CORROSION EFFECTS ON FAILURE AT VARIOUS SCALES IN SUSPENSION CABLES

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ABSTRACT

Suspension cables structures, whose constitutive material is mainly steel, suffer from the continuous aggression of the environment (urban, industrial, marine...).

The effects of this aggressiveness appear through corrosion whose direct consequences are the strong modifications of the geometrical and mechanical characteristics of the components. This induces a notable reduction of the resistant capacity of the cable with time, being able to result sometimes in its partial rupture.

An analysis is carried out to evaluate the effect of the factors affecting the performance of the long-term cable life. It consists on:

1) the development of a model allowing to predict the remaining strength of a cable for various levels of mechanical damage or corrosion of its components (wire, strand and cable behaviors),
2) the estimation of the residual lifespan (for a given service requirement),
3) the evaluation of the risk of failure for a given service load.

The approach consists in a multi-scale approach with a complete decoupling between the scale of the wire and that of the cable. Two independent phases are considered:

First phase (local description): one determines the constitutive law of an isolated strand section (whose size equals the anchoring length), and thus evaluates its response in terms of statistical distributions of wire's failure.

Second phase (integrated description): explicit laws are deduced from the preceding phase results. It is necessary to integrate, identify and calibrate as well the constitutive laws as their statistical distributions.

The statistical data related to the temporal development of corrosion, obtained through monitoring, can be integrated as well at the scale of wire as at the scale of strand section in a cable.

The cable model can include population of strand's section with different corrosion evolution rates, because of more or less aggressive environment. We show that for a service load, the theoretical mean lifespan varies between 70 and more than 150 years according to assumptions made on the development of corrosion. This highlights the importance of monitoring, since it can feed models with additional data.

1 INTRODUCTION

Like all civil engineering structures, bridges are subjected to the action of time and consequently to the ageing which is one of the main causes of reduction of their bearing capacity and their reliability. This question is important for suspension bridges and in particular for their main suspension cables. If the reliability of these systems has been widely studied, only few works account for durability effects and have linked the models with data obtained on the field (Matteo [1], Haight [2], Camo [3], Crémona [4]).

In order to ensure the exploitation of the structure under optimal conditions, a fine analysis of its safety must be combined with procedures of inspection defined consequently. Unfortunately, many cables have never been subjected to an inspection or, in the contrary case, only in a very partial way, because of the limits of the techniques of inspection (visual, acoustic...). The analysis relating to safety consists in connecting the measurement of the residual resistance of the cable to the data of inspection (when they exist) of the latter. This link is difficult to establish, even if it is known that the concept of "safety factor" of the cable is somewhat insufficient to characterize its present state.

Majority of works related to the determination of the bearing capacity of a suspension cable are statistical models which does not integrate the complexity of the mechanical description (behavior, force redistribution ...). Crémona [4] proposed a more mechanical approach of the problem, but without however describing degradation by corrosion.

In order to have models being able to assist the manager in decision phase, we choose to work according two following axes:

1) To evaluate the effect of the factors affecting the long-term performance of the cable. It requires development of a model of the strength of a cable with various levels of damage of its components, and to connect the modeling of the behavior of a wire (starting from the type of degradation) with that of a set of wires considered then collectively (strand) and finally with that of a set of strands (cable).

2) To develop a model of the residual lifespan (for a requirement of given service), since the physical and/or mechanical characteristics evolve with time, due to the influence of the cable environment.

The model should also make possible the evaluation of the risk of failure for a requested level.

The modeling of the system will be based on a set of assumptions relating to the mechanical behaviors at the various scales, to the form and kinetics of corrosion, to the progression and to the distribution of corrosion at the cable scale.

2 MULTI SCALE APPROACH

A system is a whole of inter-connected or interdependent elements so that the state of the system depend on its components states. A main suspension cable can be regarded as a system, made up of a set of strands laid out in parallel (for example 60 for the bridge of Tancarville, 37 for that of Aquitaine). A strand itself consists of a set of twisted wires (169 per strand for Tancarville bridge, 217 for Aquitaine bridge).

