Fatigue test of a large diameter steel wire rope of a cable-stayed bridge

Autor(en): **Dijkstra, Onno D. / Dooren, Frank van**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

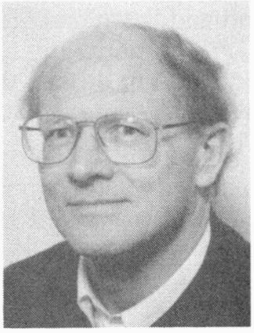
Band (Jahr): **76 (1997)**

PDF erstellt am: **08.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-57471

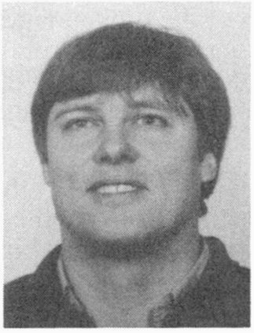
Fatigue Test of a Large Diameter Steel Wire Rope of a Cable-Stayed Bridge

Onno D. DIJKSTRA
Civil Engineer
TNO
Rijswijk The Netherlands



Onno Dijkstra, born 1945, received his civil engineering degree at the Delft University of Technology. Since 1974 he has worked for TNO and has been involved in fatigue and fracture mechanics research and consulting.

Frank van DOOREN
Senior Engineer
Dir.-Gen. Public Works
Zoetermeer, The Netherlands



Frank van Dooren, born 1963, received his civil engineering degree at the Delft University of Technology. Since 1988 he has worked for the Directorate - General for Public Works and Water Management and is now senior engineer at the steel department of the Civil Engineering Division.

Summary

Broken wires were found in the cables of a bridge after 15 years in service and it was decided to fatigue test a spare length of the cable. This paper presents the results of the fatigue test on a large diameter (∅ 101 mm) locked coil cable of the bridge. The initial variable amplitude fatigue load was determined by measurements on the bridge. A high constant amplitude fatigue load was necessary to get wire failures in the cable. The test shows that the cable is capable of resisting the design load although deterioration of the cable is clearly visible on the outside of the cable. Based upon the results it was recommended not to take any replacement actions. Monitoring the cables every five years was recommended.

1. Introduction

During maintenance work of the locked coil cables (∅ 101 mm) of a cable stayed bridge some broken wires were found. At that time the bridge was 15 years in service. The management of the bridge was concerned about the remaining lifetime of the cables.

Preliminary investigations of the fracture surface of some broken wires removed from the bridge cables indicated that fatigue starting from minor fabrication defects were the cause of the wire failures. These defects were laps, defined as imperfections caused by impressing or working an excess of metal or an irregularity into the surface of a wire.

At the time of bridge erection a 4 meter cable with conical end sockets was supplied and placed on the bridge. This was available for testing and was transported to the laboratories of TNO Building and Construction Research in Rijswijk, Netherlands and tested in a 10 MN test rig.

The cable was installed and prestressed before fatigue testing. The fatigue test was carried out in three phases with three different increasing load spectra. After the fatigue test the cable was dismantled into separate wires. The experimental results were evaluated and fatigue fracture mechanics analyses were carried out on single wires [1], thus enabling conclusions with regard to the remaining fatigue life to be made.

2. Preliminary investigations

After the "lucky" discovery of some broken wires in the cables of the bridge, the total length was investigated during maintenance work. The widths of openings in broken wires were measured. The relatively small number of broken wires and the small width of openings due to cracks (reduction of cable cross-sectional area only over a short length) indicated that there was no immediate danger for the use of the bridge.

Parts of the broken wires were taken out for investigation and the actual effect of the traffic (stress spectrum during an ordinary day) was measured. Preliminary fatigue analyses indicated that the laps found on the broken wires were too small to result in broken wires after such a short time. However, no other explanation than fatigue initiated at the laps due to the traffic load could be found.

Because the inside of the cables could not be investigated easily and no simple model could be made to investigate the future deterioration of the cables TNO was asked to carry out a fatigue test on the available 4 meter cable with sockets.

