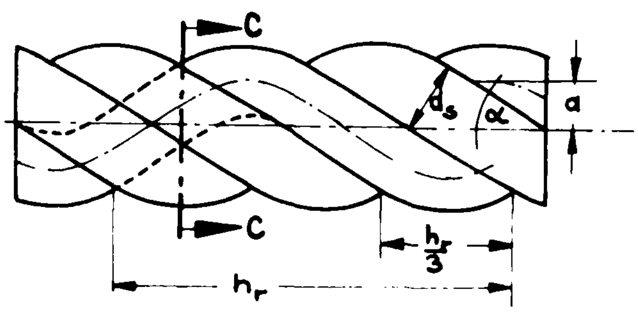
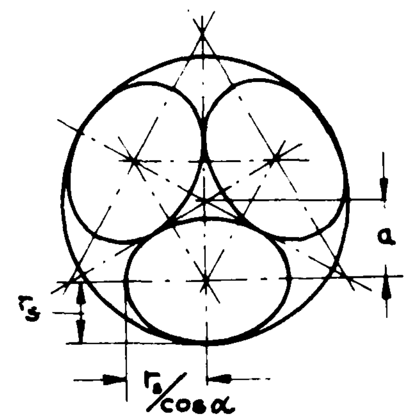


Figure (3-3) Geometry of the twisted rope.



cross-section C-C, enlarged

So the equation for the elliptical cross section of the strand in the rope is:

$$x^2 \cos^2\alpha + y^2 = r_s^2 \quad . . . . (3\text{-}4)$$

The radius of the strand axis helix a is computed in Equation (3-5) with the help of the tangent equation of an ellipse under 30° tangent angle due to the arrangement of three ellipses around the rope center.

$$a = r_s \left(\frac{1}{3 \cos^2\alpha} + 1 \right)^{1/2} \quad . . . (3\text{-}5)$$

The helix angle of the strand axis versus rope axis is

$$\tan\alpha = 2\pi\, a/h_r \quad . . . . (3\text{-}6)$$

which in combination with Equation (3-5) leads to

$$\sin\alpha = 4\pi\, r_s\, [\, 3(4\pi^2\, r_s^2 + h_r^2)]^{-1/2} \quad . (3\text{-}7)$$

It is convenient to express the helix length of a rope as a multiple of the strand diameter $d_s = 2\, r_s$. With $h_r = m\, d_s$ Equation (3-7) becomes

$$\sin\alpha = 2\pi\, [\, 3\, (\pi^2 + m^2\,)]^{-1/2} \quad . . . . \quad (3\text{-}8)$$

Equation (3-8) is illustrated in Figure (3-4). Himmelfarb[9] gives the relation the relation between rope helix length h_r and helix angle α as

$$\sin\alpha = 3\, d_s/h_r = 3/m \quad . . . . \quad (3\text{-}9)$$

This equation only shows the length of the projection of the strand along the rope axis without considering the distance a in relation to the helix angle α. But it will be equivalent to the more correct Equation (3-8) when the maximum helix angle is reached. Then the projection of the three strands along the rope axis is equal to the

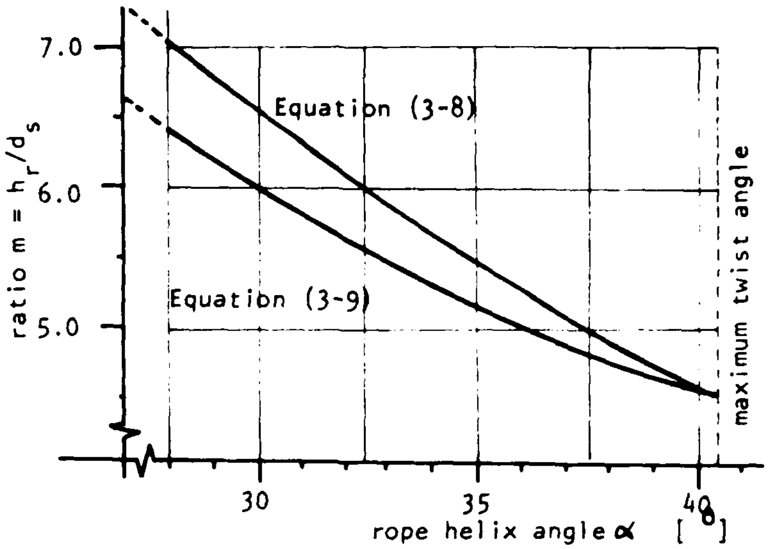


Figure (3-4) Rope helix angle for different ratios $m = h_r/d_s$

helix length. Then h_r in Equation (3-9) is equal to h_r in Equation (3-7). With Equation (3-9) = Equation (3-7) and substitution of a out of Equation (3-5) we get for α_{max}:

$$\cos\alpha_{max} = \left(9/\pi^2 - 1/3\right)^{1/2} \quad \text{or} \quad \alpha_{max} \approx 40.5° \quad \ldots \quad (3\text{-}10)$$ [10]

This would be the maximum angle at which a three strand rope could be formed without distortion of the rope strands. The distortion and thus an even tighter angle could be possible at very long helix length of the multi-plies in the strand and a low foreturn, which would lead to loosely packed sloppy rope strands. The minimum rope lay angle for regular strand materials is around 28°. Less flexible strand structures would allow for smaller helix angles and still maintain a compact rope structure. Wire rope strands will resist any tight laying in the rope due to their bending stiffness. Preferable, six wire strands are arranged around an equal sized center to avoid sharp bending of the strands in the rope.

3.2.2.3 Bending and Torsional Deformation in the Twisted Rope Structure

Due to the helical arrangement of the multi-plies in the strand and the strands in the rope, considerable bending elongation is induced in the multi-plies arranged in the strand and in the strands themselves twisted together to form the rope. The bending strains increase with larger helix angles and with decreasing number of multi-plies in the outer layer of the strand. The bending elongations in a wire rope strand have been determined by Shitkow and Pospechow.[11] The elongations depend on the twist angle and number of wires per strand layer, corresponding to the multi-ply layers in a twisted fiber rope. The formula used to obtain the bending elongation of the outer wires is:

$$\mathcal{E}_b = \sin^2\beta_o \left[1 + (\tan\gamma/\cos\beta_o)^2\right]^{-1/2} \times 100 \;......(3\text{-}11)$$

Where β_o is the helix angle of the outer wire or multi-ply, $\mathcal{E}_b$ is the bending extension in percent of the outer fiber of the outer layer and $\gamma = 90° - 180°/n_o$, where n_o is the number of wires or multi-plies forming the annular cross section in the strand. With Equation (3-11) the bending elongations have been computed. Their dependancy on fiber rope helix angles and number of wires or multi-plies is given in Figure (3-5).

The actual bending elongation in the multi-plies is difficult to define, since more multi-plies than wires can be pressed into

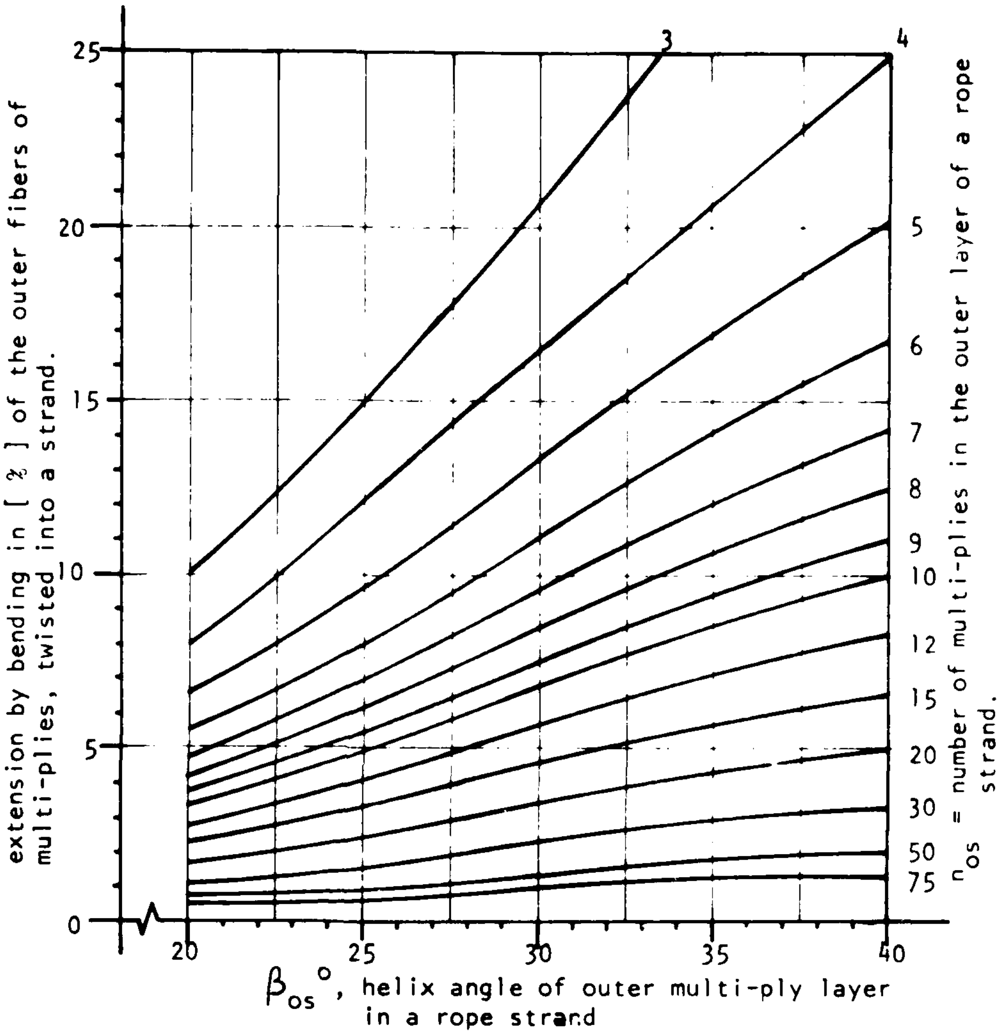


Figure (3-5) Extension of the outer fibers of the multi-plies by bending due to arranging them in the outer layer of a strand depending on the number of plies in the outer layer and the twist angle. (Equation 3-11)

one layer due to their deformation into wedge shaped ribbons. The multi-plies will try to avoid the maximum bending elongation at the outside by packing themselves closer toward the strand center, thus automatically making the cross section more compact. The neutral flexure axis, which is tacitly assumed to be in the center of gravity of the multi-plies, may not be positioned there in reality. The yarns are positioned as helixes around the multi-ply axis, therefore, they will probably stretch only about 1/3 of the theoretical value of Figure (3-5). Finally the filaments travel as helixes around the yarn axes in the multi-plies and will come into the position of the outer fiber with the maximum bending elongation even less often.

