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Case study

A failure analysis study of a prestressed steel cable of a suspension bridge

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ABSTRACT

This paper presents results of a failure analysis study to characterize the damage phenomenon that occurred in prestressed steel cables of a suspension bridge. This study includes: material characterization using chemical, microstructural and hardness analysis; fractographic analysis by scanning electron microscopy (SEM); mechanical tests of the material in static tension; fatigue tests (*S–N* curves) and fractographic analysis of fatigue fracture surfaces. The fatigue tests were carried out in laboratory air only and in the laboratory air also but after previous exposure in tap water to simulate the working environment of the cables. Fractured surfaces of the rods were of brittle failure type and also of cup and cone type. Due to the characteristics of the work environment (close to a river) stress corrosion was also observed and it is likely oxygen embrittlement was obtained.

Results from fatigue tests and fractographic study allow to the conclusion that the main cause of cable failure, which led to a collapse of the bridge, was stress corrosion cracking (SCC).

1. Introduction

This paper presents the study of the damage causes occurring in one of prestressed steel cables of a suspension bridge. The bridge is used to cross one of the most important rivers in the centre of Portugal. The main structural elements of the bridge are steel cables. Each cable is composed of 84 wires, distributed by 12 (6 + 1) twisted wires. Each of the wires has a thickness between 4.5 mm and 4.65 mm. All the damaged cable part, subject of this study (Fig. 1) matched inside the anchor, with a length of 1950 mm.

The damage in the wires caused the collapse of the bridge. As a result there was a significant disturbance in traffic over the bridge because it stopped for a significant period of time and were made repair operations (NOE, 2004). In some wires occurred failures due to excessive oxidation, corrosion. Therefore, was performed a study to assess the damage process.

The cables presented distinct fractures modes, identified macroscopically:

- 21 wires, corresponding to all three rods winding, exhibited ductile fracture surfaces, type “cup and cone” (Fig. 2), near the beginning of the anchor (between 100 and 250 mm).

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Fig. 1. Damage cable part (subject of this study) matched inside the anchor, with a length of 1950 mm.

Fig. 2. Ductile fracture surface, type "cup and cone".

- 45 wires fractured the distance between 600 and 900 mm from the beginning of the anchor and showed high state of corrosion (Fig. 3a), brittle fracture type displayed some, of which end, in "arrow point" (Fig. 3b and c), developed along in various lengths, sometimes reaching 50 mm.
- The remaining wires have not undergone any fracture.

This paper presents a summary of the more relevant results obtained in this failure analysis study:

- Chemical, mechanical and microstructural material characterization.
- Fractographic analysis by scanning electron microscopy (SEM) of samples obtained directly from damaged cables.
- Study the fatigue behaviour through tests performed under field conditions, the most similar to environmental conditions that the cables were subject (with and without river water contact). Then the cables have been tested in air with and without tap water exposure.
- Fractographic analysis by scanning electron microscopy (SEM) of fatigue specimens tested.

Were done fatigue tests to obtain the fatigue strength of the material of the cables in an environment similar to that in service and in specimens taken from those in service, i.e. in the gripping zones of the wires and also outside the gripping zones for comparative purpose. The corrosion properties were also evaluated in terms of weight loss, which in this case was found to be negligible. However was obtained significant pitting.

a) b) c)

Fig. 3. Brittle fracture surface showing: (a) corrosion; (b) and (c) "arrow point".

2. Chemical, mechanical and microstructural characterization of the cable material

The tensile tests carried out following ASTM E8 specification were done in cylindrical specimens with gauge length $l_0 = 20$ mm, taken from the wires with thickness between 4.5 and 4.65 mm. The dimensions of the wires and cables were carefully checked using a digital micrometre with an accuracy of 0.02 mm. The mean values of the mechanical properties obtained on tensile tests, with a deformation speed of 1.0 mm/min (Branco and Sousa e Brito, 2006; National Laboratory of Civil Engineering, 2007), were:

- Yield strength, $S_y = 1652$ MPa.
- Ultimate strength, $S_{ut} = 1899$ MPa.
- Rupture strain, $\varepsilon = 8\%$.
- Reduction of area, $q = 7\%$.

Mean hardness value obtained in 10 specimens was 556 HV2 (Vickers scale with 2 kgf applied load). The material showed brittle type behaviour with high strength and low elongation (Branco and Sousa e Brito, 2007).