3. Test specimen and instrumentation

The specimen is a locked coil cable with both ends provided with end sockets. The free cable length between the sockets is 3.72 m. The cable has 9 layers of wires. The outer two layers were full lock Z shaped wires (see Figure 1). Further specifications were as follows:

Nominal diameter	D =	101 mm
Cross-sectional area	A =	6900 mm^2
Minimum breaking load	Ff =	9030 kN
Aggregate breaking load	Fa =	10076 kN
Apparent Young's modulus	Ea =	150000 N/mm^2

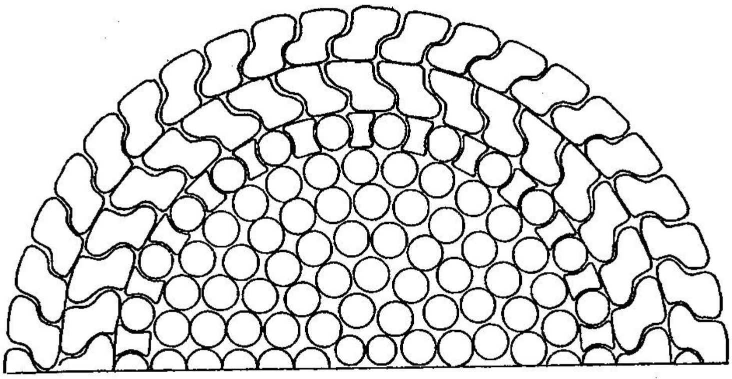


***Fig. 1** Cross-section of steel wire rope*

The specimen was equipped with ten strain gauges on the outer wires. These gauges were located on different wires in two cross-sections at 1/3 and 2/3 of the cable length. Displacement measurements between the two sockets were carried out during the whole test. Displacement of the socket filler material was measured during the second part of the fatigue test as it turned out that the socket filler material was moving into the sockets.

4. Loading

4.1 Preloading

Before the fatigue test the cable was preloaded. This was done in the same way as for the cables in the bridge. The cable was loaded ten times between 900 kN and 3000 kN. Strain and deflection measurements were carried out during preloading. From these measurements an apparent Young's modulus of 156000 N/mm^2 was found (nominal value 150000 N/mm^2). The measured strain range corresponds very well with the theoretical value (based on cross-sectional area and Young's modulus equal to 210000 N/mm^2).

4.2 Fatigue testing

The fatigue loading on the cable during the first phase was based on strain measurements on the cables in the bridge in the year 1990 during 11 hours. Using traffic counting during a longer period the measurements were extrapolated to a year spectrum of 817898 cycles. The cumulative year spectrum of the stress ranges is given in Figure 2.

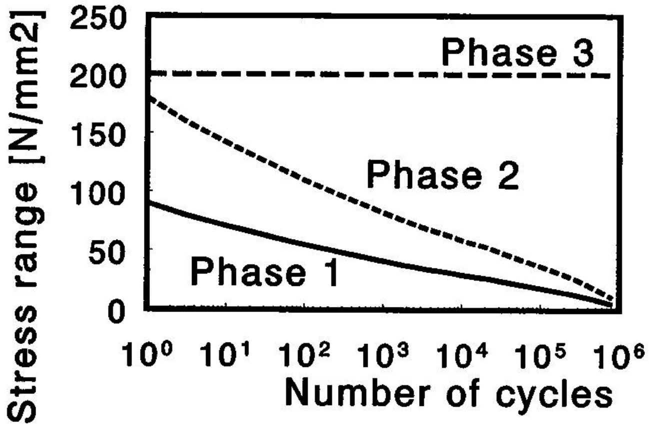


Fig. 2 Cumulative stress spectra

Using a random selection procedure the stress ranges of the year spectrum were put in a certain sequence and translated to a variable load sequence for the cable. The minimum loads were set at a constant value of 2350 kN (stress in the cable 341 N/mm^2), corresponding to the dead weight load in the cable in the bridge. With a maximum stress range of 90 N/mm^2 in the spectrum the maximum load in the cable is 2971 kN. The maximum load range is approximately 70 % of the load range due to the design traffic load.