So the fiber bending elongation will be only a small fraction of the values of Figure (3-5), although additional bending elongations are caused by the arrangement of the filaments in the yarns and the yarns in the multi-ply. Depending on the inter-fiber friction some of the bending elongation will be compensated by reduction of the bending compression zone. So neglect of the fiber bending deformation in the rope in the theoretical procedure seems allowable, at least with fibers having fairly high elongation at break. Kilby[12] calculated, that for fibers with breaking extensions smaller than 8% and for larger filament diameters, bending elongation in yarns can become important. Except glass fiber, all cordage fibers have breaking extensions over 10% and do not show permanent bending deformations after being manufactured into strands.

In forming a rope, the strands undergo large bending elongations and compressions due to gyration in the fairly tight rope helix. This elongation and compression can be determined out of Figure (3-5) for $n_o = 3$. For some angles α_o these elongations are listed in Table (3-1). The table shows that the strand structure has to show considerable flexibility in order to allow for these deformations. This flexibility is made possible to some degree by the different packing density of the multi-plies in the strand structure and by

α°	22	24	26	28	30	32	34	36	38	40
ε_{ob}[%]	11.9	14.0	16.2	18.4	20.8	23.2	25.7	28.1	30.6	33.0

Table (3-1) Additional bending extensions ε_{ob} of the strand at the rope surface for different rope helix angles α in a three strand rope

stretch and compression of the multi-plies themselves. In the twisted rope construction - similar to cross lay in wire rope - the rope fibers and multi-plies are nearly parallel to the rope axis at the rope surface and at right angles to it near the rope center. The angle of inclination with respect to the strand axis remains unchanged. The multi-plies near the rope center are in the compressed zone and have to increase their packing density in this area to cope with the strand compression. In the surface zone of the rope, the strand gets the large amount of bending stretch due to its bent configuration. The bending can be overcome by looser packing of the plies, but to some extent seems to stretch the multi-plies made of coarse polypropylene monofilaments from a twisted rope. The plies showed permanent bending at those areas, where they had been located at the rope surface. Multi-plies of finer textile multifilaments did not show this permanent stretch.[13] Since the multi-plies in the rope travel continuously between compressed and stretched conditions and probably compensate for some of the different stretch conditions, it is assumed here that the resulting influence of the bending elongations and compressions can be neglected in this calculation.

The diameter of the filaments is very important with regard to their bending stiffness. The bending stiffness is defined as E x I, where E is the Young's modulus of the fiber and I the moment of inertia of the cross section. I grows with the fourth power of the diameter of cylindrical structure. If a given solid cross section of known bending stiffness is replaced by an equally sized cross section with n fibers, the total bending stiffness would be only 1/n of the value of the solid cross section. This is important since by going to smaller and smaller diameters even metallic fibers can be extruded despite their high Young's modulus.

The bending stresses induced in wires when forming wire ropes are larger than the tensile stresses caused by regular rope use.[14] This is due to the considerable higher bending stiffness of rope wires.

The influence of the torsion in changing fiber properties, after being manufactured into fiber ropes, is of small importance since the twist changes of the multi-plies, particularly at larger strands diameters, is very small. It is also reported for textile yarns, that torsion and bending have small influences only.[12, 15, 16]

3.3 THEORY OF ROPE EXTENSION

This second section of the theoretical rope mechanics shall enable us to obtain the elongation of the rope components under a known axial rope stretch. This is done by computing the change of the rope geometry using probable deformation assumptions. It is assumed that the basic rope geometry will not change and flatten, when extended and that the deformation will "stretch" the geometry by maintaining a constant volume of the rope elements. This constant volume assumption for large deformations, like in fiber ropes, is presently the best assumption.[17] It is the deformation law which an ideally elastic body would follow.*

It is convenient to compute the deformation in steps, determining in the first step the stretch of the strands in the rope and, in the second step, the stretch of the multi-plies in the strand. This technique assumes that we know the load elongation properties of the multi-plies. These calculations are done in the following two sections for twisted ropes.

3.3.1 Theoretical Extension of the Strands in a Stretched Twisted Rope

Equation (3-8) described the helix angle of the strand axis in the rope. With subscript o for the zero stretch condition Equation (3-8) can be rewritten as:

$$\sin^2\alpha = \sin^2\alpha_o \ (\pi^2 + m_o^2)/(\pi^2 + m^2) \quad \ldots . \quad (3\text{-}12)$$

*For smaller deformations up to 10%, a constant Poisson ratio of .5 could be taken to describe the ratio of diameter reduction to axial strain, even at 30% extension the error would be only 3%.

Following Treloar [18] we introduce:

$$\lambda_r = \frac{\text{length of the stretched rope}}{\text{length of the unstretched rope}} = \frac{l_r}{l_{r_o}} = \frac{h_r}{h_{r_o}}$$

$$\lambda_s = \frac{\text{length of the stretched strand}}{\text{length of the unstretched strand}} = \frac{l_s}{l_{s_o}} = \frac{h_s}{h_{s_o}}$$

The constant volume assumption will give for the strands:

$$h_s \, d_s^{\,2} = h_{s_o} \, d_{s_o}^{\,2} \quad \text{or} \quad d_s = d_{s_o} \, \lambda_s^{-1/2} \quad . \; . \; . \; . \; . \; (3\text{-}13)$$

Relations between elongated strand and rope axes shows Figure (3-6). It is $l_{s_o} = l/\cos\alpha_o$, $l_s = \lambda_r/\cos\alpha$ or as Equation (3-14): $\sin^2\alpha = 1 - \lambda_r^2 \cos^2\alpha_o/\lambda_s^2$,

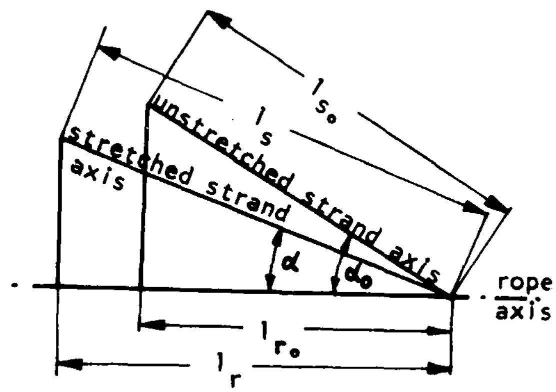


Figure (3-6) Strand and rope axis stretch

Combining the three previous equations will give for $\lambda_s = f(\lambda_r, \alpha_o)$ Equation (3-15) as

$$\lambda_s^3 - \lambda_s^2 \frac{\sin^2\alpha_o}{\lambda_r^2 \, (1 + 3\cos^2\alpha_o)} - \lambda_s \lambda_r^2 \cos^2\alpha_o - \frac{3\sin^2\alpha_o \cos^2\alpha_o}{1 + 3\cos^2\alpha_o} = 0$$

This equation is easier to solve as $\lambda_r = f(\lambda_s, \alpha_o)$ as Equation (3-16):

$$\lambda_r = +\sqrt{\frac{\lambda_s^2}{2\cos^2\alpha_o} - \frac{1.5\sin^2\alpha_o}{\lambda_s(1 + 3\cos^2\alpha_o)} + \sqrt{A^2 + B^2 - A \cdot B/0.3}}$$

where $A = \lambda_s^2/(2\cos^2\alpha_o)$ and $B = 1.5\sin^2\alpha_o/[\lambda_s(1 + 3\cos^2\alpha_o)]$

Equation (3-16) determines the rope extension for any usual rope lay angle α_o and any strand extension $\varepsilon_s = (\lambda_s - 1) \times 100$, its results are given in Figure (3-7).

