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Fatigue Testing of Wires and Strands: Test Procedures and Experimental Studies

Essai à la fatigue de fils et de torons: Méthodes d'essai et études expérimentales

Ermüdungsprüfung von Spanndrähten und Spannlitzen: Versuchstechnik, und -ergebnisse

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SUMMARY
A survey is given, which is more related to material and tests than to theory, on the subject of size effects and the fatigue behaviour of prestressing steel. Possibilities of life determination are indicated and the presentation of test results is discussed. Some comments and recommendations are given for the experimental performance of these fatigue tests and possible test strategies are discussed. New test results are shown shortly and porposals for future investigations are given.

RÉSUMÉ
Le présent rapport traite des effects de la dimension des éprouvettes sur le comportement à la fatigue de l'acier de précontrainte. Il aborde les aspects pratiques, tels que "matériau" et "essai", par opposition à une approche théorique. Les durées de vie probables sont indiquées et les résultats d'essais sont présentés. Quelques commentaires et recommandations sont données sur la valeur expérimentale des essais de fatigue et sur des programmes éventuels d'essai. Des résultats récents sont présentés et des recherches futures sont proposées.

ZUSAMMENFASSUNG
Das Ermüdungsverhalten von Spannstahl wird in einem Überblick vor allem bezüglich der Auswirkung der Prüflänge dargestellt. Diese Darstellung richtet sich weniger auf die Theorie als vielmehr auf die Praxis der Versuchstechnik und auf das Werkstoffverhalten aus. Möglichkeiten für eine Berechnung der Lebensdauer werden kurz angesprochen und die Darstellung von Versuchsergebnissen diskutiert. Hinweise und Empfehlungen zur Versuchstechnik werden gegeben und Strategien zur Ausführung derartiger Versuche diskutiert. Neuere Ergebnisse von Ermüdungsversuchen an Drähten und Litzen unterschiedlicher Prüflänge werden mitgeteilt und Vorschläge für zukünftige Untersuchungen unterbreitet.

INTRODUCTION

In nature and in technology two basic terms are used to describe the geometry of a body: shape and size.

The shape is given by the ratio of the lengths observed, whereas the size is determined by their absolute values. It is astonishing that the Latin word "ratio" not only means "proportion", but also, in the figurative sense, "reason". Human reason relates intellectual values to each other.

Within the scope of this workshop the influence of size, more precisely length, on the fatigue strength of high strength prestressing wires and strands will be examined.

From practical experience we all know that the fatigue strength of ropes and tendons is primarily determined by the fatigue properties of the anchorages. The fatigue strength of the anchorage thus limits the loading permitted in service. The fatigue strength of the free length of a pretensioning element is usually considerably higher.

There are two reasons why it is necessary and worthwhile to investigate the effect of length on the fatigue strength of prestressing steels:

- the quality testing of prestressing steels
- the theoretical treatment and description of the length effect with the aid of statistical laws.

The procedure for quality testing prestressing steels is laid down in national and international standards. The dependence of fatigue strength on the test length is little known today and is hardly ever treated in the standards. Thus the specification of a required fractile with a certain confidence level only makes sense when a corresponding minimum test length is also stated. This fact is insufficiently anchored in the heads of the specialists who create the standards.

The practical engineer can only handle an effect such as the size effect on fatigue strength when the relevant laws are expressed in a formula and, better still, illustrated in easily interpreted diagrams.

Within the scope of this workshop, both topics will be dealt with and discussed.

HISTORICAL BACKGROUND

Timoshenko [1] has traced back the history of materials strength to the times of the ancient Egyptians, Greeks and Romans. Knowledge of the size effect goes back at least as far as Leonardo da Vinci (ca. 1500 AD), who made experimental studies on the dependence of the (static) strength of iron wires on their length and observed that long wires are weaker than short wires of the same diameter. Chaplin [2], around 1880, applied the weakest link theory to the effect of length on the tensile strength of metal bars of constant cross-sectional area.

Among the earliest authors to discuss the size effect on fatigue were Peterson [3] in 1930, Weibull [4] in 1939 and Aphanasiev [5] in 1948. The statistical theory of extreme values (weakest-link theory) plays an important role in studies of the size effect on material strength. Weibull [6] also used extreme value theory to give the first reasonably satisfactory explanation of the volume effect on material strength.

Freudenthal and Gumbel [7] employed the Weibull distribution to describe the life of fatigue loaded components. Freudenthal gives in [8] a starting point for taking into account the volume of highly loaded materials. Castillo et al. [9] showed theoretically that for fatigue results under constant amplitude loading, the Weibull distribution is the only distribution that meets the requirements of stability, compatibility and limit conditions.

A comprehensive literature review up to the year 1976 on the subject of "size effect" was carried out by Harter [10].

In more recent times it is above all the works of Heckel and co-workers [11-15] that deal theoretically and experimentally with the size effect on fatigue strength.

EFFECT OF LENGTH, EFFECT OF SIZE

The length effect is a part of the size effect and this may be divided up, according to Kloos [16], into the following basic effective mechanisms (Fig.1):

- geometric aspect
- technological aspect
- statistical aspect

A complete decoupling of these size effect mechanisms is experimentally impossible. By holding various parameters constant, however, the influence of the individual mechanisms may be observed separately under certain conditions.

GEOMETRICAL EFFECT

In this category belong all the influences that are based on the geometrical differences between the components. The geometrical aspect of the size effect may be explained with the aid of the different stress gradients in the components and with the help of the conceptions macro and micro supporting effect created by Neuber [17].

The geometrical aspect includes all effects that cause a change in the crack growth rate and in the final crack length during the fatigue life. Hence this effect shows up essentially only after the crack initiation stage.

TECHNOLOGICAL ASPECT

The technological influence is based on the effects of size, shape and distribution of crack nuclei in the volume of the material on the crack initiation and propagation. During mechanical and thermal treatment, namely, cross-section and volume dependent changes of this kind often arise in the material.

Effects caused by mechanical and thermal surface treatment processes with elements of differing size (e.g. differing extents of residual stress fields or hardening zones) must also be included in the technological aspect.

Technological effects may influence the crack initiation and propagation phase. With components of differing size they lead to differences in the life. With parts of equal size that were fabricated from different regions of a larger material volume, they lead to different amounts of scattering in the life.

