Fatigue testing and force distribution in steel wire ropes

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Essais de fatigue et distribution des forces dans les câbles en acier

Ermüdungsversuche und Kraftverteilung in Stahldrahtseilen

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SUMMARY
Wire ropes and strands under tension are subjected to attendant stress, which influences their endurance. A description of the stress measurements on wire ropes in regular lay and strands leads to the suggestion: Five wire rope lays or fourteen wire lays may meet the independence assumption in statistical theories. This is equivalent to 30 times the rope diameter, or fourteen wire lays for strands. The minimum length of a fatigue test sample must be taken as two layer longer to cover influences of the rope terminals.

RÉSUMÉ
Des câbles en acier et des torons sont soumis à des tensions additionelles, lesquelles ont une influence sur l'endurance. Une description des mesures de tension sur un câble croisé et un toron conduit à la suggestion: 5 fois le pas de câblage ou 14 fois le pas de toronnage correspondrait à l'indépendance admise dans les théories statistiques. Ceci correspond à une longueur de 30 fois le diamètre du câble, ou 100 le diamètre d'un toron. La longueur minimale de l'éprouvette doit être augmentée de 2 pas de câblage ou de toronnage au moins pour prévenir les influences des attaches du câble.

ZUSAMMENFASSUNG
Zugbeanspruchte Drahtseile und Litzen sind Nebenspannungen unterworfen, die die Ermüdung beeinflussen. Aus Spannungsmessungen an Kreuzschlagseilen und Litzen wird abgeleitet, daß 5 Schlaglängen eines Seiles oder 14 Schlaglängen einer Litze nötig sind, um die Voraussetzung statistischer Unabhängigkeit zu erfüllen. Das ist äquivalent zu 30 Seildurchmessern oder 100 Litzendurchmessern. Die Mindestlänge eines Probestücks muß mindestens zwei Schlaglängen zusätzlich umfassen, um einen Einfluß der Seilverankerungen auszuschalten.

1 INTRODUCTION.

Taking into the account what has been published on the theory [1] and the experimental experience [2] [3], there is little doubt of the existence of a length effect on fatigue failures of steel wire ropes and strands. In the case of wire ropes and strands, however, the backgrounds of this effect may give rise to further discussions.
Research on steel wire ropes in the Laboratory of Materials Handling at Delft was mainly focused at repeated bending over sheaves of ropes under tension. The reason was, that the wire rope endurance with this type of dynamic load appeared to be much shorter than with pulsating loads on straight wire ropes and further that bending over sheaves happens in most transport equipment. Still, certain measuring results give indications with regard to some aspects of the length effect on fatigue testing of steel wire ropes and strands.
It should also be observed, that in the case of some applications like in mooring ropes, hoisting ropes and boom ropes of heavy duty cranes, which some times have a length of more than 1 km, it may be wise to take into account the length effect.

Theoretical as well as experimental reflexions on tensile fatigue testing of drawn steel wires mostly mention the distribution of initial micro-cracks or flaws as the main cause of fatigue failures. If applications of steel wire ropes or strands are involved, however, more influences should be mentioned. In those cases next to the influence on the endurance of the notorious fretting process other factors play a role. These can be divided into influences on the load capacity and influences on the strength.

The tensile load capacity is influenced by:
- The distribution of the load among the wires of the wire rope or strand.
- Attendant stresses due to the geometry of the rope or strand.
- The response of the rope or strand on the dynamic load.
- Local influences of the rope terminations on the state of stress.

The influence of the response and of the rope terminations can be large. Still these will not be considered here, because they strongly depend on the application or construction and give little general information on the length effect.

The strength of the rope or strand will be influenced by:
- The re-establishing property of wires in the wire rope or strand.
- The variation of the material strength of the composing wires.
- The distribution of the damage over the length of the rope.

The distribution of the damage mainly depends on the application, while the distribution of the material strength depends on the quality of the wire. As far as the rope strength is concerned, this paper will be restricted to the re- establishing property of a wire rope or strand.

2. LOAD DISTRIBUTION IN WIRE ROPES.

Different from individual reinforcing bars or prestresssing wires, many attendant stresses appear in steel wires of stranded wire ropes, if they are subjected to a tensile force. Even in case such wire ropes are not bent over sheaves and remain in a straight position, attendant stresses such as contact pressure and bending stress, will reduce the endurance of the individual wires.Direct measurements of the contact pressure between wires and strands are not possible without influencing the rope mechanism. Because of this reason it is difficult to draw up a well verified model of the distribution.Still the contact pressure is interesting, as it can be a factor of a fretting process.It can also be concidered, that the contact pressure is caused by components of the tensile forces in the curved wires and strands. These components have the direction of the principal normal and keep the strands and the rope firmly in their circular shape. Further, contact pressure appears to have at least a relation with the tensile stress in the wires and the tensile force in the strands. So for more than one reason measurements of normal stresses in the wires can be useful, because the results also tels something of the contact pressure.