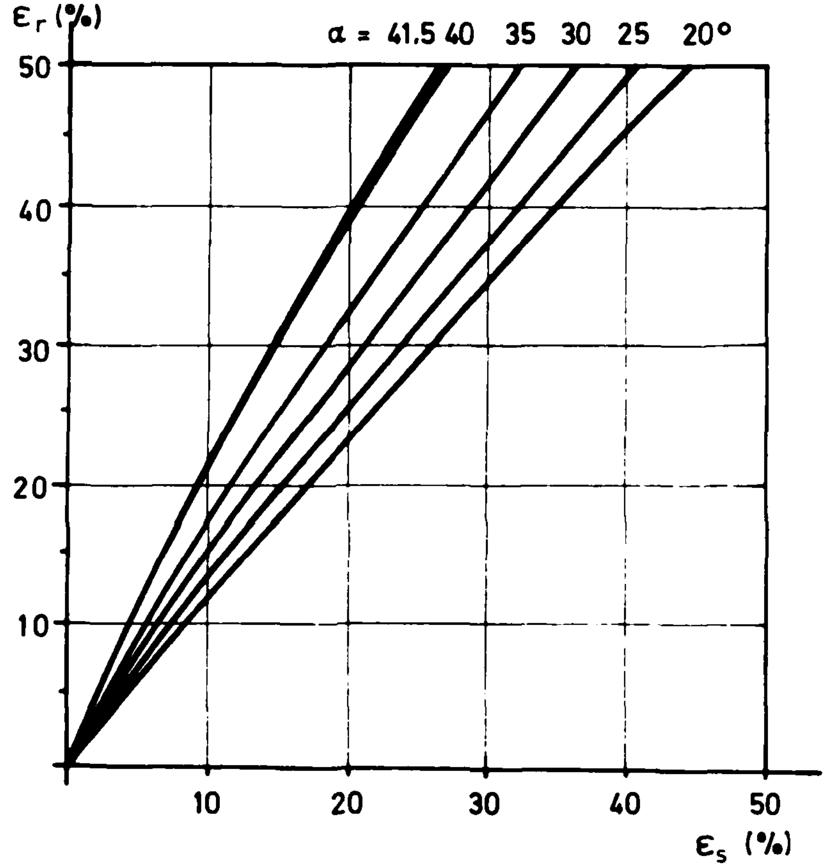


Figure (3-7) Theoretical extension of the strands in a stretched twisted rope.

It is seen, that with increasing rope helix angles α_o the strand extension is considerably smaller than the rope extension.

3.3.2. Theoretical Extension of the Multi-Plies in a Stretched Strand

Analogus to the previous chapter, the extension of multi-plies or multi-ply layers under a known strand elongation will be derived here. Theoretically a stretched strand reacts like a stretched macro-yarn made of continuous filaments with no migration. Therefore it can be covered by the yarn equations of Treloar and Riding[19]. With Equation (3-1) and the introduction of

$$\lambda_m = \frac{\text{length of stretched multi-ply}}{\text{length of unstretched multi-ply}} = \frac{l_m}{l_{m_o}} = \frac{h_m}{h_{m_o}}$$

it can be written, analogus to Figure (3-6), $\lambda_m = \lambda_s \cos\beta_{ir_o} / \cos\beta_{ir}$ (3-16A)

and
$$\lambda_m = (\lambda_s^2 \cos^2\beta_{ir_o} + \sin^2\beta_{ir_o} / \lambda_s)^{1/2} \quad \ldots\ldots (3\text{-}17)$$

Equation (3-9) gives the relationship between the extension of the multi-plies λ_m and the strand λ_s, depending on the helix angle of the multi-plies in the strand β_{ir_o} after having formed the rope. Results of Equation (3-17) are shown in Figure (3-8).

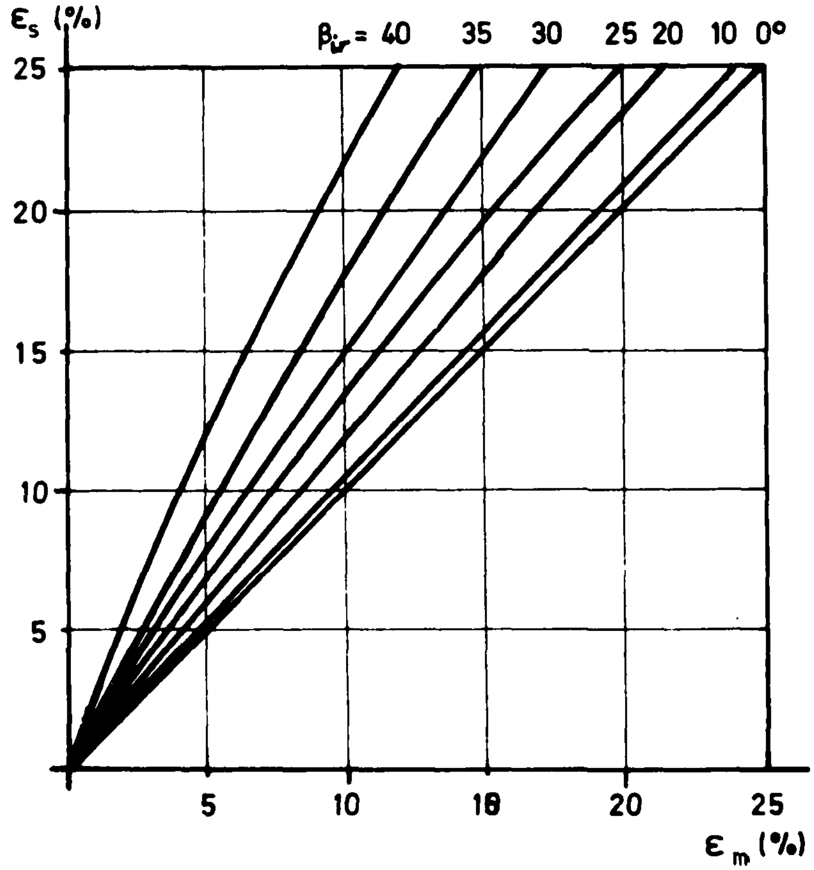


Figure (3-8) Strand extension ε_s, multi-ply extension ε_m, and multi-ply helix angle β_{ir_o} according to Equation (3-17)

Combining Equation (3-17)with Equation (3-2) to relate the multi-ply elongation to the original helix angle β_{io} before forming the rope will lead to Equation (3-18)

$$\lambda_m = \left(\frac{\lambda_s^3 - 1}{\lambda_s [1 + \tan^2 \beta_{io} (1 + h_{so} \cos \alpha_o (\mu - \cos \alpha_o) / h_{ro})^2]} + \frac{1}{\lambda_s} \right)^{1/2}$$

In this equation strand and rope construction is included. The buckling b_{co} of the multi-plies located in the center of the strand [Equation (3-3)] has to be subtracted. The actual extension of the center multi-plies will be $\mathcal{E}_{mc} = (\lambda_{mc} - 1 - b_{co}) \times 100$ in [%] or $\lambda_m - b_{co}$ in Equation (3-18). For $b_{co} > \lambda_{mc} - 1$ there will be no extension, just unfolding of the center multi-plies. λ_m has to be computed for each layer of multi-plies in the strand. For parallel center multi-plies with $\beta_{io} = \beta_{ir_o} = 0$, the value for λ_m is equal to λ_s. For all other angles, the multi-ply elongation is smaller than the strand axis stretch. So a strand is an unevenly strained structure in which the center multi-plies will reach their breaking extension first. This fact causes the center yarns of manila-ropes to break into stort peaces at ab.. 80 to 99 % of the final rope breaking extension. This is not observed in synthetic fiber ropes, probably due to yielding. The outer multi-plies get the smallest stretch, but they suffer high bending elongations, and deterioration by surface abrasion and ultraviolet radiation. There seems to be an advantageous stress strain distribution over the strand cross section for rope use. The inclination of the multi-plies in the rope with respect to the rope axis, and thus their elongation response, changes constantly. The inclination of the multi-ply to the strand axis however, stays constant. The actual elongation at distinct points of the multi-ply in the rope is only significant for the bending elongation, since it can be assumed that the different tensile elongations of the multi-ply equalize at each full helix of the multi-ply around the strand axis. Therefore, the seperate computation of strain, and later stress, for strands and multi-plies seems to be an allowable simplification. In the first step the strand stretch at known rope stretch is obtained from Figure (3-7). Then the strand elongation will determine the multi-ply elongation of Figure (3-8) or Equation (3-18) for the corrected multi-ply helix angles of Equation (3-1) via Equation (3-2) and Equation (3-3) for the center multi-plies. We omit here the influence of production tensions.[20] They lead to a recovery of the rope after manufacturing. The recovery can be easily pulled out of the rope at first loadings. The recovery from production tensions is probably responsible for part of the first pronounced stretch of new fiber ropes at low loads. The rope has to be pretensioned to $200D^2$ in tensile tests to eliminate this influence.

It is now possible to determine the extensions of the rope components, strand and multi-ply, at any given rope stretch of the twisted rope.

3.4 RESPONSE OF THE MULTI-PLIES TO THE ROPE EXTENSION

The load-elongation behaviour of the standard multi-plies built of fibers suitable for use in cordage, are assumed to be known, since they are standard production units manufactured in large quantities by the cordage companies. The multi-plies used have a diameter range of .08 - .15", their construction differes with the material used and its fineness. In the previous section the extensions of the multi-plies at known rope stretch were computed. The load elongation curve will now give the load response of the multi-plies to their extension. Decreasing load response per multi-ply is obtained from the multi-ply layers as we go from the strand center to its surface. This calculation does not include transverse forces which are compressing the strand structure due to higher fiber bending of the outer multi-ply helixes. The transverse forces would reduce the tensile forces on the multi-plies.

In particular for larger strands it is desireable to have small elongation (load) differences in the multi-plies of the strands. This could be obtained with loose twisting of the strand itself or by a high degree of buckling of the center multi-plies by high foreturn, and of course also by choosing multi-plies of different materials. The strand twist can't go below a minimum value, since the strand looses its compactness and torsional resistance. The shape of the load-elongation curve of the chosen multi-ply is most important for the load difference of the multi-ly layers in the strand. Multi-plies with high Young's modulus will show higher load differences. See Figure (3-11). Also the degree of anisotropy of the fiber material, in particular its relative transverse strength will influence the strength efficiency of the multi-plies in strand and rope.