STATISTICAL EFFECT

The statistical size effect enables one to explain the scatter in the number of cycles to rupture in fatigue tests on completely (ideally) identical samples.

If one considers, for instance, a long wire under repeated loading in tension, then with appropriate loading at a certain point, namely at the crack nucleus with the least resistance (weakest link), a crack is initiated that finally leads to rupture. If both fragments are further tested with the same loading, then further cycles are possible before failure, i.e. the life of the two fragments is greater. Continuation of this procedure yields for the fragments the same scatter in the number of cycles to fracture as one would have obtained by dividing the wire at the start into a number of short lengths and testing these separately.

The most sensitive crack nucleus observed on the long wire has an upper limit to its cracking susceptibility. The susceptibility to cracking can only be of such a magnitude that the wire does not already rupture during the fabrication process as a result of the loading inherent in the process (e.g. during drawing). One may therefore expect long wires to show a low number of cycles to rupture with low scatter. The shorter the wire, the higher the mean number of cycles to rupture and the higher the life scatter.

The effect of the statistical aspect with a randomly shaped component in a condition of inhomogeneous stress may be described, according to Böhm [12], with the aid of the so-called stress integral. Since the crack initiates preferentially at the surface, the stress integral is usually calculated for the surface. With the dimension of an area, it represents a measure for the size of the highly stressed surface. With increasing size of the highly stressed material surface, the probability of the existence of larger crack nuclei grows accordingly. These lead to shorter lifes.

If one tests wires and strands of the same geometrical dimensions that originate from the "identical" material and "identical" fabrication, then the importance of the geometrical and technological aspects is very much reduced and the effect of the statistical aspect may be examined almost without hindrance. Identical geometrical dimensions also mean that the number of cycles to rupture may be used as a clearly observable measure for comparison, and not the technical crack, which is difficult to find.

PHASES IN FATIGUE BEHAVIOUR

Under cyclic loading, changes of state occur in the material from the first cycle onwards. If flaws that may be designated as cracks do not exist at the beginning, then hardening and softening processes lead initially to microscopic fatigue cracks. Inhomogeneities such as inclusions, phase boundaries, etc. also lead to the formation of crack nuclei on account of the stress concentrations caused by them. Fatigue cracks arise mainly at or just below the surface, since at this location (a) the highest loading often exists (bending, torsion, notch effect), (b) the attack of any corrosive media takes place, (c) a certain surface roughness exists or (d) surface flaws or damage have arisen during fabrication or transport. In multi-component systems like strands, the fatigue behaviour is mostly determined by the response of the contacting surfaces to fretting [21].

With continued cyclic loading, microcracks may propagate on account of their notch effect. The so-called microcrack growth takes place within the order of magnitude of a few grain diameters. A precise distinction between crack formation and microcrack growth is impossible. During the phase of microcrack growth, the propagation rate is still very strongly influenced by the immediate environment. If the crack leaves the region dominated by the material microstructure, the further growth may be calculated by the methods and laws of linear elastic fracture mechanics, provided that the correction functions for the stress intensity are available. The corresponding crack size is termed the technical crack. From this size onwards, the material behaves quasi homogeneously. If the crack has attained a size that is critical for the momentary loading, then final fracture occurs as a result of unstable crack propagation.

The life of cyclically loaded components may thus be divided up into four sections:

- Crack-free phase
- Formation of one or more crack nuclei and microcrack growth

- Stable crack propagation
- Unstable crack propagation (final fracture)

The typical scatter in the life of cyclically loaded samples and components may be explained by the irregularities in the material microstructure or in the size of the crack nuclei originally present. Depending on the local loading, cracks that may possibly develop further to a microcrack occur at various times because of randomly distributed flaws with varying influences. The actual (stable) crack propagation from technical crack up to failure gives rise to little scatter with components of identical geometry and fabrication under constant test conditions.

FLAWS AND LIFETIME CALCULATION

From the efforts to be able to deal with the fracture mechanism in cracked components arose the discipline of fracture mechanics, which is also the basis for calculating the propagation behaviour of cracks. The flaws distributed in the material may be regarded in their effect as ficticious initial cracks. The possibility thus arises of assigning to each flaw, according to its sharpness, a certain crack length. The flaws are then represented by a distribution of their crack lengths. Moreover, it is not the basic distribution of all cracks that is characteristic for the life of a cyclically loaded component, but the distribution of the largest cracks, since these are responsible for the later fracture. According to Schweiger [13], the distribution of the largest initial cracks is usually expressed in the form of an exponential function:

$$F(a) = \exp\left[-\left(\frac{a}{a_v}\right)^{-c}\right] \qquad (1)$$

The parameters a_v and c are measures of the absolute size and scatter, respectively, of the maximum crack lengths (Fig. 2).

According to [18], fatigue failures in cold drawn wires were always initiated at surface flaws with depths between 30 and 100 µm. These cracks were probably produced during the drawing process [18]. If cracks are already present, the initiation period may be neglected and the life calculated by integration of the Paris Law [19]:

$$\frac{da}{dn} = C(R) \cdot (\Delta K)^{m(R)} \qquad (2)$$

where a is the crack length, da/dn is the crack growth rate per cycle, ΔK is the stress intensity range and C(R) and m(R) are experimental coefficients dependent on the stress ratio R. Both the coefficients C and m are found to be independent of crack depth, mean stress and frequency [20].

For crack growth rates below 10^{-9} m/cycle, a threshold value of the stress intensity range ΔK_{th} has been observed. The threshold stress intensity range is dependent upon the stress ratio R and the following empirical relationship was found [20]:

$$\Delta K_{th} = 5.54 - 3.43\,R\,[\mathrm{MPa \cdot m^{1/2}}] \qquad (3)$$

During the fatigue of strands, the formation of crack nuclei is primarily caused by fretting corrosion [21]. On a seven-wire strand with a centre wire and six outer wires, the line contact length is twelve times the strand length: six contact lines between the outer wires and six between the outer wires and the centre wire. Whether and to what extent local compression and displacements occur along the line contacts depends primarily on the diameter and relevant tolerances in the outer and centre wires. It is known that the fatigue strength of components that are in contact with each other is considerably reduced. Patzak [22] states that the fatigue strength of components subjected to fretting corrosion may be reduced to as low as 10 % of the value obtained without fretting. Hence the reduction of fatigue strength by fretting corrosion may exceed that caused by other factors, such as stress concentrations as a result of the notch effect in the anchorage.