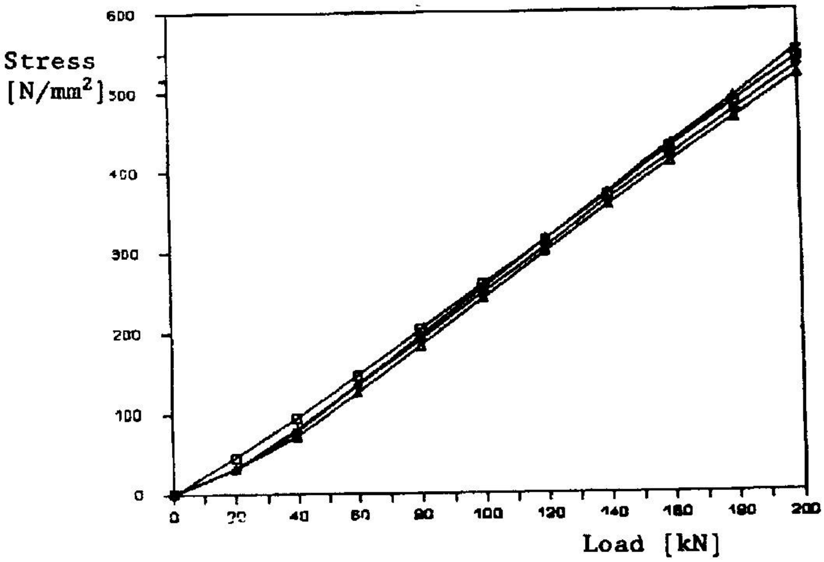


Fig.1 Mean value of normal stress of four tensile tests.

2.1 Stress measurements.

Measurements of normal stresses can be performed by using very small strain gauges with a measuring gritt of about 1 mm times .6 mm. If sufficient strain gauges are cemented more or less random, each at the outer surface of its own wire crown and in the direction of the wire axis, considerable differences in normal stresses will be found.

At Delft these stress measurements were carried out for many years. The tests were performed with about twenty strain gauges, cemented within a distance of two times the lay length of the test rope. From the results the following interesting conclusions can be drawn:

- Apart from the lower loads, the mean value of the normal stresses approximates a linear function of the tensile load.
- As could be expected because of the lower tensile stiffness, the mean value of the normal stress at the outerwires is 5 to 20 % lower than the calculated mean tensile stress of the rope. The difference depends on

the type of wire rope.

- The differences in normal stress at outerwires can be characterised by the standard deviation of the normal distribution.
- A new rope, which is not yet exposed to a dynamic load, can under normal load conditions show very large relative standard deviations. In the past even values of 90 % of the mean value were measured.
- After running in with 10,000 load cycli of moderate load amplitudes, the standard deviation decreased to a lower value.

  Before fifteen years this value was not less than 50 % of the mean value, measured under a tensile load of 25 % of the ultimated breaking load.

  When nowadays ropes are tested under such conditions, standard deviations are found of 30 up to 35 % . This improvement of the quality must be attributed to the quality asurance systems, which many ropemakers have introduced.

2.2 Measuring results.

As an example figures 1, 2 and 3 showe the results of stress measurements performed on a 6x25 Filler wire rope with an independant wire rope core. This rope with a diameter of 26 mm was laid in ordinary lay with a lay-length of 167 mm. The ultimated breaking load (U.B.L.) was 434 kN, while the actual breaking load was 485 kN. Within a length of two times the lay-length of the rope (335 mm) 20 strain gauges were cemented. All gauges were distributed among four strands and four gauges on the same wire.