3.5 DETERMINATION OF TENSILE FORCES AND MOMENTS IN STRAND AND ROPE

The position of the multi-plies in the strand and rope is known, but for yarns the position of the fibers can only be estimated. The load reaction of the multi-plies to extension in the rope was obtained here directly without the "detour" of the energy method of Treloar and Riding.[21] The direct method gives information on the internal load distribution over the strand cross section, but yields higher, less precise loads at given extension since traverse forces are neglected.

The direct load method uses two steps to get the rope load response to extension. First <u>the strand reaction</u>:

A multi-ply in the layer i of a strand inclined at an angle β_{ir} with respect to the stretched strand axis generates, under the load F_m along the strand axis, the load $F_m \cos\beta_{ir}$. In each of the i multi-ply layers arranged in the strand cross section are a known number of multi-plies n_i. The total force generated along the stretched strand axis F_s is then:

$$F_s = \sum (n_i \; F_{mi} \cos\beta_{ir}) \quad \ldots\ldots\ldots \quad (3\text{-}19)$$

where $$\cos\beta_{ir} = \lambda_s \cos\beta_{ir_o} / \lambda_m \quad \ldots\ldots\ldots\ldots \quad (3\text{-}16A)$$

The buckling of the center multi-plies has to be subtracted form their elongation and the load F_{mc} is accordingly lower. The radial components of the multi-ply loads are $P_{mi} \sin\beta_{ir}$, they build up a strand moment M_s of:

$$M_s = \sum (n_i \; P_{mi} \sin\beta_{ir} \; r_{mi}) \quad \ldots\ldots\ldots \quad (3\text{-}20)$$

where r_{mi} is the distance of the strand axis to the multi-ply axis or center of gravity of an infinite small section of the multi-ply layer. It is: $r_{mi} = r_{mi_o} \lambda_s^{-1/2}$ and $\sin \beta_{ir}$ obtainable from Equation (3-16A). This moment tries to untwist the loaded strand or to diminish the helix angles β_{ir}.

<u>Load reactions of the strands in the rope</u>: In the stretched twisted rope, three strands with the strand force F_s and the moment M_s are inclined at the angle $\alpha < \alpha_o$ with respect to the rope axis. In rope axis direction the strands will generate according to Figure (3-9) the resulting force:

$$F_r = 3\ F_s \cos\alpha = 3 \cos \alpha_o \frac{\lambda_r}{\lambda_s} \sum (n_i\ F_{mi} \cos \beta_{ir}) \quad . . . . (3\text{-}21)$$

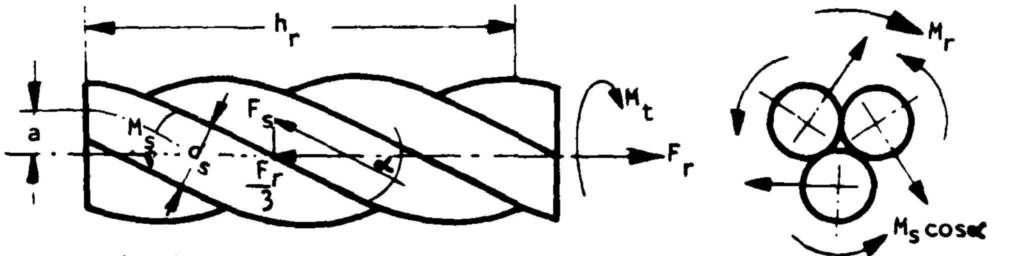


Figure (3-9) Forces and Moments in a twisted rope.

The strand moments, M_s, react in the rope inclined at α as $3\ M_s \cos\alpha$. Since twist directions of rope and strand are opposite, the moment M_s acts to untwist the strands and twist the rope together. At the same time the three strand loads, F_s, generate a moment M_r in the rope cross section. This rope moment M_r acts opposite to the strand moment M_s. It tries to twist strands together and to untwist the rope. The total moment M_t in the rope, which should be zero if possible, is

$$M_t = M_r - 3\ M_s \cos\alpha = 3\ (\ F_s\ a \sin\alpha - M_s \cos\alpha\ ) \quad . . . (3\text{-}22)$$

$\sin\alpha$ is obtained of Equation (3-22) and a of Equation (3-5) as

$$a = r_{so}\left[\frac{1}{\lambda_s}\left(1 + \lambda_s^2/(3\cos^2\alpha_o\,\lambda_r^2\right)\right]^{1/2} \quad . . . (3\text{-}23)$$

Equation (3-19) through (3-23) give, for known rope extensions, the strand and rope loads F_s and F_r and their moments M_s, M_r and M_t as primary response of the twisted rope. Since the rope is prevented from rotation in a tensile testing machine, the tensile machine has to take up the resulting moment M_t and will measure only the tensile load F_r.

The energy method, as mentioned, is now used to obtain resulting forces, or specific stresses, in yarns and multi-plies, as developed by Treloar and Riding.[21,22] It would be used for a twisted rope by transforming the specific stress strain curve of the multi-ply, by intergration, into the energy strain function of the multi-ply. Rope geometry and geometry change under rope extension will give the energy per unit volume at each part of the rope cross section. Integration over the cross section gives the total deformation energy of the structure at the given strain. The resulting specific stress along the rope axis is obtained by differentation of the rope deformation energy with respect to the rope strain. The load is obtained by multiplication of the resulting specific stress by the rope weight per unit length.

This energy detour is mathematically more elegant than the direct computation of the specific stresses or loads, since forces are vectors, but energies are scalars. It is more precise, since it includes the calculation transverse forces which mathematically have not been solved for large extensions by the direct tension or stress method.[17]

Up to this time the energy method has not yet been applied to the ropes structural mechanics. Only the direct load or stress method has been tried without consideration of the transverse forces. Comparative stress strain curves obtained from yarns in tensile tests and yarns computed by the energy method show remarkably small differences between both curves.[17]

3.6 THEORETICAL LOAD ELONGATION CURVES OF TWISTED ROPES

If the calculation in the last section is repeated for a sufficient number of rope extension values, the resulting rope loads, F_r, give sufficient values to draw the theoretical load elongation curve of the rope. This rope curve depends on the twist angles of rope and strands and the load elongation properties of the multi-plies used. A calculation was done on a CDC 1604A computer at the Technical University of Hannover/Germany. The program combines the geometrical data of the unstretched rope and the material data for the multi-plies used. It computes, with rope or strand extension as the variable, the load extension reactions of the multi-plies, strands and the rope following the equations given above.[23]

The theoretical breaking strength of the rope may be reached at the moment the first multi-plies in the rope are stretched in excess of their breaking extension. These multi-plies are located in the strand center. Their breakage should start a catastrophic failure of the other multi-plies and thus the whole rope. This breaking assumption can be changed by various material and construction dependant influences. The computed rope loads are higher than the actually measured, since the transverse forces omitted in this calculation, would react as negative forces in Equations (3-19) and (3-21).[24] As comparative rope tests show, the results are strongly material dependent. Tests done with nylon multi-plies by Wilson[25] showed, that a nylon monofilament under compression by the other monofilaments twisted around it can increase its breaking extension over 50% of its "uncompressed" value. The breaking extension of the monofilament yarns increased with increasing twist. The higher anisotropy of polyester filaments seems to yield twisted structures which break before reaching the breaking extension of the fibers. The load elongation properties of multi-plies made of some materials seem to be changed considerably by the strand and rope manufacturing process.[26] The computation considered only the load elongation properties of new multi-plies before manufacturing them into strands and ropes.

These, and probably some other influences, aggravate a simple comparison between computed and experimental load elongation curves. They show that different materials react differently on construction changes and that the theoretical rope breaking strength can not be predicted without material dependent factors. A more precise investigation of these influences would be helpful.

3.7 COMPARISON OF TWISTED ROPES: THEORETICAL AND EXPERIMENTAL LOAD ELONGATION CURVES[27]

3.7.1 Construction and Testing of the Ropes

3.7.1.1 Construction of the Test Ropes Used

The goal was set to find out as much as possible about construction and material influences on the load elongation behaviour in tensile tests of twisted ropes, not their behaviour under typical in use loading or stretching conditions. Therefore, 1" diameter ropes of 5 different materials were manufactured on the same equipment with each 16 different constructions by combination of 4 different strand and 4 different rope twists.

The materials used were high tenacity continuous filament nylon 6, polyester, monofilaments made from polyethylene and two types of polypropylene. From each material, suitable multi-plies were taken as reference for rope tests.

3.7.1.2 Testing of the Ropes

The ropes were broken on a horizontal rope testing machine in the TNO Material Testing Institute in Utrecht (now Ijmuiden), Holland. The ropes were held in the machine unspliced in long conical grips developed for rope testing by Dr. J. Reuter. This testing method gives 10 to 15% higher breaking loads than the testing of spliced ropes. The testing machine moves with constant pulling head speed (nearly constant speed of deformation for the sample) and measures the responding load. Measuring of the elongation at given loads was done manually with a tape about ten times during one test, the breaking elongation was extrapolated from the corresponding load-time graph drawn by the machine.

The multi-plies were tested to obtain their load-elongation behaviour. For each material these multi-plies showed properties with very small variability. Their load elongation curves are given in Figure (3-10).

3.7.2 Theoretical and Experimental Load Elongation Curves of the Ropes

3.7.2.1 Procedure and General Observations

The geometric and material data of a test sample were fed into the computer and the theoretical load elongation curve was obtained and compared with the actual experimental curve of the sample. The computer print gives results at steps of 2% extension of the rope. The extension of the multi-plies in the different strand layers is printed out. It is seen, at what theoretical extension of the multi-plies a theoretical load equal to the rope breaking strength is obtained. It could be seen, if the break of the rope occured before, at, or after the most stretched center multi-plies reached their breaking elongation. Strong material dependent behaviour was found.