According to DIN 50900 [23], fretting corrosion is understood to be the damage of materials which contact each other under a normal force and execute oscillatory movements of very small extent, i.e. ca. 0.1 to 300 μm. In the contact surfaces, mechanical and physicochemical processes work together, whereby the chemical processes are initiated by the mechanical. When at least one of the contact pairs is a metal, oxidation phenomena occur in the fretting regions. Because of the small fretting movements, the wear particles arising, which as oxides have a volume 2.2 times that of the metal, can leave the fretting region only slowly or not at all. In the friction loaded surface, local stress peaks arise that are superposed on the cyclic loading, which may give rise to premature cracking. Since the notch sensitivity of steel increases with increasing tensile strength, the loss of fatigue strength in high-strength steels is especially marked owing to the sharp notch effect of the cracks. In the fatigue loading of steel components subjected to fretting corrosion, it must be additionally taken into account that even with small stress ranges, fractures occur after two million load cycles. An infinite life range in the classical sense does not exist [24]. According to [24], the fatigue strength decreases with increasing compression and increasing relative displacement in the μm range. A general statement on the influence of these two parameters, however, appears to be difficult, since it is the combination of these values existing in a specific case that is decisive. With regard to the effect of the loading frequency, the majority of investigators [25] state that the values in the finite and infinite life ranges decrease with falling frequency. In tests [25] the fatigue strength at 2.9 Hz was 20 % lower than at 50Hz. In the low frequency tests, ca. 20 % higher fretting coefficients arose at low cycle numbers than at high frequency. The influence of frequency with fretting corrosion may thus be explained by the fact that at low frequencies the time dependent corrosion effect is of higher importance, and on the other hand, that the fretting indices are increased by ca. 20 % though oxide formation.

GRAPHIC REPRESENTATION

The results of fatigue tests with constant amplitude loading are summarized in the so-called S-N diagram (Wöhler diagram). The scales on both axes are normally logarithmic. On the abscissa, the life is plotted as a number of cycles. The ordinate represents the loading, in the case of prestressing steel, usually the range $\Delta\sigma$ of the stress. The failure criterium laid down is either a previously defined crack, usually between 0.1 and 1 mm in size, or the fracture of the sample, here the rupture of a single wire. In one-step Wöhler tests on steel, a pronounced limiting number of cycles appears, which depends on the loading and the environment. For steel under normal laboratory conditions, a value of two million cycles is reported.

The not insignificant scatter of life and strength values on fatigue loading is generally taken into account by statistical evaluation. Apart from S-N curves for a failure probability of 50 %, one often finds additional curves for 10 and 90 %. The scatter of test results on a load level is characterized with the aid of various distribution functions. Buxbaum [26] names as the five most commonly used functions:

- Normal distribution
- Log normal distribution
- Linear exponential distribution
- Weibull distribution
- Arc sin $\sqrt{P}$ transformation

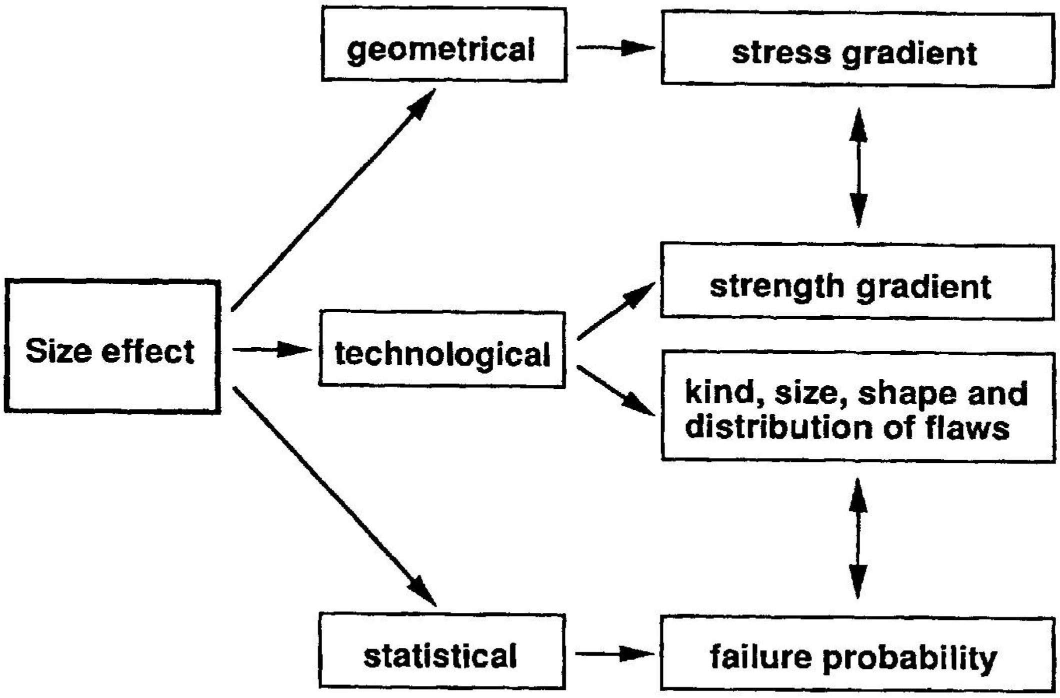

Fig. 1: The different aspects of the size effect, after Kloos [16]