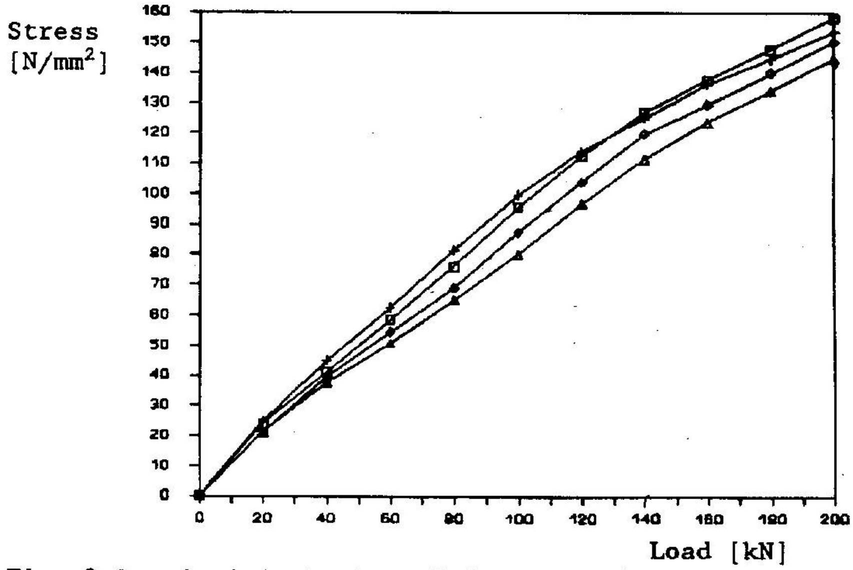


Fig. 2 Standard deviation of four tensile tests.

After preparation the sample was subjected to a tensile test in steps of 50 kN up till a maximum of 200 kN, which means up to 40 % of the actual king load. At each load step the train of the 20 gauges was measured by a fast automatic data logger, which put the results into a personal computer, where these were transformed into stresses and stored in a data base. The data base was connected with a spread sheet programme to produce the graphs in the desired shape. These instruments reduced the risk of measuring errors due to changes in tensile load, mistakes in the calculations and the graphs.

After the static tensile test, the sample was subjected to a pulsating test. The upper bound of the load was 200 kN and the lower bound was 20 kN. The test frequency was 2.5 Hz. After 5000

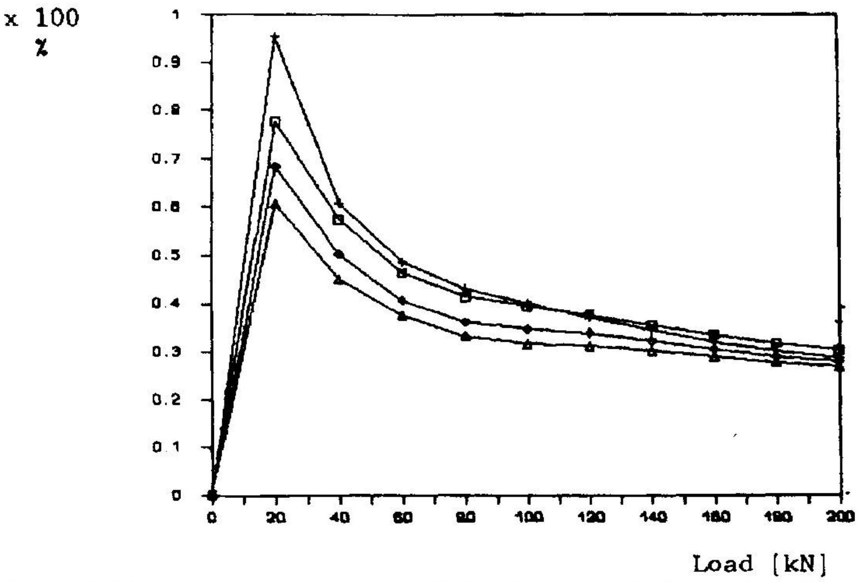


Fig. 3 The relative standard deviation of four tensile

load cycles the pulsation test was interrupted to repeat the tensile test with stress measurements. After two periods of 5000 cycles followed by a static tensile test, the wire with four strain gauges was slit with a small grinding machine. This artificial wire fracture was made in the wire with the strain gauges nr.2 and nr.4. The distance up to the gauge nr. 4 was 7 lays of the wire in the strand, while the gauge nr. 2 was at 12 layst from the fracture. After a second tensile test in order to look after the influence of the fracture, the pulsating test with interuptions was continued. The experiment was ended with a rope fracture at one of the rope terminations after 35260 cycles. This termination was a clamp of the wedge type.

As shown in figure 1, the character of the average stress did not change due to the pulsating load. The value of the average stress under a tensile load of 200 kN tended to decrease by 3,5 % of the maximum stress of 550 N/mm^2.