The study of the behavior of a cable is consequently a multi-scale study where one can distinguish three scales: the scale of the wire, the scale of the strand and the scale of the cable. The systemic diagram of a suspended cable is thus a system: parallel (K strands) – series (m sections of strands) - parallel (N wires). The choice of these three scales can be justified as follows [5]:

a) The behavior of a wire governs the behavior of the whole of the cable. The processes as well as rates of degradation due to the environment (corrosion...) are different for each layer (external layers being more exposed),

b) When the wire are twisted and rolled up between them, a broken wire has the capacity of anchoring over a given length, called the anchoring length (being worth from 1 to 2,5 times the step of foreturn according to Raoof [6]) and which defines the dimension of the section of the strand. The behavior of a strand is deeply related to the behavior of its weakest section (system is in series),

c) The strands being laid out in parallel, the resistance of the cable depends on their individual resistances and the type of sharing load redistribution (local, global).

This approach makes possible to go up from individual damage of wires to the overall degradation and thus to the effective strength of the cable.

Uncoupled multiscale approach is performed while distinguishing:

- a local description whose result is the constitutive law of a section of insulated strand, and in evaluating its response in terms of statistical distributions,
- a global description where one will uncouple local and global calculations by identifying explicit laws obtained from the results of the preceding phase. Analytical expressions will be derived for average constituve laws at strand section scale as well as for their scatter. A

numerical "data base" is then built, to which one will make calls for any later analysis at the cable scale.

3 WIRE SCALE

3.1 Material constitutive law

Steel wire is the elementary component of a cable. Its section can be circular (3 to 10 mm) or Z-shaped. It is generally obtained by wiredrawing and has a high tensile strength. Behavior tension of the wire observed in experiments is elastic plastic with a very scattered ultimate strain, which makes this behavior brittle or ductile. It is modelled by the eqn (1) with 4 parameters:

$$\begin{cases} \sigma = E\varepsilon & \text{if} \quad \sigma \le \sigma_e \\ \sigma = \sigma_e + \dfrac{E(\varepsilon - \varepsilon_e)}{1 + C(\varepsilon - \varepsilon_e)} & \text{if} \quad \sigma \ge \sigma_e \end{cases} \quad \text{with :} \quad C = \frac{E\varepsilon_u - \sigma_u}{(\sigma_u - \sigma_e)(\varepsilon_u - \varepsilon_e)} \tag{1}$$

ε_e, σ_e are respectively the elastic strain and stress, ε_u, σ_u are the ultimate strain and stress, E is the Young modulus (it can be taken as the 4th variable instead of ε_e or σ_e). Resulting from the manufacturing process, each wire taken individually is different. The vector $\{X_w\}$ defined by:

$$\{X_w\}^T = \{E, \sigma_e, \varepsilon_u, \sigma_u\}^T \tag{2}$$

is thus a vector of random variables. The choice of the statistical distributions of each parameter and the expression of their distribution functions $F(x_i)$ depend on the availability of information. Eqn (3) shows the cumulative distribution of the ultimate stress σ_u which is a 3 parameter Weibull distribution.

$$F(\sigma_u) = 1 - \exp\left(-\frac{l_r}{l_{70}} \left(\frac{\sigma_u - \sigma_{min}}{\sigma_0} \right)^{m_\sigma} \right) \qquad \text{for all } \sigma_u \ge \sigma_{min} \tag{3}$$

where m_σ is the Weibull parameter, σ_{min} the minimal value and σ_0 the shape parameter (related to scatter). The size effect is taken into account through the l_r/l_{70} ratio where l_r is the anchoring length and l_{70} is the reference length of the tested samples (70 cm).

3.2 Corrosion

The corrosion process is a random space and temporal process. At the strand's section level, corrosion is propagated from external towards internal wires: the probability $p_\Delta t(i)$ for a healthy wire in a layer i to become corroded during a step time Δt is supposed to be constant per layer and to decrease from the external layers towards the internal layers. At the wire level, corrosion also propagates from surface towards the core after an initiation phase.

The resulting effects of corrosion on a set of wires will be to progressively modify the strength distribution $F(\sigma_u)$ from an initial value (given by eqn (3)) to an updated distribution at time t (figure 1).