Chemical composition of the cable material is indicated in Table 1. This analysis was performed using a spectrometer emission spark, Baird Spectrovac 2000, according to the PD 05.4/009 and PD 0.54/012 standards (Branco and Sousa e Brito, 2006; National Laboratory of Civil Engineering, 2007). Showing that the structural material was of high strength and low ductility, hypereutectoid steel (%C > 0.8%) of manganese type.

There were observed very fine microstructure, aligned in the longitudinal direction with non-metallic inclusions. Fine pearlite regions were visible by SEM (Fig. 4a and b).

3. Fractographic analysis of damaged wires

Fractographic analysis was performed by scanning electron microscopy.

Specimens with ductile failures (cup and cone type) identified for small magnifications with secondary failures of the radical type starting from a central zone (Fig. 5a and c); larger magnifications of that central zones identified typical morphologies of this fracture mode, designated by "coalescence of cavities" (Hull, 1999) (Fig. 5b and d).

Table 1
Chemical composition of the cable material.

Element	[%]
Carbon (C)	0.91
Manganese (Mn)	0.59
Phosphorous (P)	0.02
Sulphur (S)	0.06
Silicon (Si)	0.39
Copper (Cu)	0.12
Nickel (Ni)	0.07
Chromium (Cr)	0.06
Molybdenum (Mo)	0.06

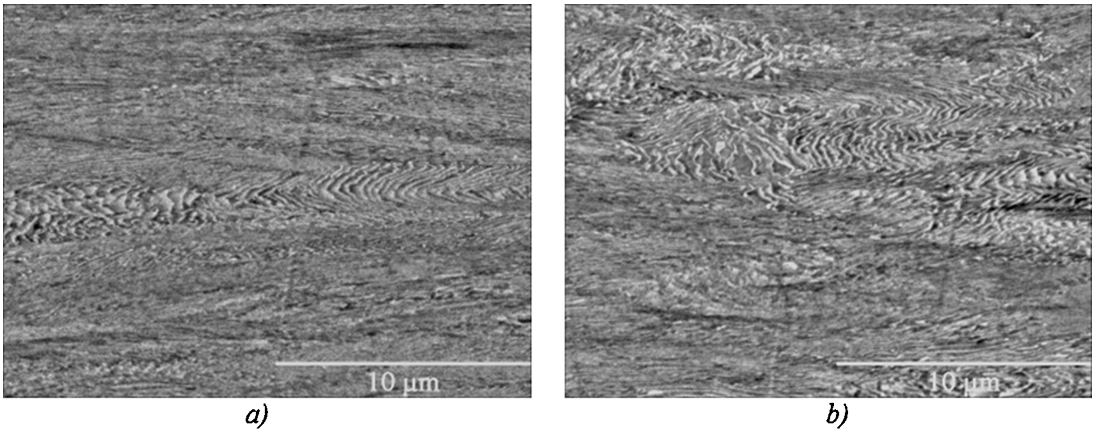

Fig. 4. Zones of fine and aligned pearlite observed by SEM.