Experimental curves nearly always have more stretch, for a given load, than the computed curves. The Young's moduli of both curves are nearly equal after leaving the starting zone of low loads. So both curves run almost parallel after having left the initial loading zone. The distance between both curves grows with decreasing strand twist. It is probable that the less twisted and therefore less compact strand cross sections flatten easily under low loads. This allows a larger initial extension without noticeable load

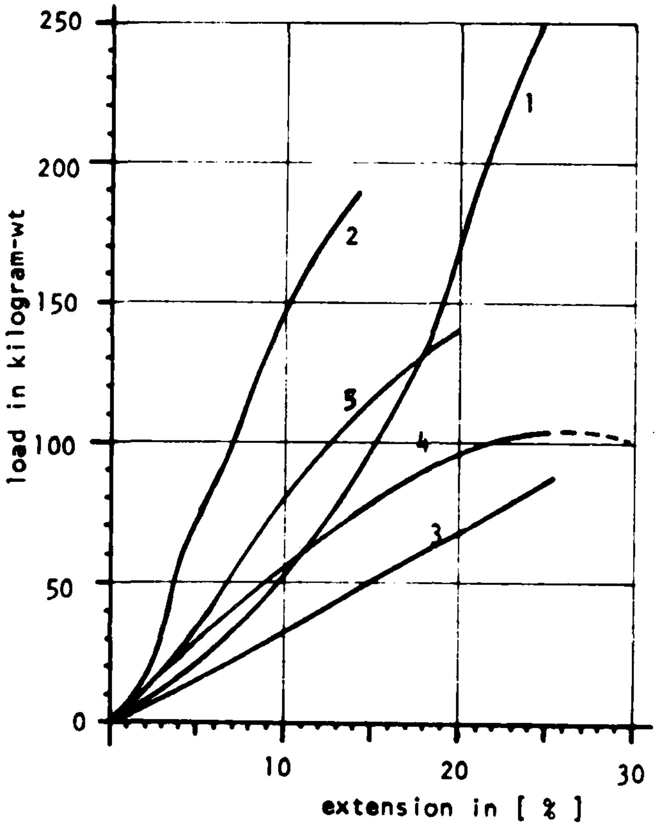


Figure (3-10)
Load-extension curves of various cordage multi-plies.
1) nylon 5-ply
2) polyester 3-ply
3) polyethylene 3-ply
4) polypropylene, unannealed, 3-ply
5) polypropylene, annealed, 3-ply

1) R 4,800 tex
2) R 3,400 tex
3) R 2,600 tex
4) R 2,500 tex
5) R 2,600 tex

(the term tex gives the weight in gram per 1,000 meter)

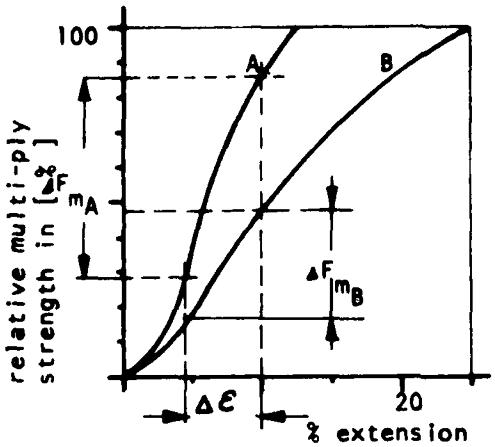
build-up in the rope. The results are again typical for each material, the tendency of the difference between experimental and calculated curves corresponds to the findings of Treloar, Riding and Wilson[18,19,24,25] for textile yarns or multi-plies. As mentioned, 16 different constructions were tested from each rope material. The results of each rope type with the smallest and the largest strand helix length, combined with two different rope helix lengths each, are given in Sections 3.7.2.3 to 3.7.2.8.

3.7.2.2 Data on Test Results and Strength Efficiency of the Rope Tests

The main test results are listed in Table 3-2. It is seen, that all materials show 70 to 85% strength efficiency for the multi-plies in the rope except for the high tenacity, low stretching polyester, which yields 48 to 62% efficiency at break. The coefficient of efficiency for the breaking lengths of the multi-plies in the rope is not listed here, all calculations were done with forces, not with stresses or breaking lengths (=specific stresses). The coefficient ȯr efficiency of the multi-plies based on breaking lengths in strand and rope would be considerably lower since the rope breaking length does not take into account the 1.25 to 1.3 times longer length, and thus weight per unit length of the multi-plies in the rope.[28]

The total strand strength is dependent on the strand twist. The strength decreases with increasing strand twist. But more important is the type and shape of the fiber and multi-ply load elongation curve. As Figure (3-11) shows the load differences in multi-plies caused by stretch differences $\Delta\mathcal{E}$ of a given strand construction are larger for material A with the higher Young's modulus.

Changes in strand twist, which change $\Delta\mathcal{E}$ will therefore influence material B much less than material A. Material A may be compared with polyester, material B with nylon. It is advantageous to have a Young's modulus which is as small as possible *immediately* before break. This is shown for material III in Figure (3-12). These materials will show the smallest strength differences ΔF_m in the multi-plies under $\Delta\mathcal{E}_m$ and thus the largest sum of multi-ply forces in the strand. The rope strength of the twisted rope will be



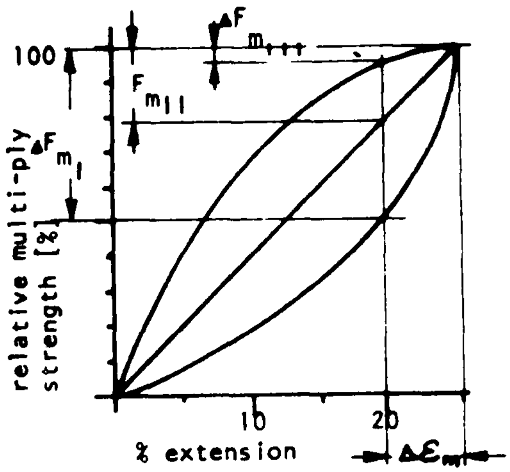


Figure (3-11): Load differences of multi-plies in a strand depending on their load-elongation curves.

Figure (3-12): Load differences of multi-plies at the strand's breaking point depending on their Young's modulus.

influenced only by the resulting strand strength and the rope lay angle α, since three components with equal properties under equal strains or stresses react together in the rope. They are not a large number of unevenly stretched multi-plies. Additional rope twist will reduce the rope strength; cold flow properties of the strands will be also shown by the rope itself.

3.7.2.3. Nylon-6 Rope Curves

Figure (3-13) shows, that the experimental curves have more stretch under equal load, than the computed curves, but about equal inclinations above 8 - 10 % of the rope's breaking load. The distance between both curves is smaller for ropes with large strand twist - Figure (3-13a). The calculated load equal to the measured breaking strength did not appear at the breaking extension of the

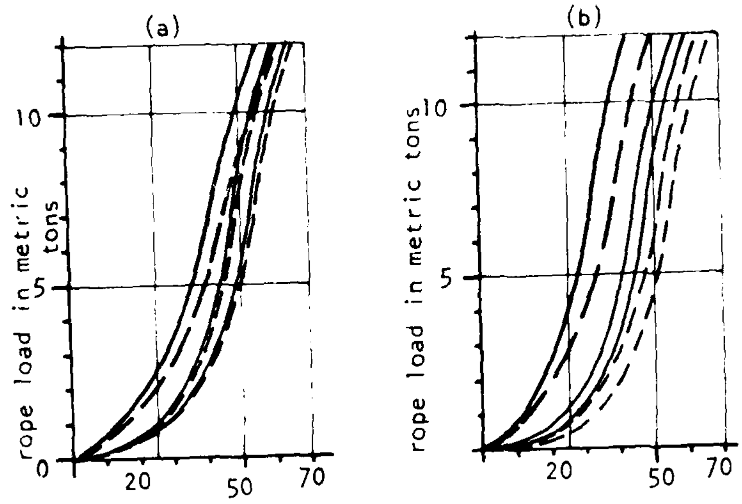
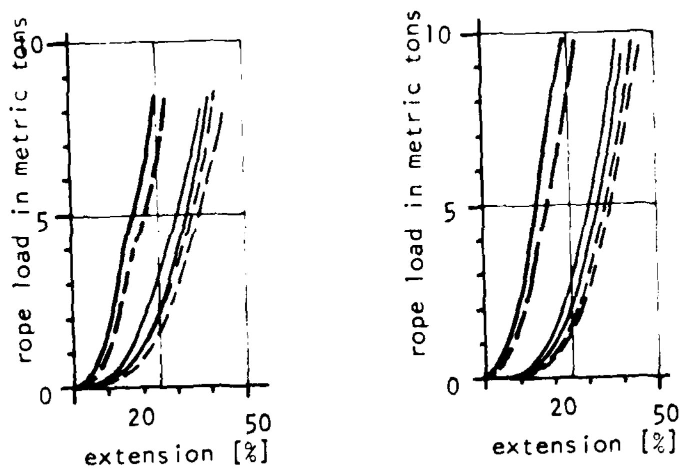


Figure (3-13) ropes from nylon-6; (a) hard twisted strands
(b) loose twisted strands



Figures (3-13) to (3-17)

Comparsion of computed and experimental load-elongation curves of three strand ropes of 1'' diameter.

thin curves: experimental

thick curves: theoretical

full curves: large rope twist

dotted curves: low rope twist

Figure (3-14) ropes from polyester; (a, hard twisted strands
(b) loose twisted strands