3.2.1 Probability of wire corrosion initiation - corrosion chart

The statistical distribution of corrosion starting time of a wire, corresponds to the probability p(i,t) that a given wire of layer i is corroded at the time T (with $T = n.\Delta t$) and depends on the layer i to which it belongs and of time T. One can connect p(i,t) and probability of transition $p_\Delta t(i)$, since a healthy wire at the time T is a wire which was not corroded during any of the n preceding intervals Δt:

$$p(i,T) = p(i, n.\Delta t) = 1 - (1 - p_\Delta t(i))^n \tag{4}$$

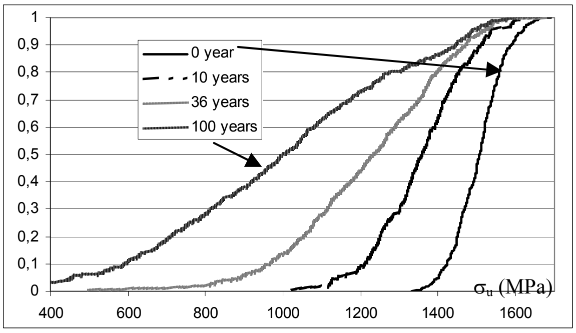


Figure 1 : Cumulative distribution function of σ_u for various times.

The eqn (4) corresponds in fact to a geometrical distribution function of $p_\Delta t$ probability.

Knowing p(i,t), one can express, at any time T, the number of corroded wires N_{ci} of a layer i, in the form of a binomial distribution:

$$Nc_i\ (t) = C_{ni}^k\ p(i,t)^k\ (1 - p(i,t))^{ni-k} \tag{5}$$

where n_i is the total number of wires of layer i. The probabilities thus defined can be identified from the observation, by measurement on a sufficient number of samples which allows identifying the probabilities from a single realization. One can then deduce $p_\Delta t(i)$ from eqn (4).

3.2.2 Corrosion kinetics

At the wire scale, the two types of corrosion most generally considered are general corrosion (presumed uniform on a wide zone, consisting in a reduction of the cross-section of the wire) and the localised (pitting) corrosion. In this case, crack located on the level of a confined zone which is propagated in an uncontrolled way when the constraint reaches a critical value.

Other types of phenomena appear sometimes, for example due to interwire friction, or to the presence of a hydrogen rich atmosphere. Lacking of available experimental data relating to these kinds of corrosion, we have chosen to describe them by the same phenomenological model, that corresponding to general corrosion. The following model is adopted:

$$c(t) = \alpha\left(t - t_0\right)^\beta \tag{6}$$

where c(t) represents the material loss (reduction of wire diameter), t_0 is the initiation time of wire corrosion, β the tendency of corrosion and α indicates the corrosion rate.

The two parameters α and β are strongly correlated, and have, for the same site, a high variability because the varying conditions of the very local environment.

The constitutive law of a strand section can be expressed by eqn (7):

$$F_{trc}(u,t) = \sum_{i=1}^{N} F_{w,i}(u,t) \tag{7}$$

where F_{trc} is the resultant strand load, N the total number of wires per strand, u the general strand displacement (= $\varepsilon.l_r$) and $F_{w,i}$ is the wire force :

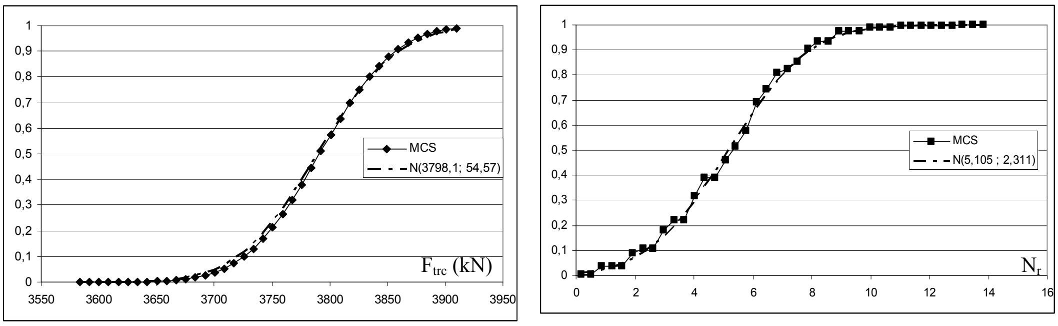
$$F_{w,i}(u,t) = \sigma(\frac{u}{l_r}, \varepsilon_e, \sigma_e, \varepsilon_u, \sigma_u).A(t, t_0, \alpha, \beta) \tag{8}$$

where A is the wire section.

Given that $F_{w,i}$ and consequently F_{trc} are random variable functions, the determination of F_{trc} requires the use of Monte Carlo simulation methods.