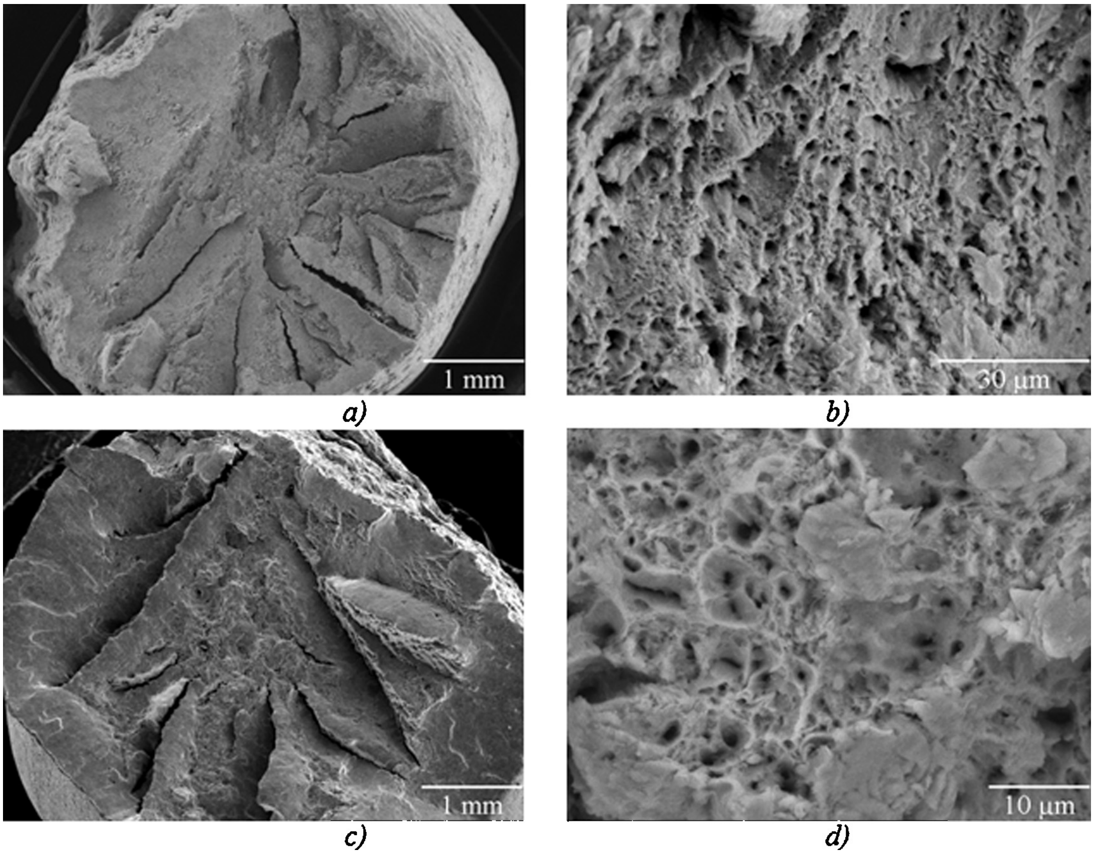

Fig. 5. SEM observation: (a) and (c) ductile type failure; (b) and (d) central zone of the specimen showing a morphology obtained by void coalescence.

Specimens with failures of the arrow point type were observed along the longitudinal fracture surfaces (Fig. 6a and b). The intense corrosion (Fig. 6b) makes the observation difficult and a is not possible to make a perfect observation of the original fracture, but in some cases descohesion inside the material is visible (Fig. 6c) showing an eventual separation of fracture surfaces along longitudinal paths of lower strength: between the multiple factors that could enhance this failure mode, are the environmental factors that cause stress corrosion, the extremities of these arrow points also show an irregular shape confirming the referred above (Fig. 6d).

4. Fatigue tests

The geometry of the fatigue specimens was the same as those in the tensile tests, i.e., cylindrical specimens with 4.35 mm diameter and 20 mm gauge length.

The specimens were tested in a servo-hydraulic fatigue test machine with $\pm$100 KN capacity, R = 0.5 load wave and test frequency 6–12 Hz. The objective of the test with R = 0.5 (Branco, 2008) was to simulate the effect of the static load of the bridge mainly induced by self-weight.

The principal objective of fatigue tests was to obtain the S–N curves of the material in a range of load cycles between 10^4 and 6×10^6 cycles, i.e. basically to obtain the finite life region of the curve. Crack propagation was not fully monitored but were made attempts to detect crack initiation. The tests were discarded after 6×10^6 elapsed cycles. Two S–N curves were obtained in the following conditions:

(i) In laboratory air only.
(ii) Also in laboratory air but after a previous exposure in tap water with controlled pH value, as in service, with a flow rate of 3 l/min, constantly wetting, and a maximum duration of 11 days (264 h exposure). The use of tap water was to simulate a corrosive environment in the specimen who has a very similar pH value as the rain in the area of the bridge.

Selected specimens and fracture surfaces will be discussed for the two zones of the cable (see Fig. 1): from zone 1 of the built-in zone, tested in laboratory air but with previous water exposure; and from zone 3 outside of the griping zone, tested in laboratory air only, i.e. without any exposure to tap water.