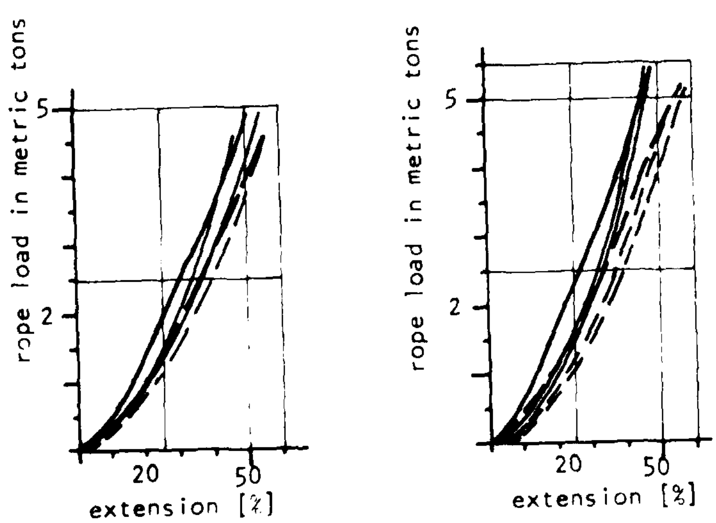


Figure (3-15) ropes from polyethylene; (a) hard twisted strands
(b) loose twisted strands

center multi-plies, but at 93 to 95 % of the breaking extension of the outer multi-ply layer. The center multi-plies are overstretched at the breaking point. The degree of overstretch clearly increases with increasing strand twist. It levels the theoretical strength drop, which assumedly should appear at increasing strand twist and does happen for all other materials tested in ropes. The theoretical overstretch of the center multi-plies at the computed rope load equal to its tested breaking strength is given in Table (3-3). The rope behaviour seems to show the "Wilson-effect"[25] to be valid in twisted ropes of nylon-6 multi-filaments.

ratio strand helix length to strand diameter h_{so}/d_{so}	rope breaks at theoretical extension of center multi-plies of	or the multi-plies exceed their tested breaking extension of 24.5 % by
4.46 (hard strand twist)	abt. 32.5 %	32 %
4.88	" 31.0 %	27 %
5.34	" 29.5 %	20 %
6.00 (loose strand twist)	" 28.0 %	17 %

Table (3-3) Change of the calculated "overstretch" of the center multi-plies in a rope at the tested rope breaking strength depending on the amount of strand twist.

3.7.2.4 Polyester Ropes

The high tenacity, low shrinking and stretching polyester used in multi-plies reacts very sensitively to changes in the strand twist, as reflected in the calculation. Within the same change of strand twist, the rope breaking load increased 30 % for polyester ropes and only 8 % for the nylon ropes.

The strength of the polyester ropes seems to be only influenced by the strand twist.

Figure (3-14) shows, that the experimental curves have considerably more stretch than the computed curves under equal loads. This discrepancy is also observed in the comparsion of yarns of the same material by Riding and Wilson [29].

The computed load equal to the actual rope's breaking load, for all constructions, appears below the breaking extension of the center multi-plies (only 65-74% of their actual breaking extension.) This early failure of the center multi-plies and the rope itself is explained by the high anisotropy or low transverse strength of these fibers. (The relative knot strength of the polyester multi-plies is about 40%, while all other materials used here give 50 to 65% efficiency). A slightly higher stretching but otherwise identical polyester from the same manufacturer increases the rope strength around 10 to 15%. This shows the large influence of a slightly higher breaking extension or less pronounced anisotropy of the fibers used.

3.7.2.5 Polyethylene Ropes

Like the polypropylene ropes the polyethylene samples were manufactured out of monofilaments of about 12 mil = (.3mm) diameter. The monofilament ropes are much stiffer for the same construction. (See Section 3.2.2.3). Strand and rope twist also influence the rope strength. Within the twist limits of the test samples, the strength increases by about 22% for decreasing rope and strand twists. The computed load extension curves are nearly identical to the experimental ones as seen in Figure (3-15). The experimental minimum breaking strength corresponds to a computed load at which the center multi-plies have reached about 97% of their breaking extension. Good agreement between computed and experimental curves is probably caused by the plastic deformation of the polyethylene rope under manufacturing tensions from which the rope does not recover. The large initial elongation of nylon and polyester ropes under light load is not found in the polyethylene ropes. Pronounced cold flow under sustained loads is a severe drawback for the use of these ropes.

3.7.2.6 Ropes from Unannealed Polypropylene

Ropes which were manufactured out of polypropylene monofilaments, showed a pronounced yield point and cold flow shortly before reaching the breaking extension. Due to the strong yielding the knot strength and the breaking extension of the multi-plies is fairly high. The use of this type of polypropylene in ropes may be as dangerous as the use of polyethylene, though the pronounced cold flow will start at higher load levels. This material is no longer produced unannealed. The improved performance of annealed polypropylene in ropes is shown in the next Section. This material shows interesting results in ropes. As in polyethylene ropes, reduction of strand and rope twist will increase the rope strength, but the breaking strength of samples with small strand twist stays under expected values. Most multi-plies in the strand have passed their yield point and start to deform permanently before the rope breaks. This plastic

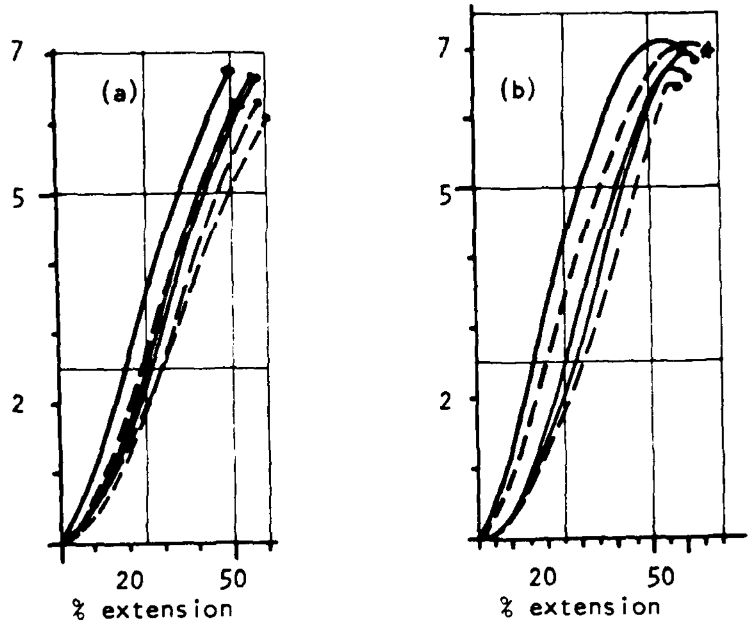


Figure (3-16) ropes from unannealed polypropylene
(a) ropes with hard twist; (b) with loose twist

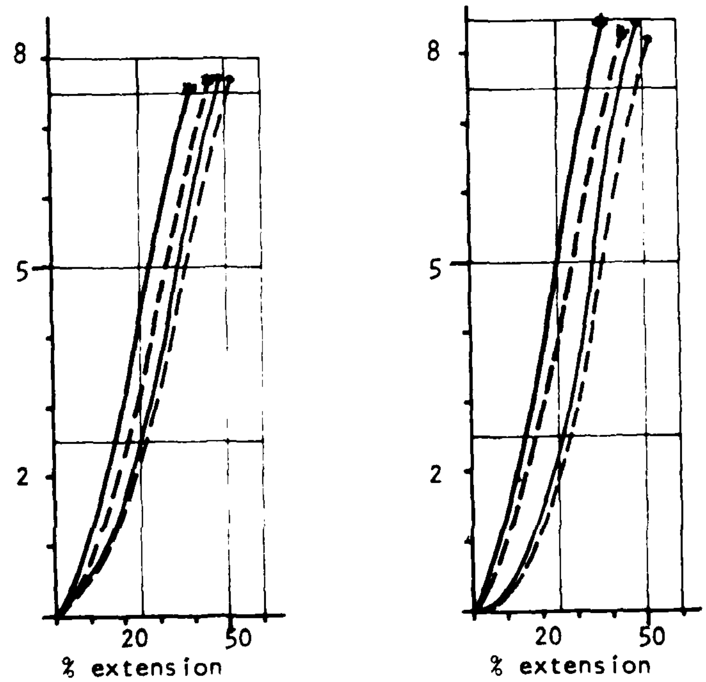


Figure (3-17) ropes from annealed polypropylene
(a) ropes with hard strand twist; (b) with loose twist

Figures (3-13) to (3-17): Comparsion of computed and experimental load elongation curves of three strand twisted rope of 1" diameter. Thin curves: experimental; thick curves: theoretical; full lines: large rope twist; dotted lines: low rope twist.

deformation is also carried on in the rope which, after reaching the maximum strength value, continues to stretch with declining load and deforms permanently, until the breaking stress of the fibers is exceeded and the rope breaks. This yield buckle disappears completely with higher strand twist, since the center multi-plies and thus the rope will break before the outer multi-plies have reached the yield zone, thus causing the yielding of the rope.

The computed curves for ropes with low strand twist also show a maximum load and then a decreasing load when extensions exceed the rope's yield point. The computed highest strength value is higher than the experimental one - 7060 to 7140 kilogram-weight, compared to 6350 to 6900 kilogram-weight. The rope strength can not be increased by further reducing the strand helix length, only the breaking extension is increased due to more pronounced cold flow. Therefore, the calculated load equal to the breaking strength of ropes with pronounced cold flow is reached at lower computed extensions for the center multi-plies, see Figure (3-16b) than for samples with higher strand twist therefore exhibiting little or no cold flow in Figure (3-16a).