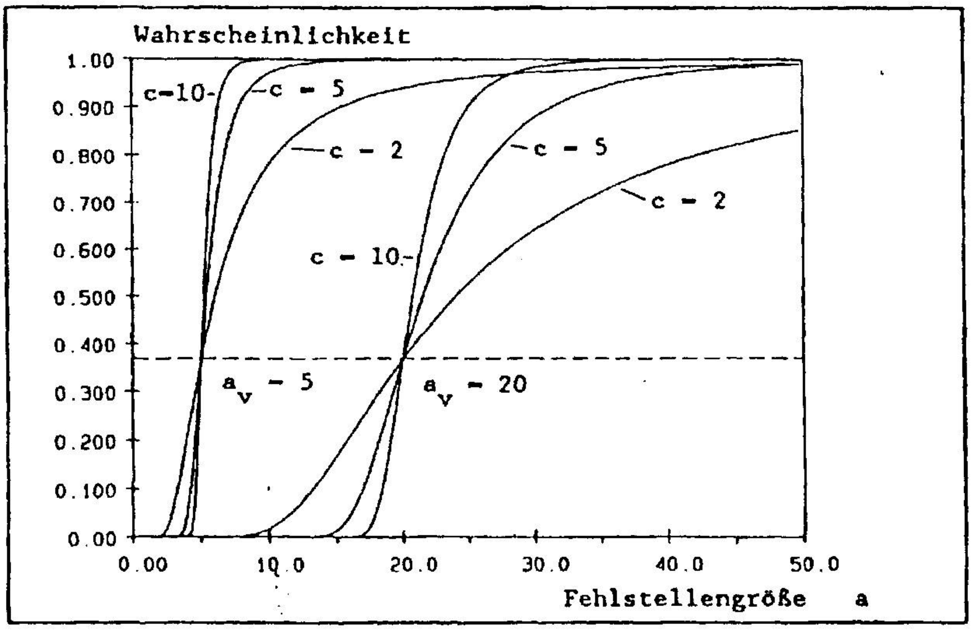

Fig. 2: Distribution function of the initial crack length for different parameter values, after Krä [15]

By suitable choice of the axes, a probability grid may be constructed for a distribution.

A failure probability may be assigned to the fatigue lives arranged in the order of increasing value according to

$$P = \frac{m}{(n+1)}, \qquad m = 1,2,\ldots,n \text{ where} \qquad (4)$$

m - is the ordinal number and
n - is the total number of tested samples per load level

This estimate has proven itself in numerous works [13]. If one plots the pairs of values obtained in this way (failure probability and fatigue life) on the probability grid, then one obtains an approximately straight line. The statistical parameters of the distribution taken as a basis may be determined from the slope and position of this line. Although the Weibull distribution must be regarded on theoretical considerations [9] as the distribution valid for the fatigue tests of the given kind, it finds only slow acceptance in the practice of test evaluation. It may seem astonishing to the statistician that the engineer is more ready to think in terms of mean and standard deviation than in characteristic fatigue life and Weibull slope.

According to [9] the description of the S-N diagram may be given by the following relation

$$E\ (N, \Delta S, L) = 1-\exp\left[-\frac{L}{L_o}\left(\frac{(N-B)\ (\Delta S-C)}{D} + E\right)^A\right] \qquad (5)$$

N - number of cycles, ΔS - stress range, L - proof length

The five parameters have the following meaning:

A: Weibull slope parameter
B: asymptotic N-limit
C: endurance limit
D: scale fitting parameter obtained for an arbitrarily chosen reference length L_0
E: constant defining the S-N threshold curve below which a zero probability of fatigue failure exists

The percentile curves can be obtained by making E equal to a constant failure probability P. This model will be the base for serveral evaluations of tests and for a special computer program reported elsewhere during this workshop.

EXPERIMENTAL PERFORMANCE OF TESTS

Fatigue tests on wires and strands are mostly carried out on equipment with hydraulic or electromagnetic drive, less frequently with mechanical resonance drive. With the hydraulic equipment, a distinction must be made between volumetrically and servo-hydraulically controlled tests. Since smaller equipment of the same capacity generally costs less, runs faster and consumes less energy, these machines, and hence short test lengths, are normally considered to be advantageous.

The effects of the test and measuring equipment on the results of fatigue tests is generally underestimated. Taking this into account, it becomes possible to evaluate deviations of the experimental values from those predicted by models.

In the following we shall first deal more closely with the accuracy and the checking of test loads. With one step fatigue tests, one assumes that the maximum and minimum values of the cyclic loading remain constant, even over long test durations and millions of cycles. The limits to this "constancy" are given for a specific test apparatus by the short and long term accuracy of the cyclic loads. Fatigue tests on wires and strands represent here a rather special case, since with relatively high preloading, a high precision in the relatively small range is required. This is based on the fact that primarily the range and only secondarily the size of the "static" component of the load determines the fatigue life. If one assumes, for example, that on a test apparatus the maximum and minimum values of the required loading can be maintained with an accuracy of $\pm$ 2 %, whereby this figure must be regarded as absolutely realistic, then for a maximum stress $S_{max} = 0.7\ S_{ult}$ and a range $\Delta S = 0.2\ S_{ult}$, there results an accuracy of $\pm$ 12 % for the range, e.g. $\Delta S = 350 \pm 42$ N/mm^2. S_{ult} marks the ultimate strength of the material. This possible deviation should also not be forgotten when the results of fatigue tests show scatter. That the limits of the test loading, apart from this, also vary from cycle to cycle and hence strictly speaking a fatigue test is executed with a range that varies randomly from cycle to cycle must also be taken into account. Hydraulically driven test equipment in general, but particularly those which are volume controlled, react sensitively to changes in ambient temperature with changes of the test load. For this reason, unwanted load changes must be expected with a day/night cycle in the case of tests of longer duration.

In order to obtain an idea of the magnitude and accuracy of the real test loads, it is recommended to measure these in series with the fixed sample clamp by means of a load cell. The control of hydraulic test apparatus by means of pressure transducers in the hydraulic system can lead to considerable error, especially at high frequencies and with large moving masses.

The clamping of samples in the fatigue machine is always one of the critical points in a test. Samples that fail in the clamping region must be rejected and merely cause costs without a result. What is understood by the clamping region is not laid down in a way that is universally valid. In the testing of wires and strands it has become the custom to regard ruptures occurring within one or two diameters of the wire or strand from the clamping position as belonging to the clamping region and to disregard these in the evaluation. It should be noted that with short test specimens, the clamping region takes up a relatively large proportion of the free length. If one assumes, for example, an effective clamping region of two diameters length at each end, then with a wire of 7 mm diameter and 150 mm length, these regions amount to already 19 % of the total length. The probability thus increases, that "normal" flaws, which come to lie in the clamping region, are wrongly rejected.