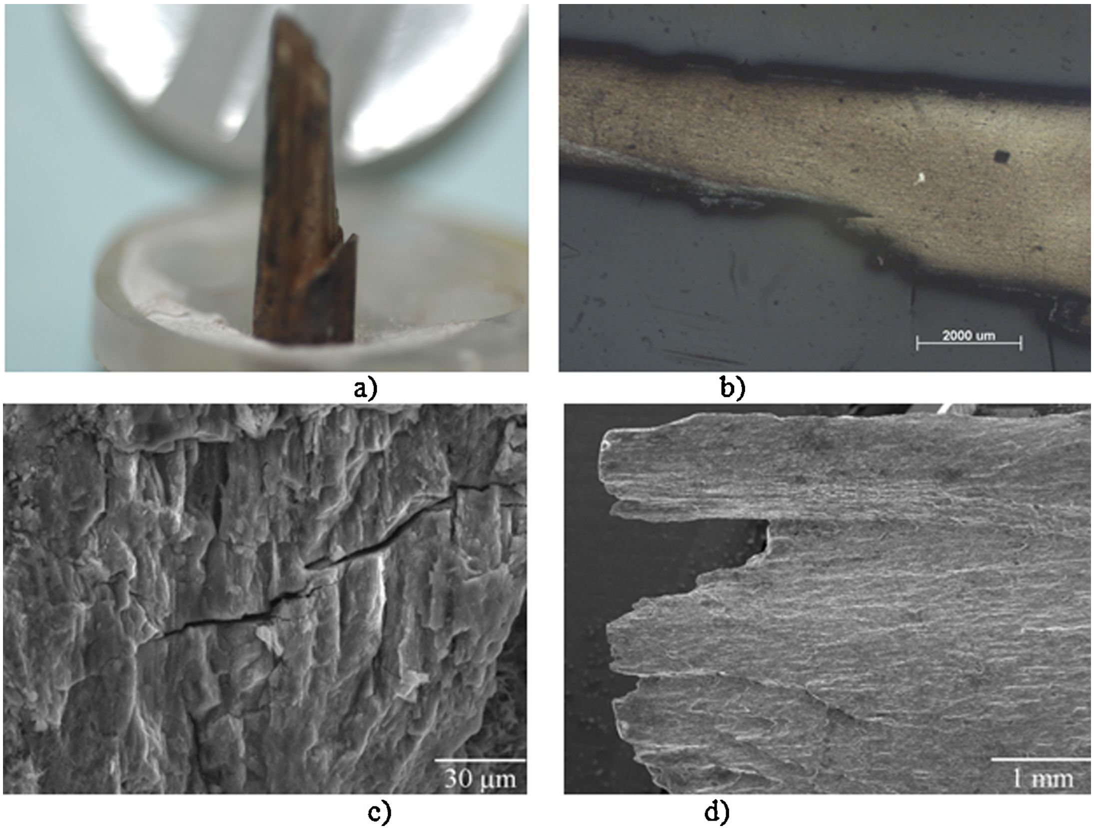

Fig. 6. Observations with several magnifications for specimens broken by arrow failure point type (a) longitudinal fracture surface; (b) intense corrosion; (c) descohesion inside the material and (d) irregular shape of extremities.

Twelve specimens were used for each *S–N* curve but in both situations, only nine valid results were assumed for the *S–N* curve since three specimens were discarded because failure occurred outside the gauge length.

The weight and diameter of the specimens were monitored with appropriate equipment with accuracies of 0.02 g and 0.002 mm respectively.

Fig. 7 shows the image of two specimens with and without the effect of corrosion in the tap water, where the significant effect of pitting, dissolution and oxidation caused by corrosion action can be noted.

4.1. *S–N* curves

The tests carried out in air with previous exposure in tap water were attempted to simulate the behaviour of the specimens in zone 1 of the built-in zone of the cable. From this fatigue tests results the correlation Eq. (1):

$$\sigma_{\max} = 3621 N_r^{-0.0822} \quad (1)$$

Fig. 7. Two specimens with and without the effect of corrosion in the tap water.

Table 2
Calculated stress values of fatigue life. Environmental conditions analysis.

Environmental conditions simulation	Maximum stress	Observations
Laboratory air only (2×10^6 cycles)	1644.65 MPa	Reduction level to get a fatigue life of 2×10^6 cycles: $\frac{1098.71}{1644.65}=0.668$
Previous exposure in tap water (2×10^6 cycles)	1098.71 MPa	
Laboratory air only (10^5 cycles)	2031.40 MPa	Reduction level to get a fatigue life of 10^5 cycles: $\frac{1405.49}{2031.40}=0.692$
Previous exposure in tap water (10^5 cycles)	1405.49 MPa	

where σ_{max} is the maximum stress in the load cycle and N_r the number of cycles to failure. This equation was valid from 10^4 to 6×10^6 cycles. The correlation coefficient was $r^2 = 0.8497$.