3.3 Consequences at strand scale

At the strand scale, Figure 2.a shows the cumulative distribution function of the peak load of F_{trc} for 1000 simulations. The number of broken wires N_r corresponding to this peak load is shown on figure 2.b. The number of broken wires is between 1 and 14 in the majority of the cases. Both of CDF (F_{trc}, N_r) are compared with a Normal distribution which seems to provide a good fit of these probabilistic distributions.



a) peak strand load b) broken wires

Figure 2: Cumulative distribution functions (MCS: Monte Carlo Sim., N : Normal distribution)

4 CABLE SCALE

To uncouple local (wire to strand's section) and global (strand's section to cable) scales and enable the analysis of the reliability of the cable, an explicit formulae, reproducing characteristics of the $F_{trc}(u,t)$ evolution has been built and identified.

The effects of the kinetics of corrosion at the cable scale are analyzed by considering that each strand has a collar at its two ends in which conditions favorable to corrosion develop. Three distinct populations of strand's sections are considered, corresponding to more or less aggressive kinetics of corrosion:

- in current zone, a population P1 (except collars),
- a second P2 population, at the level of the collars, subjected to a general corrosion (that identified in experiments),
- a third population P3, always at the level of the collars, concerning a fraction f of the strands, subjected to a corrosion with the more aggressive kinetics representing pitting corrrosion.

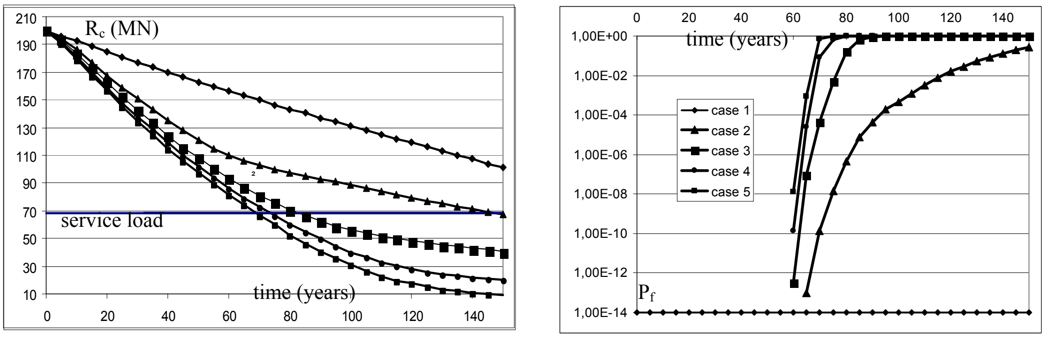
The percentage of elements belonging to the P3 population is varied in order to see the effects of its change on the strength of the cable. Table 1 provides the respective percentages of each corroded population. The P3 population percentage is very discriminating. According to the percentage of sections belonging to the P3 population, the reduction of resistant capacity can be very severe.

For a service load of about 68 MN and an initial strength of 199.5 MN, the theoretical average lifespan (figure 3.a) varies between 70 and more than 150 years according to the assumptions taken into account and relating to the reative population percentage (between P2 and P3). The strenghts' scatter is very reduced at the initial time and grows with corrosion. Figure 3.b shows the considerable growth of probability of failure.

In the current state of available data, it is not possible to go further in the analysis and no information reinforce such or such assumption. The evolution of temporal mean strength R_c and consequently the estimation of the residual lifespan of the cable can be apprehended only through more detailed inspections (detection of broken wire as well as of that of corroded wire, particularly those having possibly undergone a localised corrosion).

Table 1: Ratios of the corroded populations.

Case	P1(%)	P2(%)	P3(%)
	Out of collars	Collars 20%	
1	80	20	0
2	80	16	4
3	80	12	8
4	80	8	12
5	80	4	16



a) mean strength b) Probability of failure

figure 3 : Evolution of the strength capacity for various combinations of corroded populations

5 CONCLUSIONS

The prediction quality is naturally conditioned by the relevance of the assumptions and the representative character of the used data. The identification, at each stage, of the necessary data relies on parameters accessible to experiment. The major observation is that the effect of the environment (through the effects of corrosion) is dominating. Taking into account several populations differing by the kinetics of corrosion, shows that the evaluation of the risk for a cable to fail is deeply affected by the chosen values for rates of corrosion.

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