3.7.2.7 Ropes from Annealed Polypropylene

This material does not show the cold flow or yield buckle in regular rope tensile tests. Similar material is now widely used to manufacture polypropylene cordage. Decreasing helix length of rope increases the breaking load without showing the yield buckle shortly before rope breakage. The comparative curves show similar Young's moduli above the initial extension. The distance between both curves is again smaller at increased strand twist, see Figure (3-17).

At an extension of 18.5% of the center multi-plies (over 95% of their breaking stretch) the computed rope load is equal to the minimum actual rope breaking strength. The ropes are, comparing their breaking length, about 15% stronger than the same samples made from the unannealed material.

3.8 CONCLUSION ON SECTION 3

The procedure described in Section 3-1 through 3-6 may be called a deformation mechanics to obtain load-extension curves of ropes, particularly twisted ropes.

The following comparison of the theoretical curves with actual rope test curves of the same construction, Section 3-7, shows that the agreement between theory and test depends to an important degree on the particular material used in the rope. The material behaviour is only incorporated in the claculation as the load elongation curve of the multi-ply, obtained before manufacturing the multi-ply into strands and ropes. Additional material parameters expressing ratio of axial to transverse strength, change of properties due to the manufacturing process, compactability depending on the number of multi-plies per strand or rope cross section, and fiber fineness, should be set up to improve the reliability of the theoretical method. With this additional knowledge of the typical material properties of the fibers used, a theoretical prediction of a rope's breaking strength and stretch can be done with more precision for all materials. The experimental additional work needed to determine the typical material parameters should be much less than experimental, time consuming, expensive systematical rope tests, since most of the parameters can be obtained from tests with multi-plies or fibers and their accuracy checked by running a few rope tests. The computation procedure has to be further improved and expanded. Improvement should be obtained by recalculation with the energy method.

The method should be broadened by including other rope constructions such as plaited and braided ropes and by starting with the fibers, not with the multi-plies.

Though the method developed thus far is by no means perfect, it has given much insight into the structure and mechanics of ropes, explaining many previously confusing rope test results.

References Section 3

1) Hearle, J.W.S., Grosberg, P., Backer, S.; "Structural Mechanics of Fibers, Yarns and Fabrics", Vol. 1, Wiley Interscience; New York, London, Sydney, Toronto, 1969, Chapter 4, p. 175.

2) Paul, W.; "Untersuchungen ueber das Kraft-Dehnungsverhalten dreilitziger Seile aus synthetischen Fasern, (Investigations on the Load-Elongation Behaviour of Three Strand Ropes Made from Synthetic Fibers)", Doctor's Thesis, Technical University Hannover, Germany, 1967.

3) Milo, J.G., "A Geometrical Model of Columbian Plaited Rope", U.S. Coast Guard Academy, Dept. of Physical Science, Report in course "Special Topics in Scientific Research", New London, Conn., May 1970.

4) Hearle, J.W.S., Grosberg, P., Backer, S.; "Structural Mechanics of Fibers, Yarns and Fabrics", loc. cit., Chapter 3, p. 101.

5) for details see: Paul, W., Doctor's Thesis, loc. cit., p. 164.

6) Paul, W., Doctor's Thesis, loc. cit., pp. 33-36

7) ibid., p. 36 - 38.

8) ibid., p. 38 - 44.

9) Himmelfarb, D., "The Technology of Cordage Fibres and Rope", London, 1957, p. 120, Equation 2

10) see also Gracie, P.S., "Twist Geometry and Twist Limits in Yarn and Cords", Journal Textile Institute 51, 1960, T 277.

11) Shitkow, D.G., Pospechow, I.T., "Drahtseile (Wire Ropes)", Berlin 1957, p. 194, 203; (This book is a translation from the original Russian edition)

12) Kilby, W.F., "The Mechanical Properties of Twisted Continuous Filament Yarns", Journal Textile Institute, 55, 1964, T 584

13) Paul, W., Doctor's Thesis, loc. cit., p. 43.

14) Bock, E.; "Die Bruchgefahr der Drahtseile, (The Hazard of Wire Rope Failure)", Doctor's Thesis, Technical University Hannover, Germany, 1909, p. 13.

15) Treloar, L.R.G.; Mather Lecture "Twisted Structures", Journal Textile Institute, 54, 1963, P 13

16) Dent, R.W., Hearle, J.W.S.; "The Tensile Properties of Twisted Single Fibers"; Textile Research Journal, 30, 1960, p. 805.

17) Hearle, J.W.S., Grosberg, P., Backer, S., "Structural Mechanics of Fibers, Yarns and Fabrics", loc. cit., Chapter 4, p. 175.

18) Treloar, L.R.G., Mather Lecture, loc. cit., P 21

References Section 3, cont.

19) Treloar, L.R.G., Riding, G.; "A Theory of the Stress-Strain Properties of Continuous Filament Yarns"; Journal Textile Institute, 54, 1963, T 156.

20) Paul, W.; Doctor's Thesis; loc. cit.; p. 52.

21) see Reference 19)

22) Hearle, J.W.S., Grosberg, P., Backer, S., "Structural Mechanics of Fibers, Yarns and Fabrics", loc. cit., p. 203.

23) Paul, W.; Doctor's Thesis; loc. cit.; p. 81

24) Wilson, N.; "The Load-Extension Properties of Continuous Filament Model Yarns"; British Journal Applied Physics; 16; 1965, p. 1889.

25) Wilson, N.; "Breaking Extension of Nylon Filaments under Combined Axial and Transverse Stresses"; Nature 1963; 198, May 4, p. 474;
Wilson, N.; "Breaking Extensions of Nylon Filaments"; Nature 1964; 202, May 30, p. 890.

26) Paul, W.; Doctor's Thesis; loc. cit., p. 75, Figure 26.

27) Paul, W., ibid.; Chapter C., pp.85.

28) Melamed, L.G., Karagodina, L.V.; "(Coefficient of Efficiency of Fiber Strength in Cordage Products"(translated)); Tekstil. Prom. (Moscow) 25, 1965, 10, p. 93.

29) Riding, G., Wilson, N.; "The Stress-Strain Properties of Continuous Filament Yarns"; Journal Textile Institute; 56, 1965, T 205.

SECTION 4

HANDLING AND MEASURING OF ROPES

Much has been written about the proper handling of ropes mainly applying to the conventional shipboard uses of cordage of all types. A good deal of this is dealing with proper stowing and using of various rope types; and with the main knots and splicing techniques, which have been so uniquely developed for ropes. Also for oceanographic buoy mooring techniques and handling some useful material has been published. It is not planned to repeat or summarize this literature here, since much of the literature is of educational or handbook type character and widely used, see Reference (1 to 7). It is tried to add here some usually not given information.

Safety Figures: There is a lot of talk on safety figures for fiber ropes but very little information and test series on which these figures could be based except practical experience. Hardly any information is available on the fatigure properties of ropes and the dependency of fatigue on the type of loading and stretching of the rope itself. But also how in typical rope applications ropes are stretched or loaded, is often not known.

Considering the difficulty in determining workable safety figures for metals, some work should be done to start to clarify this problem for fiber ropes. The different performance of new and used rope, the possible reduction of rope strength by abrasion, too sharp bending, sunlight radiation, overheating, hazardeous chemicals, rust, cutting a.s.o. makes it impossible to use standard figures

for all applications; and to use rope without proper inspection over longer periods of time as relyable "tools". So different loading and stretching conditions will require different safety figures, depending additionally on time and environmental conditions.
Fixed or predictable loading conditions exist in running and fixed rigging, where safety figures have been set up, listed in Table (4-1).

type of fiber	running rigging	fixed rigging
nylon, high tenacity	12	9
polyester, h.-tenacity	12	9
polyolefins, "	8	6
blend (mixture)	8	6
manila	7	5

Table (4-1) Safety factors for ropes used in rigging [8] *

It is possible to compute safety figures for any static loading condition with known loadings and loading times, if more tests similar to Flessner's[10] would be performed. Also figures for rope use in dynamic applications could be set up by running suitable test series. In particular in towing of ships a lot of not yet known energy interaction between tug and towed object is happening. Severe impact loads due to sudden coming tight of the rope by different speed of ships in regular towing operations or by wave

* The much higher safety figures for nylon and polyester ropes have been found necessary from experience, since due to their higher strength theses ropes would become too small on the same job and would be too much weakened by cutting and abrasion, resulting in a too short service life under standard rigging conditions. See[9]

reactions can become dangerous for the mooring rope. Sudden load increases can also be caused by yawing of the towed vessel, since the beam to frictional resistance of a ship can be up to 20 times larger than bow to resistance, which can increase the tension in the rope very pronounced already at small yawing angles.

Harbour moorings in open ports fail, for they don't provide sufficient stretchability, if the ship is surging in seiches. The upper end of a buoy mooring cable seems to fail more often due to insufficient ability to stretch and to absorb shockloads caused by the wave action on the buoy than by static wind and current forces. Ropes under shock load conditions can fail already under loads less than 10% of the rope's static breaking load. Safety figures for ropes can often be given only after checking the entire system in which the rope shall be used. This in particular, since many rope uses are dynamic, not static loading situations. A lot of literature giving the static and dynamic "inputs" into a mooring system can be found,[11, 12, 13, 14, 15] but only little is mentioned about the rope reaction and thus reliability of a mooring system.

Measuring of often long lengths of oceanographic buoy ropes is often a difficult problem. Often rope lengths in taut moorings with hopefully less than 1% error in length shall be used. Since ropes under slight tensions show often stretch of several percent, and change their length in addition often considerably in use, it seems to be impossible with the 'yardstick' method to get rope lengths precise enough for buoy systems.