Also the standard deviation decreased by 13 % of the maximum value after the periods of the dynamic tensile load. See figure 2. Apart from the load of 20 kN the standard deviation increased rather linearly with the tensile load up to 140 kN, which means 30 % of the ultimated breaking load. At a further increase of the load, the deviation tends to stay behind.

The relative standard deviation (fig. 3) has a tendency to approach asymtotically to a value of 31 % before and 28 % after the dynamic load cycles.

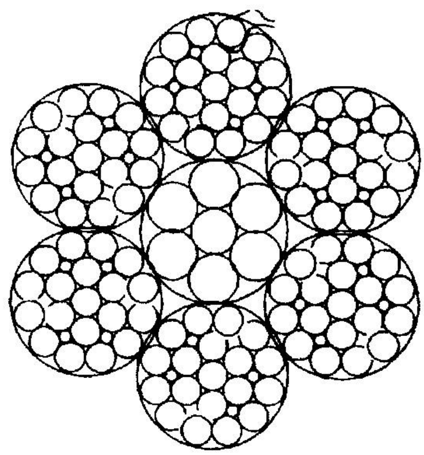


Fig. 4 Strain gauges in and outside the strand.

2.3 Stress measurements inside the strand.

The stresses of the measurements described above were normal stresses and even though the sum of the bending stress and the tensile stress will influence the development of fatigue cracks, it w ould be interesting to separate them. The separation of the tensile stress can provide more certainty about the tensile load distribution.

Therefore, in a new experiment a second strain gauge was cemented in the same wire cross section but just opposite to a gauge on the crown of an outerwire. To ensure that a wire could be taken out of

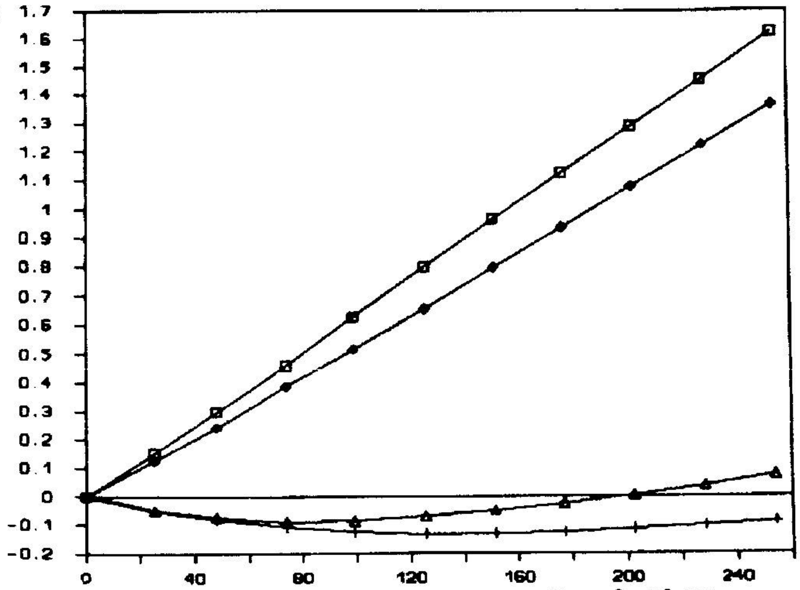


Fig. 5 Measured stresses at a wire in and outside the strand.

a strand in order to cement the gauge inside the strand, a strand had to be taken out of the rope first. The wires around the measuring wire had to be carefully treated in such a way, that the gauge inside the strand would stay free and that the electrical lead wires of the gauge could be guided outside, without running running the risc to be cut off during the measurements. The following step was to carefully replace the wire into the strand and to replace the strand into the rope. The last mentioned action caused a difficult problem, because we could not get the strand back exactly at the same position as before the treatment. It did not lie tight enough around the steel core and, therefore, it was less stiff than the other strands.

Still the measuring results of that experiment are sufficiently interesting to show some of them here.The test procedure of this experiment was more or less equal to the procedure of the described experiment where only gauges at the outside of the rope were used. Figure 5 shows the measured stresses of two pairs of strain gauges, which are very high at the inner side (an avarage of 1460 N/mm$_2$ under a load of 50 % of the U.B.L.) and very low at the outer side (an avarage of 0 N/mm^2 under the same tensile load). How the normal stress appeared to be devided in tensile stress and bending stress, is demonstrated in figure 6 and figure 7.

In this case the tensile stress was of the same order as the bending stress.