The frequency of the loading was depending on the magnitude of the load(stress) range according to Equation (1), with a maximum frequency of 5 Hz, giving an average frequency of 4.16 Hz.

$$f = 53 / \Delta\sigma \quad (1)$$

A total of 30 million cycles (approximately 37.7 year spectra) were applied to the specimen. As no visible or measured damage was noticed the fatigue test was stopped and the test was continued with a higher fatigue load in the second phase.

In the second phase the variable part of the loading was doubled with regard to the first phase (see Figure 2). The minimum load was kept on the first phase level (2350 kN). The same relation between load range and frequency was used, resulting in an average frequency of 2.5 Hz for the second phase. The maximum load during the second phase was 3592 kN.

A total of 4 million cycles (approximately 4.9 year spectra with double stress ranges) were applied to the specimen. As again no visible or measured damage was noticed the second phase of the fatigue test was stopped and the test was followed by the third phase.

In the third phase a constant amplitude load with a load range of 1380 kN ($\Delta\sigma$ = 200 N/mm^2) was applied (see Figure 2). The minimum load was again 2350 kN. The frequency in the third phase was 0.45 Hz. The maximum load during the third phase was 3730 kN.

A total of 1.266 million cycles were applied to the specimen in this third phase.

5. Experimental results

5.1 Phase 1 and 2

During phase 1 and 2 the regular measurements of the displacements and the strains did not show very interesting results.

The only real interesting thing is that the socket filler material was moving into the conical socket. This was discovered during the first phase after approximately 3 million cycles. From then on this phenomenon was measured by a displacement gauge at the centre of the back of the conical socket. This movement of the socket filler material results in an increase in the distance between the sockets. So, the displacement gauges for the change in length of the cable are also measuring this movement.

5.2 Phase 3

During this phase a small number of wires were broken and a larger number of wires were pulled out from the sockets. Most of the failed wires were from the outer layer (layer number 9). The development of the number of broken or pulled-out wires of the outer layer is almost linearly proportional to the number of cycles (see Figure 3). The first wires to be pulled out (two) were found after 463000 cycles and at the end of the test at 1.266 million cycles a total of 32 outer wires were broken or pulled-out.

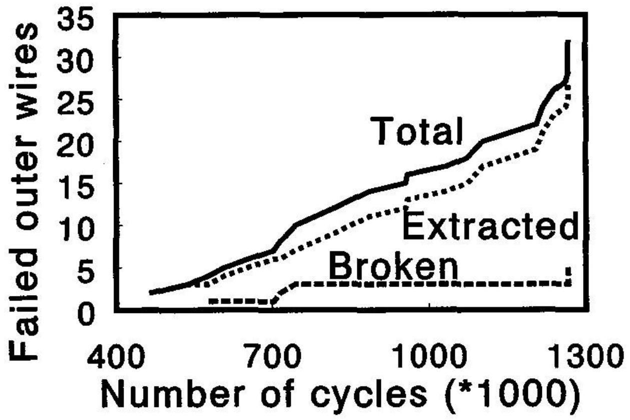


Fig. 3 Number of broken or pulled-out outer wires as a function of the number of cycles

After the test the cable was unravelled and seven additional broken or pulled-out wires were found in internal layers (4 in layer 8 and 3 in layer 7).

The test was load controlled, so that broken wires resulted in an increase in displacements.

Recordings of the strain and displacement gauges were carried out 52 times during the 1.266 million cycles. Measurements were taken at the minimum value of the load cycle (2350 kN) and the maximum of the load cycle (3730 kN).

The recording of the change in distance between sockets as the test load cycled from the minimum to the maximum load indicated an increase in flexibility at the end of the test due to broken and pulled-out wires (see Figure 4). The theoretical change in length due to the loss of cable section is approximately 5 mm. This agrees well with the measured value of between 4.5 and 5.0 mm.