It is recommended therefore, to determine much more precise rope lengths by weighing the rope. The procedure, which should be made in the rope manufacturing plant, to avoid weight changes due to water absorption may be suggested as follows:

1) The rope-conditioned at 70°F and 65% relative humidity- is put under a pretension of $200D^2$ in lbs. A suitable length (3-10ft) is marked.

2) On a tensile rope tester several feet of the rope are stressed by loads and strains similar to the predicted use. A rope to be used at the bottom end of the mooring is put under a constant load equal to the anticipated current drag and other tension in the line. A rope at the upper end of a mooring is put under a constant pretension equal to the current load and additionally under cycling loads or extensions similar to the computed buoy reaction in waves on the mooring line. In particular with nylon lines tests should be made wet. The static test has to run till creep increase is negliable. The cycling test has to be run till the master hysteresis loop stops to change.

3) Depending on the design consideration the change in length of the original marking distance after the test under step 2 under $P = 200D^2$ has to be measured at a suitable machine tension either at $P = 200D^2$ or at the anticipated current load. This new length is $l + \Delta l$.

4) An untested, conditioned piece of the same rope is pretensioned now to $200D^2$ and the same length as in step 1) is marked. The rope is then cut at the marks and weighed on a precise

balance.

5) The weight w of a new rope of the length l under $200D^2$ pretension has been determined. It is also known, that the rope after being subjected to stress and strain conditions simulating the in use situation has changed its length to $l + \Delta l$.

6) Since the rope length $l + \Delta l$ has still the weight w determined in step 4) the total weight w_t for a planned total rope length l_t can be computed. It is

$$w_t = \frac{l_t \times w}{l + \Delta l} \qquad .... \quad (4\text{-}1)$$

7) In the rope plant the rope is cut now at the weight w_t and should have the desired length l_t.

References Section 4

1) Bureau of Navy Personnel; Navy Training Course, "Boatswain's Mate 3 & 2'; Navpers 10121-D, Washington D.C., Chapters 3, 5, 10 - 13; 3rd. edition, 1964.

2) Haas, F.J.; "Fiber Line" in "Handbook of Ocean and Underwater Engineering". Myers, J.J.; Holm, C.; McAllister, R.F.; editors, McGraw Hill, 1969, p. 4-42.

3) Knight, A.M.; "Modern Seamanship"; 14th edition, van Noostrand Co. Inc.; 1966.

4) Bertaux, H.O.; Ocean Engineering Course 13.71; Buoy Systems Engineering, Lecture 1 - 7, Mooring Line Components; Woods Hole Oceanographic Institution, Woods Hole, Mass.; 1968.

5) Snyder, R.M.; "Buoy System Components"; in "Handbook of Ocean and Underwater Engineering", loc. cit.; p. 9-94.

6) Department of the Navy, Bureau of Ships, Buships Notice 9180; Ser 633S-247, Mar. 27, 1962.

7) Isaacs, J.D.; Faughn, J.L.; Schick, G.B.; Sargent, M.C.; "Deep Sea Moorings Design and Use with Unmanned Instrument Stations"; Bulletins of the Scripps Institution of Oceanography Vol. VIII, 1962-64; University of California Press; Berkeley and Los Angeles, 1964, p. 271.

8) Figures from Columbian Rope Company, Sales Bulletin # 41, July 10, 1964.

9) Heller, Jr., S.R.; "The Cost-Effectiveness of Natural and Synthetic Fiber Ropes in the Marine Environment"; Dept. of Mechanical Engineering, Report 70-4, Institute of Ocean Science and Engineering; The Catholic University of America, Washington D.C.; April 1970.

10) Flessner, M.F.; "Creep Tests on Synthetic Mooring Lines", Vol. 1-3, U.S. Coast Guard Academy, Academy Scholars Report, New London, Conn., 1970.

11) Wilson, B.W.; "Elastic Characteristics of Moorings", Journal of the Waterways and Harbors Division; Proceedings American Society of Civil Engineers, Vol. 93; No. WW4, Nov. 1967; p. 27, Refernces 4, 5, 10 - 22 on wave motions of moored ships.

12) Wilson, B.W.; "Treshold of Surge Damage for Moored Ships"; Institute Civil Engineers, Proceedings; Vol. 38; Sept. 1967, p. 107.

13) Hooft, J.P.; "Mooring of Ships at Sea"; International Marine and Shipping Conferenc , June 10, 1969; Section 1, Preprints, p. 9-3, 1969.

References Section 4, cont.

14) Dawson, A.J.; "The Design of Inland Waterway Barges; SNAME - Transactions; 1950, p. 6.

15) Strandhagen, A.G.; Schoenherr, K.E.; Kobayashi, F.M.; "The Dynamic Stability on Course of Towed Ships"; SNAME - Transactions; 1950, p. 32.

16) Benford, H.; "The Controll of Yaw in Towed Barges"; International Shipbuilding Progress, Vol. 2, No. 11; p. 296.

17) Baier, L.A.; Discussions to 14) and 15); SNAME - Transactions 1950; p. 22.

Appendix A

ROPE TERMS AND DEFINITIONS

Since ropes are fairly complex textile structures, some terms frequently used in dealing with them are explained. Reference is made to special dictionaries[1,2] and to the "rope nomenclature". The main components of a rope and the different rope types are explained.

Filament: A fiber of extreme or infinite length, as obtained by the extrusion process of fiber-forming substances. Filaments in a bundle as obtained out of one extrusion process are called multifilaments, sometimes also tow. A filament over .1mm or 4 mils in diameter is called monofilament.

Fiber: "A unit of matter characterized by having a length of at least 100 times its diameter or width, and with the exception of monocrystalline glass fiber, having a definitely prefered orientation of its crystall unit cells with respect to a specific axis."
"The essential requisites for fibers to be spun into yarn include a length of at least 5mm = .2 inch, also pliability, cohesiveness, and sufficient strength. Other properties, more or less desirable include elasticity, fineness, uniformity, durability and luster. Fiber was limited to spinnable staples, but now it also includes continuous filaments, monofilaments and tow"[1] Synthetic cordage fibers are usually continuous filaments and monofilaments, sometimes also split fiber film and staple fiber. Short fibers like cotton or wool are called staple fibers. All natural fibers could be called staple fibers except silk. Synthetic fibers are often cut into

staple fibers of comparable lengths like e.g. cotton, to be able to spin them to yarns on cotton machinery and get similar textile appearence like the natural fiber.

Yarn: A yarn is an assembly of filaments or fibers, which has a thin, mostly cylindrical structure with a small cross section compared to its length. The yarn is formed usually by twisting filaments together, but a zero twist bundle of continuous filaments is also called yarn. Yarns may also be composed of glass fibers, metal wires or ribbons of fiber film, metal or paper.

Multi-ply: Multi-plies are made of a small number of yarns, twisted together in the twist direction opposite to the yarn twist. This method of twisting some textile structure opposite to the preceding twist is called cable twisting. Common multi-plies are e.g. three-plies, five-plies a.s.o.

Rope Strands: Strands are the principle elements of the rope structure, by twisting, braiding or plaiting strands together a rope is formed. Strands are cylindrical textile structures, formed by multi-plies or yarns twisted around one another, similar like fibers are twisted around one another to form a yarn. Strands like yarns have either left hand (S) or right hand twist (Z). Rope strands can be produced only to 1.5 to 2" diameter with reasonable strength efficiency of the material used and reasonable compactness. At ropes requiring larger strands a twisted rope is manufactured in the right size to serve as strand.

Twisted Rope: also known as three-strand-rope, is the traditional still widely used rope type. It consists of three strands, which are twisted together on a rope laying machine or in the past on a rope walk. The strands of the twisted rope are firm and hard by additional foreturn which is put in on the rope laying machine. Twisted rope like plaited rope has a fairly high stretch under load. Production lengths are limited, the rope is torque-balanced, but not torquefree and therefore should be used in non critical applications only. Splicing is done by "tucking" the strands into the rope. Twisted rope over 10" to 12" circumference can only be formed by twisting three regular twisted ropes together, this type of rope is called cable-laid rope.

Plaited Rope: also called square braid due to its cross section is a special 8-strand braided rope, widely used now as mooring hawser in the merchant marine. It is manufactured on a square-braider. The difference to regular braids is that the 8 strands get additional foreturn on the square braider to maintain a hard strand surface. The unspliced rope length is limited by the size of the strand bobbins. It is spliced similar to twisted rope by "tucking" the strands back in the rope. Plaited rope is torquefree, comparable in its stretch behaviour with twisted rope.

Braided Rope: A rope structure formed by a machine or hand process by crossing at least 8 parallel strands diagonally over and under one or more of the others in a "Maypole" fashion. Flat, tubular or solid (mainly cylindrical) constructions can be formed this way, for cordage purposes only tubular or solid constructions are used. The manufacturing machine is called a braider, usually described by the number of strands it can braid together, like 16-strand braider, 20 strand braider a.s.o. These ropes are often offered as double braids or 2 in 1 braids, these consist of a cylindrical center braid and a tightly surrounding tubular cover braid. Both ropes have to match in their load-elongation behaviour and can be spliced by back insertion of the core into the cover and the cover into the core. Braids are usually torquefree and can be manufactured in unlimited lengths. They elongate about half the amount of the stretch of comparable twisted and plaited ropes under similar loads.

References Appendix A

1) The Textile Institute, "Textile Terms and Definitions", 5th edition, Manchester, England 1963.

2) Fairchields Dictionary of Textiles, New York 1959