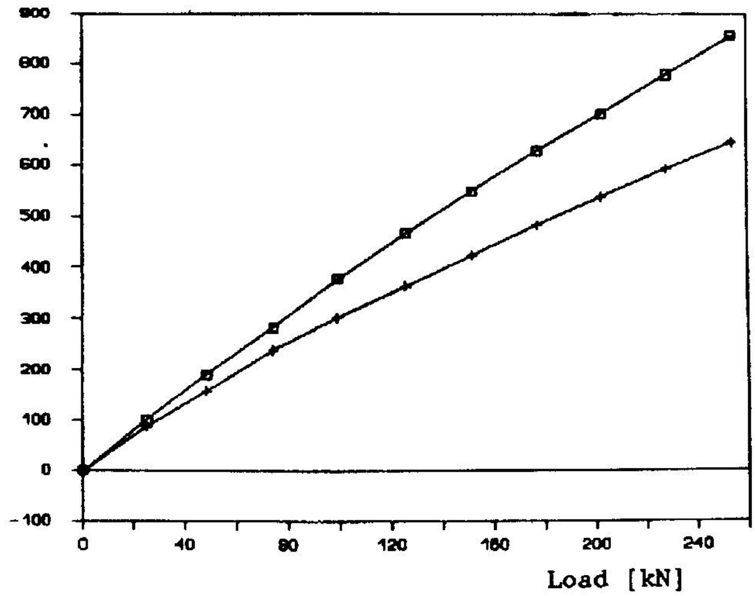


Fig. 6 Tensile stress.

The results are compared with the normal stresses of gauges at the crowns of wires of other strands

than the one with gauges inside. These stresses were **measured at** the same time as those in figure 5. The results - **a maximum** average **normal stress** of 760 N/mm^2 does not give rise to **serious** objections against the maximun average **tensile stress of figure 6** (740 N/mm2). The maximum of the average bending stress of figure 7 (740 N/mm^2), however, is much too high, due to the change in the position of the treated strand already mentioned.
The results of this experiment indicate that one can assume, that the variation of the normal stress is mainly caused by attendant bending stresses and that the distribution of the tension load among strans and wires is more even than the deviation of the bending stress.

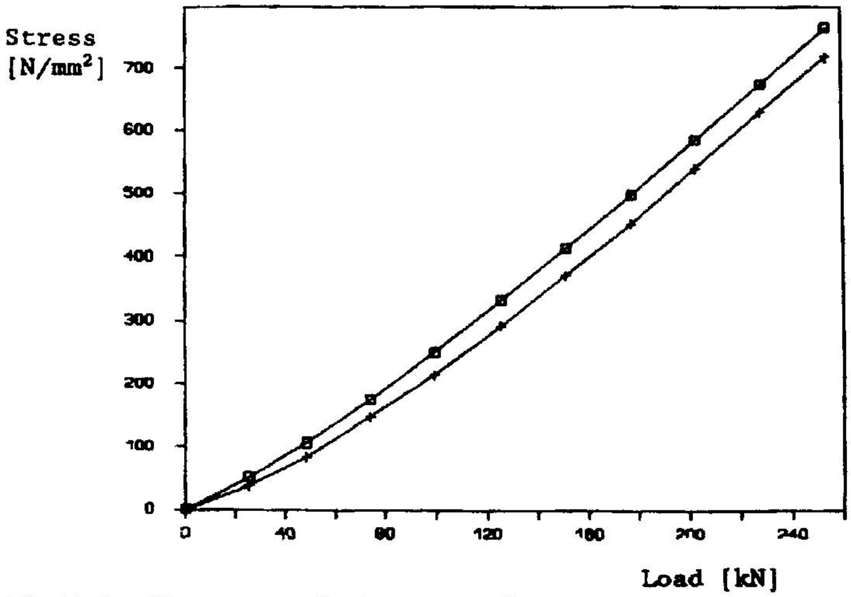


Fig.7 Bendingstress in an outerwire.

2.4 The re-establishing length of a wire fracture.

When describing the first experiment, the make of an artificial wire fracture is mentioned. The intention of that fracture was to verify the earlier found relation [4] between the full re-establishment of the wire function after a fracture and the number of lays of the wire in the strand. The relation was, that 7 lays of a wire in a strand after a wire fracture, the wire will bear its full part of the load again.