Eq. (1) in logarithmic form became in expression (2).

$$\log\sigma_{max} = \log 3621 - 0.0822\log N_r \tag{2}$$

Therefore Eq. (2) obtained in tests with previous exposure in tap water gives a good approach for the specimens in the cable in the griping regions where there is contact with water of the river.

The best fit of the linear regression of the experimental results (fatigue tests carried out in laboratory air without any previous exposure to tap water) was obtained with Eq. (3):

$$\sigma_{max} = 4574N_r^{-0.0705} \tag{3}$$

The correlation coefficient of Eq. (3) was $r^2 = 0.9208$, higher than the correlation coefficient of Eq. (1).

Eq. (3) is also valid from 10^4 to 6×10^6 cycles.

These specimens were from zone 3 (Fig. 1), outside of the griping zone of the cable, where there is not previous corrosion case.

For the stresses of Eqs. (1) and (3) it was assumed that the fatigue limit could be $0.6\sigma_{urs}$ as noted in the literature (Branco, 2008) and confirmed by the experimental results.

It is seen that the exponent of the curve is very low (−0.0705) as similar as the remaining specimens that are exposed to tap water (−0.0822); the exponents of the both *S–N* curves are low (<−0.1), i.e. a small variation in the exponent *n* of the curves gives a great variation in the fatigue stress or fatigue life.

For the typical values of fatigue life of 2×10^6 cycles and 10^5 cycles, the corresponding values of the applied stress may be calculated substituting in Eqs. (1) and (3) and this gives the set values presented in Table 2.

These two values of fatigue life were chosen because they are usually considered in fatigue calculations in metallic structures (Eurocode 3, 2005).

For this prestressed steel it is seen that the calculated nominal stresses for the usual design lives in fatigue loading conditions under constant amplitude loading, given in Table 2, the lowest value occurs for the conditions where the environmental effect is dominant, i.e. for exposure in tap water and longer fatigue life (2×10^6 cycles).

With corrosion the fatigue strength is lower (compare 2031.40 MPa with 1405.49 MPa and 1644.65 MPa with 1098.71 MPa). There is a significant reduction in fatigue strength in corrosion environments, but occurs a smaller reduction in the fatigue life.

The results indicate that minor reduction in the fatigue stress will cause a great reduction in the fatigue life, i.e. there is a great dependency of the fatigue life with the applied stress. Than, the results will depend considerably of small overloads that could be induced by dynamic or environment effects (small increase in applied stress will give a great reduction in life).

Considering the results obtained in the fatigue tests it is seen that the type of steel of the wires is rather sensitive to the fatigue stress.

When the results were obtained after previous exposure with tap water it is expected that the fatigue loading will start with the material in an embrittlement stage; i.e. the initial previous exposure phase is comparatively long, although no fatigue loading was applied in this preliminary phase. The results in Table 2 indicate that with previous exposure in tap water, fatigue life of 10^5 cycles is obtained with 69% reduction factor for the applied stress. For the life of 2×10^6 cycles this reduction factor is 67% for the applied stress.

5. Analysis of the fractures surfaces of fatigue specimens

In selected specimens, from zone 1 with long and short fatigue life, the fracture surface was inspected with SEM for magnifications ranging from 20× to 5000×.

Fig. 8a and b shows with small magnification (20×) the specimens fracture surface. It can be observed a radial cracking of the surface. In Fig. 8a the fracture surface is rougher and the steps of propagation are more visible because the crack growth rate is higher, giving a shorter life. The fracture surface showed in Fig. 8b is more uniform as a result of a small stress level and a longer life (lower crack propagation speed viewed as can be confirmed by the lower degrees or steps).

Fig. 9 is a fractographic image with magnification of 5000× of the same specimen of Fig. 8. With this increased magnification it is possible to analyse some details like the fracture mode that is void coalescence and secondary cracking (Fig. 9a). Intergranular failure mode is observed in Fig. 9b which is one of the mechanism failures.