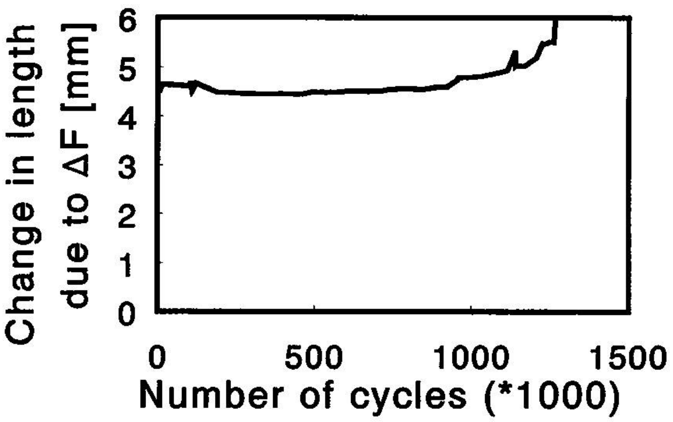


Fig. 4 Change in length due to load range as a function of the number of cycles

The loss in cross-section due to broken wires at the end of the test was approximately 20%. This means an increase in flexibility of 25%. The change in length at the end of the test was approximately 6 mm. These figures agree very well with each other.

The increase in distance between the sockets at maximum load during the fatigue test is approximately 22 mm (see Figure 5). The displacement of the socket filler material is responsible for 5 mm of this displacement (see Figure 6). The loss of 32 outer wires means a loss in cross-section of 1650 mm^2 (6900 mm^2 to 5250 mm^2) and can be equated to an additional length at maximum load of 4 mm. The loss of the wires in the inner layers (7 broken wires) is responsible for 1 mm. The remaining increase in length of 12 mm can not be explained directly. Causes for this length increase can be an overall sliding of the wires in the socket filler material or relatively more sliding of the inner wires with regard to the outer wires.

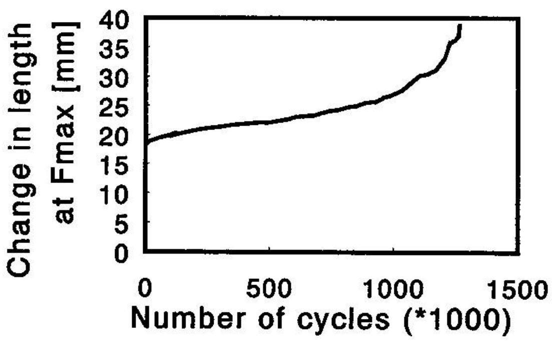


Fig. 5 Increase in length at maximum load as a function of the number of cycles

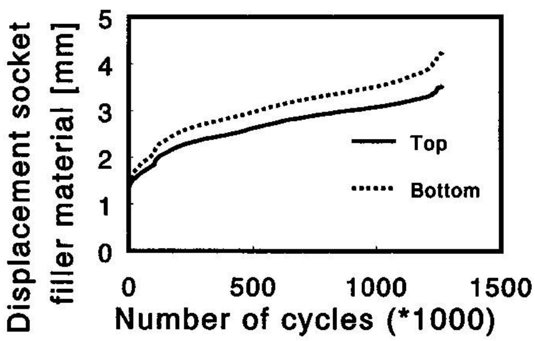


Fig. 6 Displacement of socket filler material as a function of the number of cycles

The strain measurements on the ten wires gave a clear indication of when a wire was broken or pulled out. In some cases it turned out that the strain readings gave an indication before the failure was discovered by visual inspection.

In some cases there seems to be an inconsistency between the readings of the strain range and the maximum strain. However it is likely that a broken wire is still strained by the fluctuating load (due to support of the neighbouring wires) while the maximum (or average) strain has dropped due to the failure.

6. Fracture and wire surface analyses

After the fatigue test the wires of the specimen were unravelled. The results of this unravelling can be summarised as follows (layer numbering from inside to outside):

layer 1 to 6	- no failures
layer 7	- 3 broken wires in the free length (1x round and 2x half lock)
layer 8	- 4 broken wires in the free length
layer 9 (outside)	- 32 failed wires, of which:
	. 13 pulled out from the top socket
	. 1 broken in the top socket
	. 5 broken in the free length
	. 7 broken in the bottom socket
	. 6 pulled out from the bottom socket

Fracture analyses were carried out on 13 fracture surfaces. Nine of the failures were due to fatigue initiation from laps. Three failures showed no fatigue crack growth and were caused by overloading. One wire failed due to the presence of an unexplained severe mechanical defect.