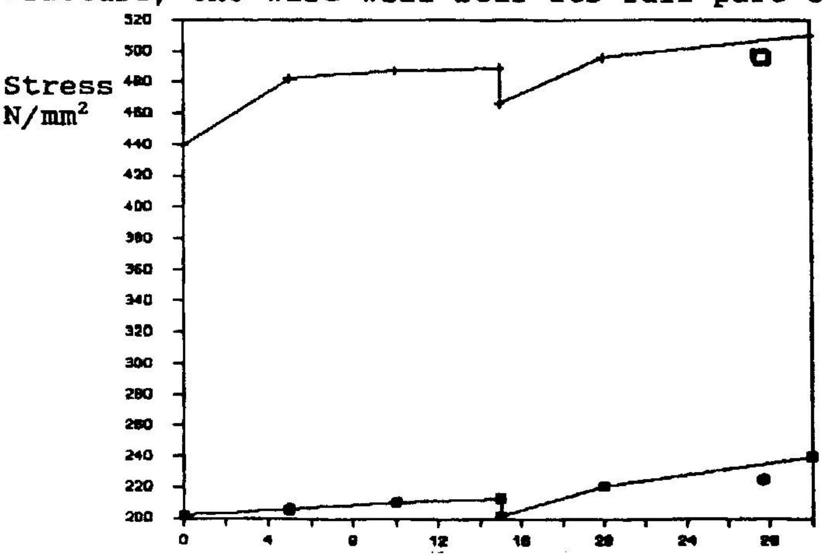
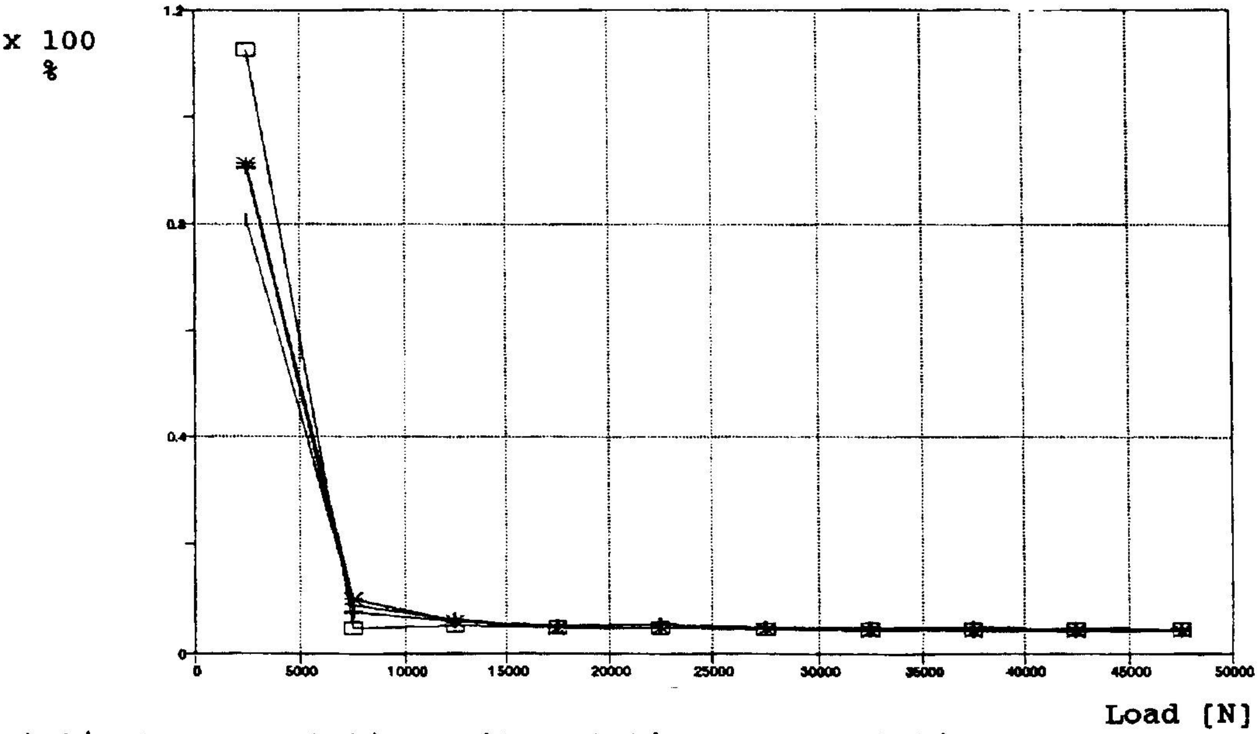


Fig.8 Stress gauge nr.4 as a function of the endured load cycles.