The actual clamping of the specimens may be effected by form fit or material fit or friction fit. In practice a combination of these principles is usually employed. Well-designed clamping systems for fatigue tests are characterized by the avoidance of stress concentrations in the sample as far as possible and measures to prevent fretting corrosion. The latter may be avoided by careful choice of contact pairs (the materials of sample and clamp), above all at the interface between the clamp and the free length of specimen. It should be pointed out that there is a possibility of making the specimen itself insensitive to clamping fractures, e.g. by introducing local residual stresses in compression by rolling the wire in the clamping region. Experience with, and details of the possibilities given and applied will be covered in a special contribution to this workshop.

TEST STRATEGIES

In fatigue tests it is the aim to obtain as much information as possible about the S-N field with as few samples as possible, more precisely: with as small a total number of load cycles as possible. The engineer is primarily interested in curves for low failure probabilities of high confidence level, as well as the asymptotic limits for the fatigue strength and the minimum number of cycles to rupture. Depending on the assignment, knowledge of the entire S-N field or, separately, the finite or infinite life ranges are of predominant interest.

It is only natural that tests in the infinite life range are evaluated only in the direction of the loading and based on test strategies that are suitable for the treatment of dual (binomial) events, such as the staircase method [27] and the Probit method [28]. Since the statistical validity of dual (binomial) events is considerably lower than that of metric (variable) events, such as the lifetime in the finite life range, one requires considerably more tests in the infinite life range in order to obtain the same statistical confidence as in the finite life range. Because of the large number of cycles needed in the infinite life range, a further increase in the expenditure of time and money occurs.

The limit number of cycles in the infinite life range should not be set too high, even when occasional fractures are to be expected after the limit number of cycles. Such rare fractures depress the mean value only negligibly, but they make the tests considerably longer and more expensive. The preference here should be given to low limit numbers of cycles combined with an increased number of tests, in order to increase the confidence in mean value and scatter.

Acceptance tests in the sense of proving a certain failure probability at a prescribed confidence level for a certain loading are often carried out in the sense of binomial results, since an agreement on the distribution function to be employed is unnecessary. One stipulates, for instance, that in the fatigue test, none out of seven samples may undergo fracture up to a prescribed limit number of cycles. This strategy is unsatisfying, since the statistical validity of these binomial events, as mentioned above, is considerably lower than with metric events. In addition, during the entire duration of the test, no information is gained on the chances of success, and after the first rupture, a new test series must be started. Here it would be far more economical of time and money to agree to a higher loading level with higher failure probability and to agree to acceptable number of cycles.

The finite life range is generally investigated by testing specimens on at least two load levels. With a fixed number of samples, one today prefers to test many samples at few levels, rather than few samples at many levels. Whether this method brings an improved "statistical efficiency" or merely a simpler test procedure is not yet clear. In the finite life range, it is best to start testing at the highest planned load level, since there the results are more quickly available and from this position one can more easily estimate the load levels required for the further tests.

Since the practicing engineer is interested in fatigue data with low failure probability, test specimens should always be as long as possible [9], provided this is allowed by the test equipment. If one reduces the results in each case to a certain test length, e.g. 1 metre, then the results from testing long specimens become not only considerably more informative, but also more favourable with regard to the expenditure of time and money.

TEST RESULTS

The Swiss Federal Institute for Testing and Research (EMPA) has over the years carried out numerous investigations on the length effect with prestressing wires and strands. Since the results will be discussed in a special contribution, they will be shown here only in summary.