Wire surface inspections were carried out on 12 wires. Some of the wires were chosen randomly and others were from broken wires. The random wires showed no defects, minor longitudinal grooves or a light crackle pattern. A number of the broken wires showed laps on the surface and a maximum lap depth of 0.5 mm was found.

7. Evaluation

7.1 General

The translation of the behaviour of the test specimen to the behaviour of the cables in the bridge is not simple. The main reasons for the difficulties are:

- The difference in length of the specimen (≅ 4 m) and the length of the cables in the bridge (≅ 6000 m). Applying the weakest link model to this situation means that we can consider the cable in the bridge as 1500 test specimens. The question is: "What is the relation between the test specimen and the weakest link in the cable".
- The fatigue load in the test is different from the fatigue load on the bridge cable (only for phase 2 and 3).
- At the end of the fatigue test the specimen was not failed completely. The maximum load in the fatigue test (3730 kN) could still be applied to the specimen, while the maximum design load (only 3250 kN) is below this value. The theoretical breaking load of the cable is 9000 kN.

In the next sections evaluations are made using the results of the total specimen (Miner summations and statistical evaluations) and fatigue fracture mechanics analyses of single wires.

7.2 Total rope evaluation

7.2.1 Cumulative damage evaluation

Using the Palmgren-Miner cumulative damage rule (Equation (2)) the total damage of the three different load spectra can be determined.

$$D_{tot} = \sum_i D_i = \sum_i \frac{n_i}{N_i} \tag{2}$$

where:

D_{tot}	=	total cumulative damage
D_i	=	cumulative damage due to stress range $\Delta\sigma_i$
n_i	=	number of stress ranges $\Delta\sigma_i$
N_i	=	lifetime at stress range $\Delta\sigma_i$

For the $\Delta\sigma$-N curve a conservative straight curve can be used (Equation (3))

$$(\Delta\sigma)^m \cdot N = (\Delta\sigma_{ref})^m \cdot N_{ref} = C \tag{3}$$

where: m = slope $\Delta\sigma$-N curve
C = a constant determining the level of the $\Delta\sigma$-N curve

Combining the two equations above gives the ratio (R_{Dexp}) between the damage of an experimental spectrum (D_{exp}) and the damage of the year spectrum ($D_{j\text{-}sp}$)

$$R_{D\exp} = \frac{D_{\exp}}{D_{j-sp}} = \left(\frac{\Delta\sigma_{\exp}}{\Delta\sigma_{j-sp}}\right)^m \cdot \frac{n_{\exp}}{n_{j-sp}} \tag{4}$$

Equation (4) can be used with an equivalent stress range ($\Delta\sigma_{eq}$) for the spectrum according to Equation (5).

$$\Delta\sigma_{eq} = \left[\frac{\sum_i (\Delta\sigma_i^m \cdot n_i)}{\sum_i n_i}\right]^{\frac{1}{m}} \tag{5}$$

The value for the slope of the S-N curve (m) is dependent on the ratio of the total life and the crack growth life. A conservative value for crack growth only is $m = 3$. For the wires of the cable a more realistic value will be 4 or 5. The calculated values for the equivalent stress range ($\Delta\sigma_{eq}$) is as follows:

13.6 N/mm^2 for $m = 3$
15.2 N/mm^2 for $m = 4$
17.0 N/mm^2 for $m = 5$

The damage of phase 3 is governing in the damage analysis (see Table 1). The damage is very much depending on the value of m. Without further information a value of 4 is considered as conservative. This conservative value gives an experimental damage equivalent to the 46000 year spectra.