Figure 8 gives the measured stresses of the strain gauge nr.4 at a tensile load of 200 kN as well as at a tensile load of 100 kN as a function of the endured periods of load cycles. The gauge nr.4 was situated at a distance of 7 lays of the wire from the fracture, which was made after three period of 5000 load cycles. Before and after cutting of the wire also the stress was measured. From figure 8 can be observed that the re-establishing length still consist of at least 7 lays of a wire in a strand. This distance corresponds with two to two and a half times the lay length of a rope. The latter is also used as half the inspection length in the discard criteria of ISO [5], because the mentioned distance of 30 times the rope diameter corresponds with two times two and a half lays , which lie at each side of a fictive rope cross section. Besides the inspection length, wire fractures and other damage will not influence the strength of that part of the rope. So, if one looks for a wire rope length that meets the independance assumption for the calculation of the length effect [1], one could consider the inspection length of 30 times the rope diameter could. If e.g. 2 to 3 times the lay length is added to this in order to cover the influence of the rope terminations, a length of about 50 times the rope diameter is found, which is suitable as a minimum length of a wire rope sample for a fatigue test.

3. LOAD DISTRIBUTION IN STRANDS.

The geometry of stranded wire ropes and single strand wire ropes are quite different and therefore their behaviour under static loads as well as under dynamic loads might also be quite different.
Next to the measurements on stranded ropes also stresses of the



static 1 static 2 static 3 static 4
Fig. 9 Relative standard deviation before the wire fracture.

outerwires in a 36 WS strand of 11.4 mm in diameter are measured. The procedure of these measurements was the same as described in item 2.1. Only the number of straingauges was diminished by 10, because of the lower number of outerwires. Therefore, the attention can be focused on the measuring results. The mean value

of the normal stresses due to the stepped tensile tests were up to 48 kN nearly linear to the tensile load and reached a **maximum** value of 500 N/mm2.
Also in this case a period of 5000 cycles of the **pulsating test** (upper load 49 kN, lower load 22 kN) caused a **small decrease by** the mean stress value. After the artificial **wire fracture was** made, the maximum of the mean value **was stabilized at 450 kN.** Before the wire fracture the **relative standard deviation of the** stresses (Fig. 9) **showed a very fast approach to a stable value of** 4.5 % After the fracture the relation **between the relative** standard deviation got a characteristic course **(Fig.10)**.
Under moderate loads the **maximum** standard deviation **was** 38 %.,