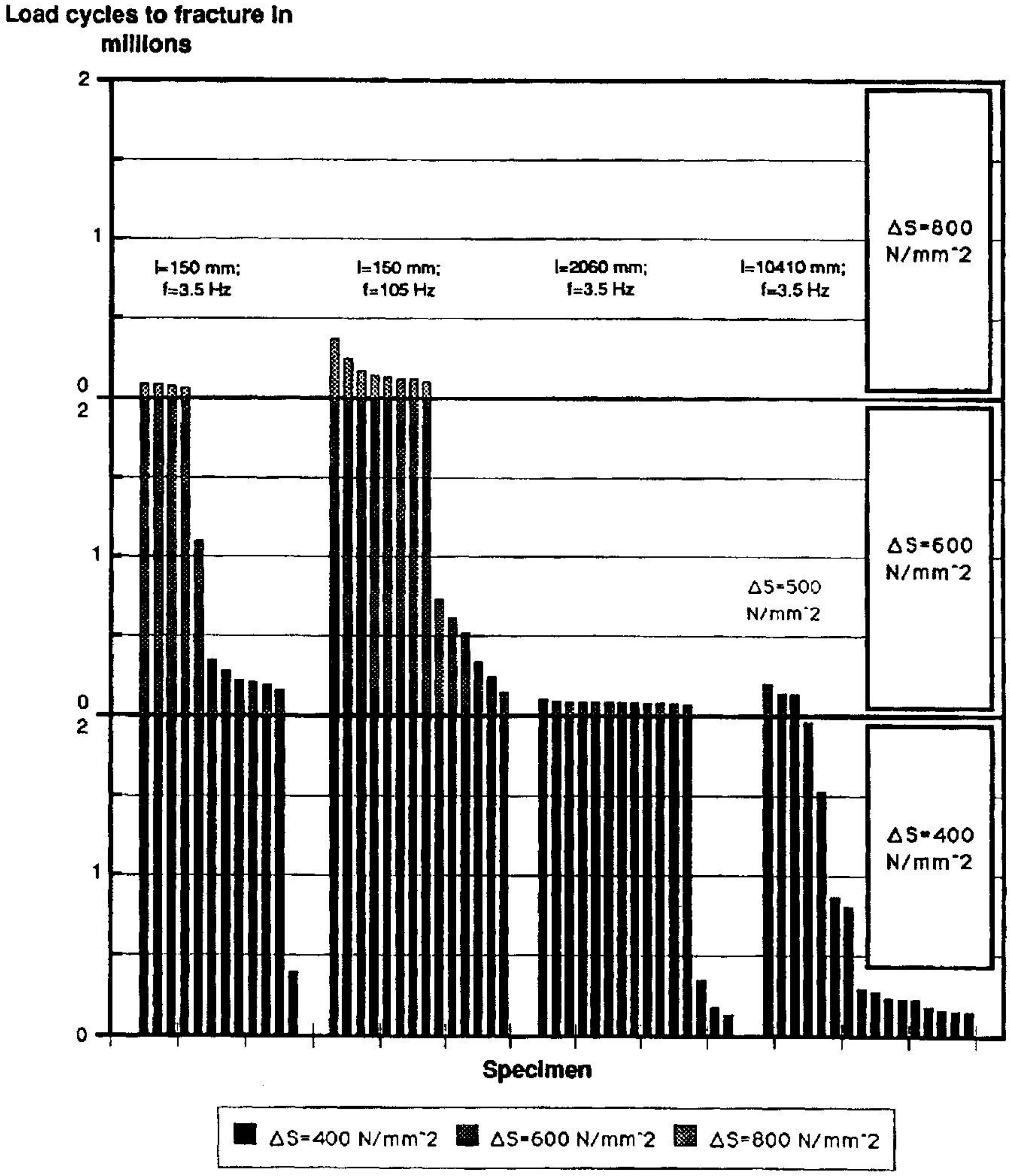

Fig. 3: **Summary of fatigue test results on prestressing wires for different proof length**

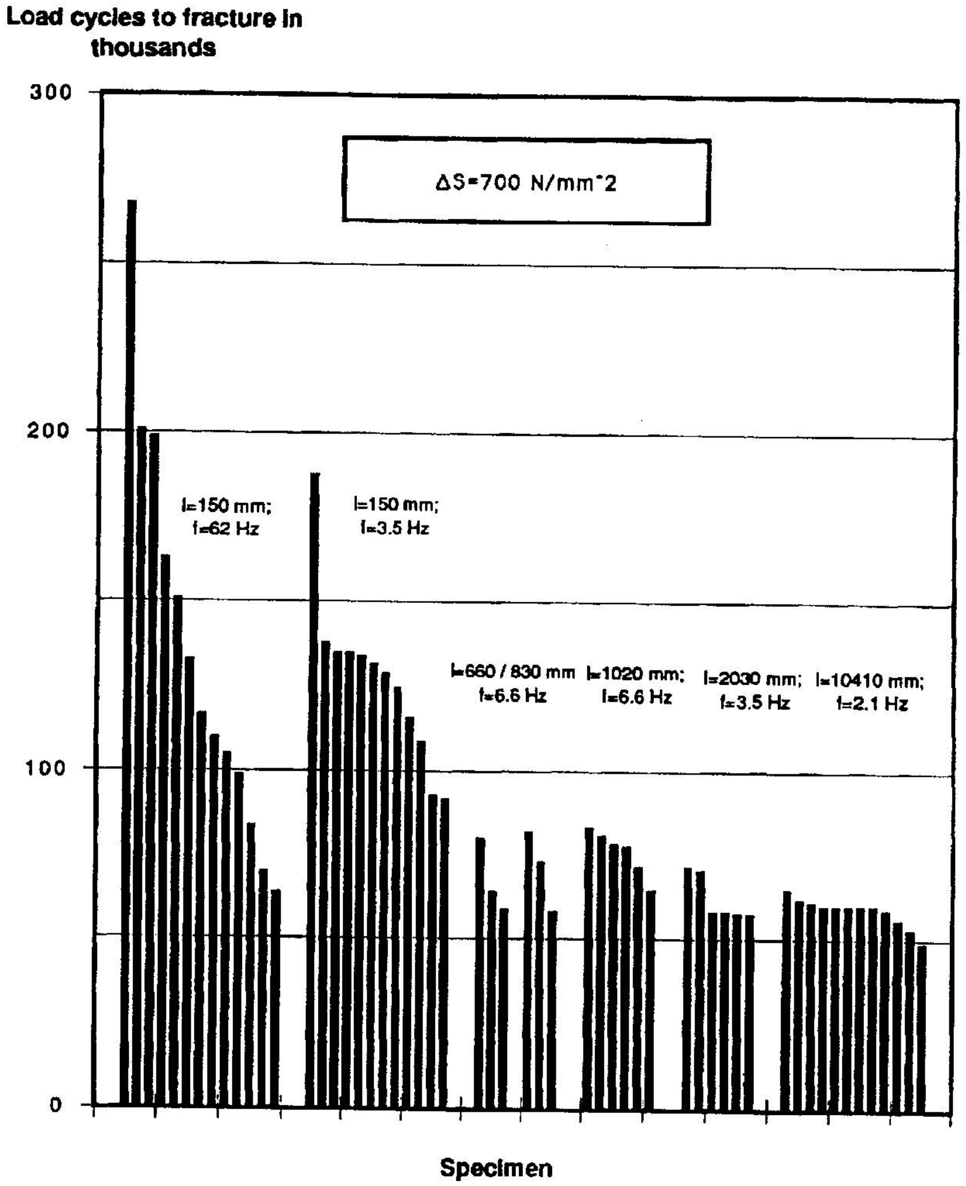

Fig. 4: Summary of fatigue test results on prestressing wires for different proof length