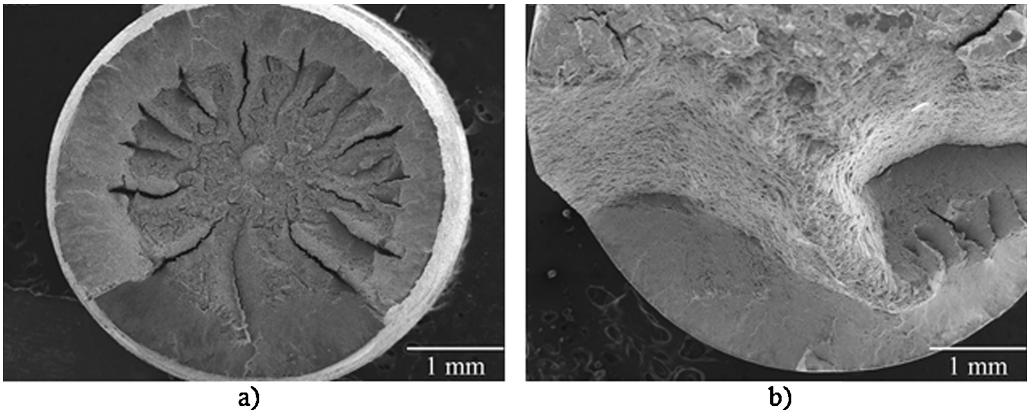

Fig. 8. Zone 1 specimens fractography (magnification 20×): (a) N_r = 36,028 cycles, σ_{max} = 1548 MPa and (b) N_r = 3,674,664 cycles, σ_{max} = 1058 MPa.

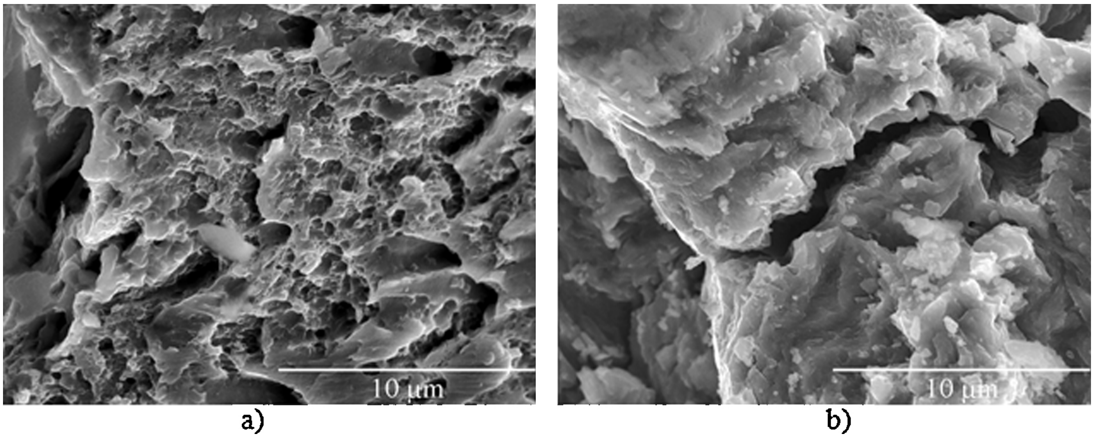

Fig. 9. Central zone specimens fractography (magnification 5000×): (a) N_r = 36,028 cycles, σ_{max} = 1548 MPa and (b) N_r = 3,674,664 cycles, σ_{max} = 1058 MPa.

6. Conclusions

- Using the microstructural analysis, were not detected differences between the intrinsic microstructures shown by specimens taken from fractured rods fail by different mechanisms, or between samples obtained from the same rods near fracture zones and on distant zones.
- Were not detected evidences of the contributions from original or microstructural defects due to material itself, or to processing such as possible responsible failure of cable, which should then be given to mechanical and environmental conditions during the service.
- For both conditions analysed in the fatigue tests (with and without initial corrosion) a great dependence was found between the fatigue life and the maximum stress in the fatigue cycle, i.e. a small variation in the applied stress causes a great variation in the fatigue cycle.
- The fractographic analysis showed that the failure of the cable occurred in two phases: at first the rods were being attacked by stress corrosion seriously affecting more than 50% of the rods, which progressively took them to fracture; when the number of remaining rods no longer met the efforts applied, they broke by ductile fracture.

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