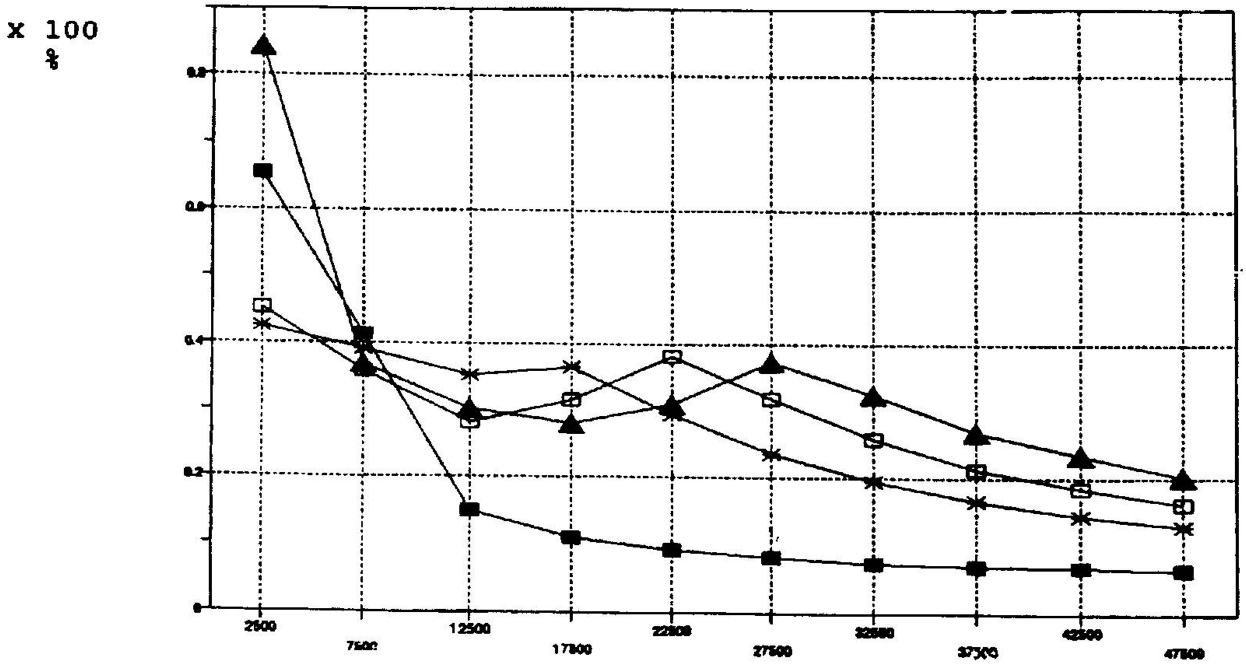
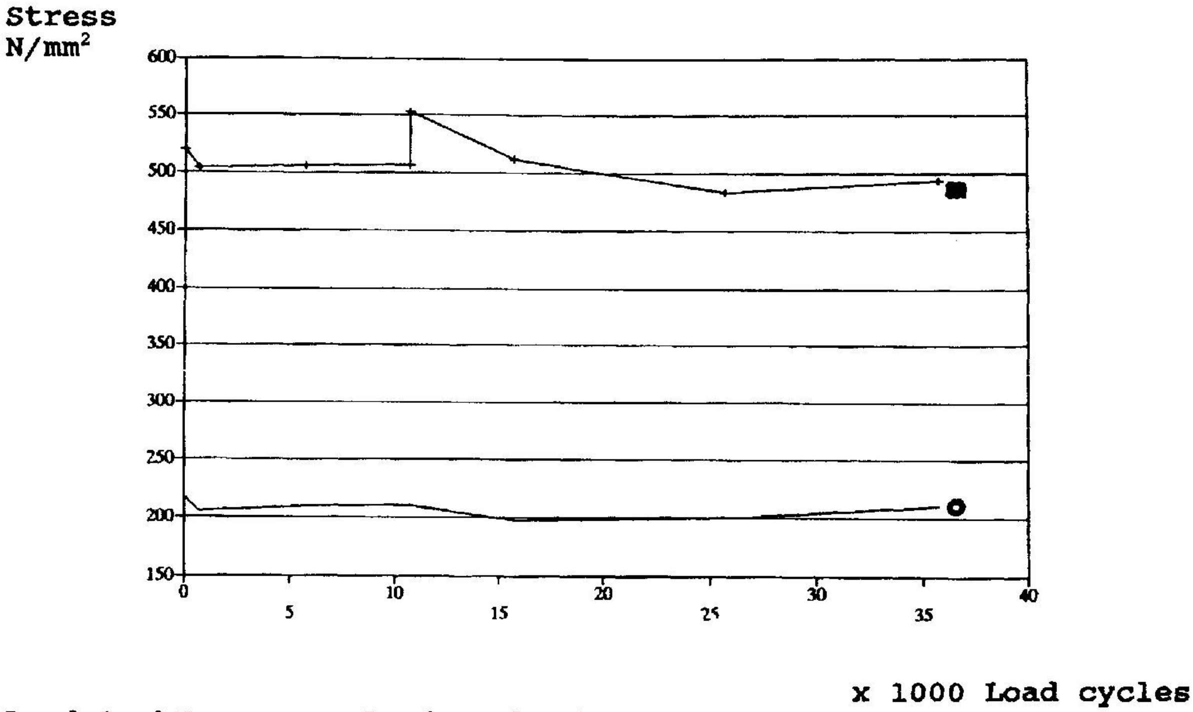


Fig. 10 Relative standard deviation after the wire fracture
static 5 ■ static 6 ✕ static 7 □ static 8 ▲

while under the maximum load it tended to approach 18 % .

3.1 The re-establishing length.

After four tensile tests alternated with three **periods of 5000** cycles of the pulsation test, a wire **fracture was simulated by** grinding off the wire at a distance of 7 lays **from strain gauge** nr.8. The figure nr. showes an **increase of the stress by 10 %.** After the next 5000 cycles of the **pulsating test the stress** returned to its original value.
The last figure indicated that a re-establishing length of a **wire** in a single strand could be a length of 7 lays. **With a lay length** of about 7 times the strand diameter and one **re-establishing** length at each side of an imaginary **strand cross section the** length which meets the independent assumption **can be taken 100** times the strand diameter. If the lay length **is much more than** seven times the strand diameter, however, the validity **must be** verified. In this case, however, the wire was not **turned out of** the rope and that must be taken as a condition.



Load 24 kN o Load 48 kN ■
Fig. 11 Mean stress of gauge nr.8 after periods of dynamic load.

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