Loading	Slope S-N curve m	Stress ratio $R\sigma = \Delta\sigma_{exp} / \Delta\sigma_{j\text{-}sp}$	Stress correction factor $f\sigma = R\sigma^m$	Lifetime correction factor $fn = n_{exp} / n_{j\text{-}sp}$	Relative damage $R_{Dexp} = f\sigma * fn = D_{exp} / D_{j\text{-}sp}$
phase 1	3 , 4 or 5	1	1	36.7	36.7
phase 2	3	2	8	4.89	39.1
	4	2	16	4.89	78.2
	5	2	32	4.89	156.5
phase 3	3	14.7	3189	1.55	4937
	4	13.1	29614	1.55	45841
	5	11.8	225375	1.55	349331
Total damage for phase 1+2+3	3				5013
	4				45956
	5				349524

Table 1 *Damage analysis according to Palmgren-Miner*

7.2.2 Statistical evaluation

Without further knowledge one test result is not enough to make a statistical evaluation (no information about scatter). However, using existing knowledge about the behaviour of welded steel specimens one can make a statistical analysis.

The standard deviation for welded joints using a lognormal distribution is approximately a factor of 1.5 on lifetime (standard deviation is ln(1.5) on the logarithmic scale)[2]. The slope of the $\Delta\sigma$-N curve is 3 for welded joints. It is generally known that for specimens smoother than welded specimens the slope and the scatter is higher. The wires of the cable can be considered as smooth specimens. Therefore the factor for the scatter has to be increased for larger values of *m*.

A design line is generally the mean minus two standard deviations. This means that with the slope of 3 and the factor of 1.5 on life there is a ratio of 2.25 for the level of the mean line and the design line. It is assumed that for the slopes of 4 and 5 this ratio will be doubled, so:

slope	ratio mean/design	standard deviation on logarithmic scale
	f^2	$\ln(f)$
3	2.25	ln(1.500)
4	4.50	ln(2.121)
5	9.00	ln(3.000)

The experimental result as evaluated in the section above has to be considered as the average value. Due to the fact that we have only one experimental result the standard deviation has to be increased with a factor F_0 depending on the number of specimens n (here $n = 1$).

$$F_0 = \sqrt{1+\frac{1}{n}} \quad \text{so:} \quad F_0 = \sqrt{2} \tag{6}$$

So, the relative design damage ($R_{Ddesign}$) can be determined as follows:

$$\ln(R_{Ddesign}) = \ln(R_{D\exp}) - 2\cdot\sqrt{2}\cdot\ln(f) \quad \text{or} \quad R_{Ddesign} = R_{D\exp}\cdot f^{-2\cdot\sqrt{2}} \tag{7}$$

The calculated relative design damage ($R_{Ddesign}$) is well above a relative design damage in 75 years ($R_{D75} = 75$) (see Table 2).

Assuming end of test as failure the reliability index (β) and the failure probability (Pf_{4m}) for the specimen with a length of approximately 4 m can be determined with Equation (8)

$$\beta = \frac{\ln(R_{D\exp}) - \ln(R_{D75})}{\sqrt{2}\cdot\ln(f)} \tag{8}$$

The failure probability of the cable in the bridge (length 6 km) can be determined by multiplying Pf_{4m} with 1500 (= 6000 / 4). The calculated failure probabilities (see table 2) increase with increasing slope (value of *m*). The more favourable mean lives for higher values of *m* are override by the higher assumed scatter. The calculated failure probabilities are low with regard to normal design requirements ($Pf = 1.6*10^{-4}$).

Slope S-N curve m	Relative damage experiment R_{Dexp}	Relative design damage $R_{Ddesign}$	Reliability index β	Failure probability 4 m cable Pf_{4m}	Failure probability 6 km cable Pf_{6km}
3	5013	1592	7.329	$1.2*10^{-13}$	$1.8*10^{-10}$
4	45956	5477	6.034	$8.3*10^{-10}$	$1.2*10^{-6}$
5	349524	15631	5.437	$2.8*10^{-8}$	$4.2*10^{-5}$

Table 2 *Relative design damage, reliability index and failure probability for 75 years*

7.3 Crack growth analyses

A fracture mechanics crack growth analysis was carried out on the single wire geometry. In these analyses the initiation phase is neglected and only the lifetime from an initial defect to a final defect is determined. The Z-shaped wire is schematised to a square cross-section with a length of 7 mm and a constant depth edge crack at one side. The stress intensity factor used was for membrane stress only and for a bending restrained situation [3]. It is assumed that the wire is supported by the neighbouring wires so that no bending deformation can occur.