Weibull - probability plot
Influence of proof length and test frequency

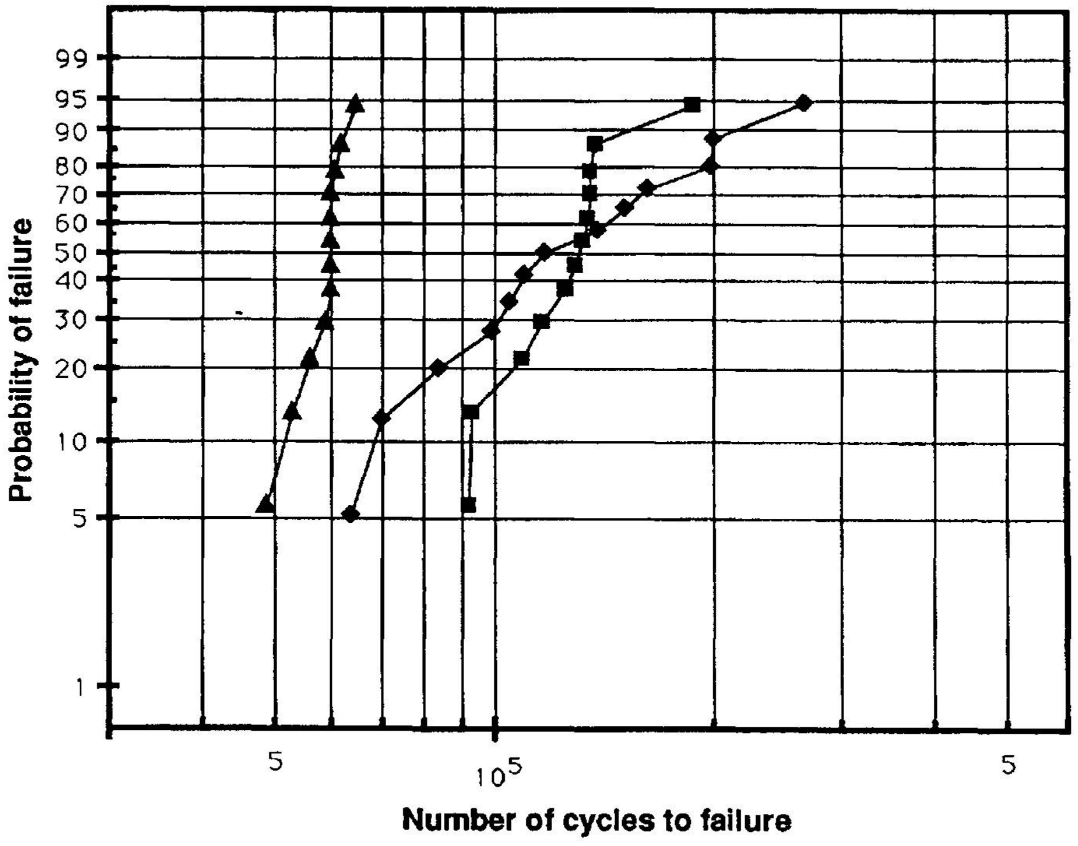

Fig. 5: Fatigue of prestressing wires

7 mm diam., stress range $\Delta\sigma = 700$ N/mm²

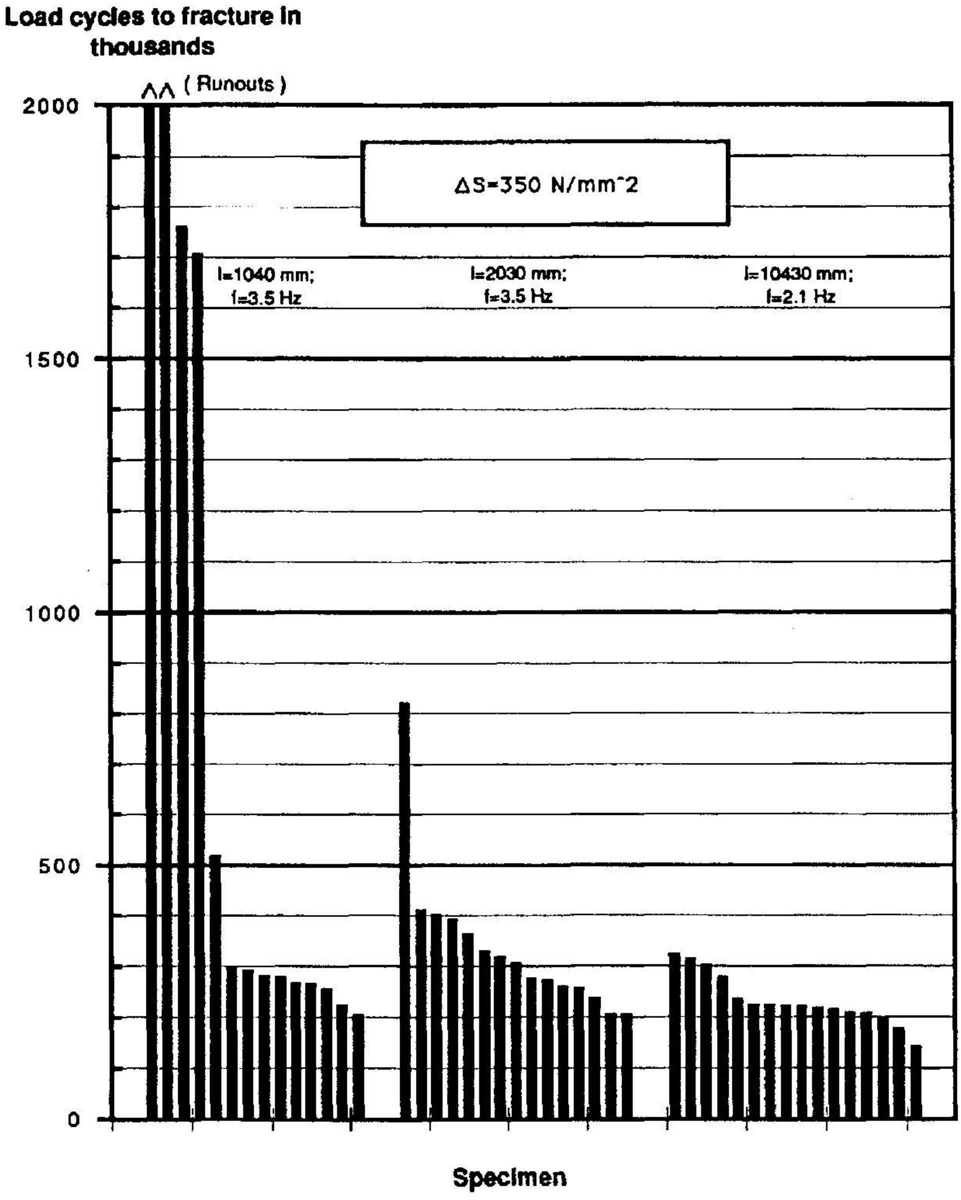

Fig. 6: **Summary of fatigue test results on strands for different proof length**