The crack growth parameters for an average and for a design (safe) da/dN-ΔK curve are taken from PD 6493 [4]. A range of initial defects was used (from 0.1 mm to 1.0 mm). The final defect for all analyses was 4 mm. The equivalent stress ranges of the bridge spectrum mentioned earlier are used.

The results of the crack growth analyses expressed as the lifetime in years, carried out with the TNO program FAFRAM [5], are given in Table 3. It should be pointed out that for small cracks the stress intensity factor is very low and well below the threshold value for normal steel. So it can be expected that the values in Table 3 are very conservative. The lowest design life is 74 years for a stress range of 17.0 N.mm^2 and an initial defect of 1.0 mm. The lifetimes determined for small initial defects are of the same order of magnitude as those found in Section 7.2.2 for $m = 3$.

Initial defect	Stress range 13.6 N/mm^2		Stress range 15.3 N/mm^2		Stress range 17.0 N/mm^2	
[mm]	$L_{average}$	L_{design}	$L_{average}$	L_{design}	$L_{average}$	L_{design}
0.1	1645	1004	1155	705	842	514
0.2	1026	626	720	440	525	321
0.3	756	461	531	324	387	236
0.4	597	365	419	256	306	187
0.5	490	299	344	210	251	153
0.6	413	252	290	177	211	129
0.7	354	216	248	152	181	111
0.8	307	187	216	132	157	96
0.9	269	164	189	115	138	84
1.0	237	145	166	102	121	74

Table 3 *Lifetime in years according to fatigue fracture mechanics analyses*

8. Conclusions, remarks and recommendations

The direct conclusions based on the evaluation of the experimental results are as follows:

- Most of the wire failures were fatigue cracks initiated at laps on the full lock wires.
- An evaluation based on Miners rule and a statistical analysis (using existing general fatigue knowledge) gives design lives of 1000 year or higher and a probability of failure for the cables in the bridge of $4*10^{-5}$ or lower.
- Fracture mechanics crack growth analyses on single wires showed design lives ranging from 75 to 1000 years.
- The general behaviour of the cable during the fatigue test showed that the degradation process is gradual. At the end of the fatigue test with a number of failed wires the cable was still capable to carry a load higher than the maximum design load.

For the bridge management the test has provided a better understanding of the fatigue behaviour of the cable and the evaluation of the test results showed an adequate safety of the cables during the design life of the bridge.

The experiment showed further that the problems are confined to the full locked wires in the outer layer. This combined with the fact that the width of openings at cracks in the broken wires of the bridge remains small (reduction of cross sectional area only over a short length) leads to the conclusion that the remaining area in any cross section will stay large even though a number of wires were broken over the length of the cables.

The experiment shows that the specimen is capable of resisting more than the design load although deterioration of the cable is clearly visible on the outside. So, the system warns before failure.

Based upon the results the bridge management was recommended not to take any replacement actions. It was recommended to monitor the actual state of the cables every five years.

References

1. DIJKSTRA, O. D., "Cable for bridge", TNO report 96-CON-R0527 (in Dutch).

2. British Standard Institution "Steel, concrete and composite bridges ; Part 10. Code of practice for fatigue" BS 5400 : Part 10 : 1980.

3. HARRIS, D. O. , J. Bas. Engineering, 89 (1967), p. 49.

4. British Standard Institution "Guidance on methods for assessing the acceptability of flaws in fusion welded structures", PD 6493 : 1991

5. DIJKSTRA, O. D., and STRAALEN, IJ. J. van, "Fatigue crack growth program FAFRAM (FAtigue FRActure Mechanics)" TNO report BI-91--51