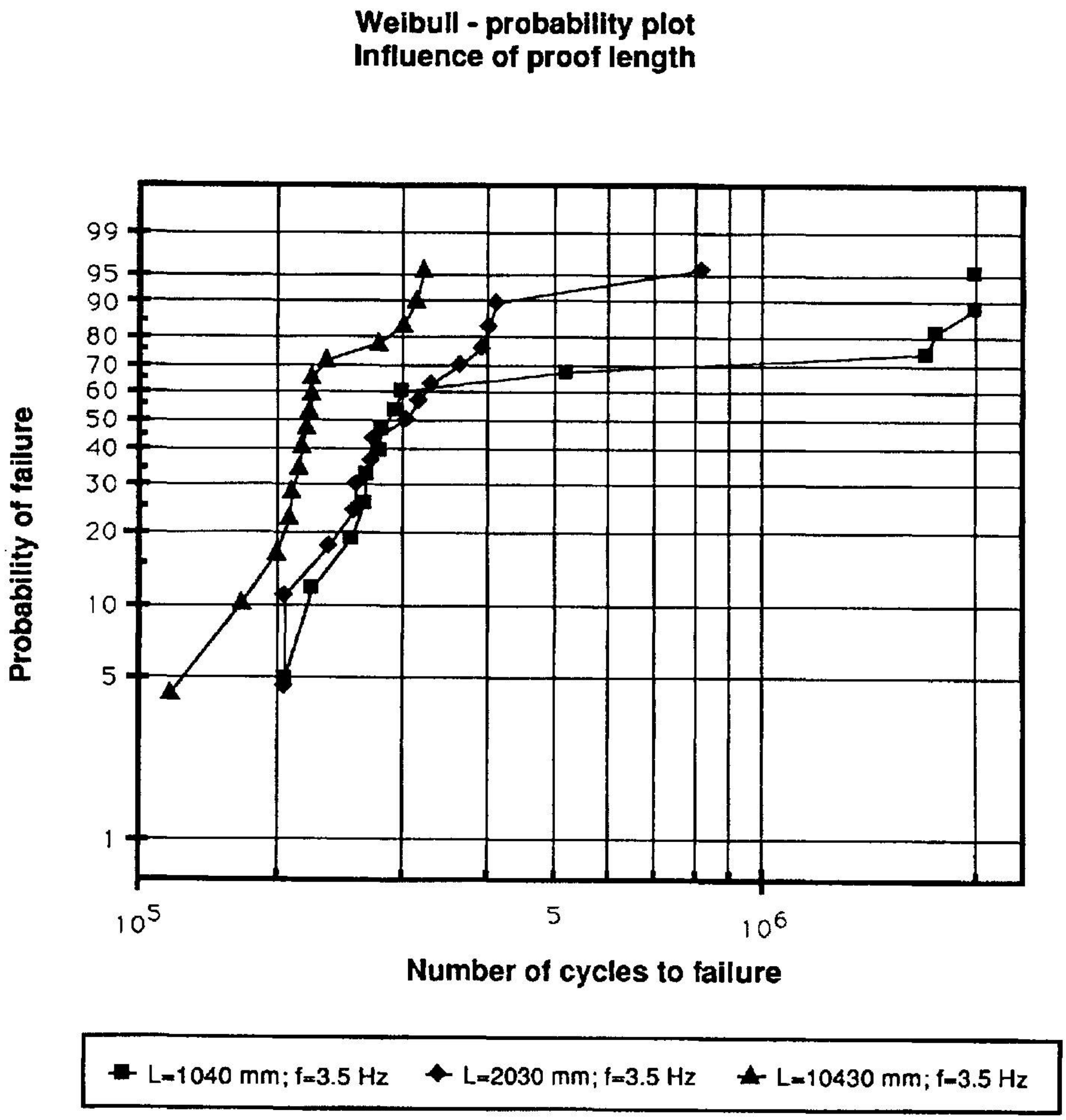

Fig. 7: Fatigue of prestressing strands
0.6 inch, stress range $\Delta\sigma = 350$ N/mm^2

WIRES

In Fig. 3 the results are shown for wires of between 150 and 10410 mm in length. For the 150 mm length, the test frequencies 3.5 and 105 Hz have also been investigated. In the tests, the maximum stress $S_{max} = 0.7\ S_{ult}$ was kept constant and with a limit number of cycles of two million, the stress range was raised from $\Delta S = 400\ N/mm^2$ over 600 to 800 N/mm^2. If one compares, at constant frequency, the number of cycles to rupture for the lengths 150 and 10410 mm, then one sees clearly the effect of the test length, i.e. shorter life with longer specimens. That such a length effect actually occurs also in the infinite life range with small stress ranges can ultimately be proved only by carrying out these time consuming tests to find the ratio of ruptures/total of tested specimens per level. With a stress range of $\Delta S = 400\ N/mm^2$, the results were for a test length of 150 mm 1 rupture in 12 samples, and for a test length of 10410 mm 13 ruptures in 16 samples.

Fig. 4 shows the results for the finite life range with a stress range of $\Delta S = 700\ n/mm^2$. The influence of the test length in the sense of larger means and bigger scatter at low test lengths and lower means and scatter with larger test lengths is clear. Plotting these results on the Weibull diagram (Fig. 5) confirms this observation. In connection with Fig. 5 there arise two questions: the model according to [9] predicts for differing test lengths the same Weibull slope, which is here not the case; it is at the present also unknown which phenomena cause a greater scatter with approximately the same mean at higher frequencies when the test length is kept constant and the frequency varied.

STRANDS

In Fig. 6 the results are plotted of fatigue tests on strands at a constant maximum load $S_{max} = 0.7\ S_{ult}$ and a stress range $\Delta S = 350\ N/mm^2$ for the test lengths 1040, 2030 and 10430 mm. The numbers of cycles to rupture shown here are for the rupture of the first wire of the seven wire strand. Although the influence of the test length is still discernable on comparing the numbers of cycles to rupture for 10430 mm as against 1040 or 2030 mm length, an increasing number of specimens show up here with decreasing test length that rupture only at higher numbers of cycles, Fig. 7. Apparently various damage mechanisms are present here. One could imagine that the importance of fretting corrosion as a crack initiating mechanism decreases with decreasing test length and hence at higher numbers of cycles to rupture, ruptures in the individual wires become effective that originate from "normal flaws".

SUGGESTED FURTHER WORK

- S-N diagram: ability to draw in curves with certain failure probability at a given confidence level. For the engineer, curves with low failure probability at high confidence level are important.
- S-N diagram: optimum conception and simple evaluation procedure for fatigue tests in the infinite life range with the goal of being able to state a load level with a low failure probability at high confidence level, with as few specimens as possible.
- Ability to determine, with non-destructive methods on wires, an equivalent initial crack length for flaws, which can lead via fracture mèchanics to an estimate of life.
- To gain more knowledge on the mechanism of fretting corrosion with strands in a greased or galvanized condition.

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