Study Committee B2

Overhead lines

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Metamodel applied to fatigue damage in overhead lines conductors

Julien SAID[1]*, Sami EL IDRISSI RAGHNI[2], Maxime GUEGUIN[2], Emmanuel CIEREN[2], Laura COHEN[1], Fikri HAFID[1], Jean-Michel GHIDAGLIA[3], Marc COULANGEON[4], Jérome BROCARD[4]
1 – RTE R&D, Immeuble Window, 7 place du dôme, 92073 La Défense, FRANCE
2 – Eurobios, 61 avenue du Président Wilson, 94230 Cachan, FRANCE
3 – Centre Borelli, ENS Paris-Saclay, CNRS, Univ. Paris-Saclay, 91190 Gif-sur-Yvette,
4 – Dervaux, SICAME GROUP, 42500 Le Chambon-Feugerolles, France

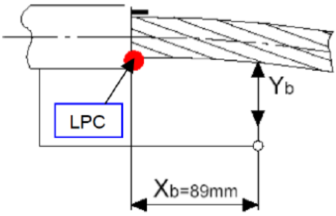
1. Context

- RTE Overhead conductors' replacement policy is currently based on age only (85 years old)
- Most commonly used conductors were installed during the same periods :
  - ACSR during the **1940-1950s**
  - AAAC during the **1970-1980s**
- This implies that many replacements are to be expected **within short periods** of time for both types.
- RTE aims to **adapt its replacement policy** by **targeting most critical powerlines**, based on physical knowledge of the assets behaviour.
- One method investigated by RTE R&D relies on experimental data to predict the **lifetime to failure** of a given conductor. These data may originate **from the literature** or **new tests** conducted in a dedicated facility.

Vibrating actuator

Method

This work aims to offer a simple and reliable tool to predict the behavior of a conductor in a given setup. Safe design zones are usually defined through two distinct approaches : the endurance limit approach or the S-N curve limit approach. On the first hand, the endurance limit consists in comparing a measurable data such as the Yb amplitude versus a tabulated value. On the other hand, **S-N curve limit or cumulative damage approaches** imply to use conductor fatigue data to establish a critical fatigue limit that can be used to predict the ultimate lifetime to failure for a given set of loading conditions. The latter has been adopted in the study, associated with **statistical algorithm** to deepen its applicability.



Experimental data, numerical modeling

Such work requires as much experimental data as possible. To this end, both the literature and new experimental tests were put to use. More than 200 experimental results were collected and listed to support this work and used as input for the statistical modeling.

For the predictive model, simple machine learning algorithms were applied : **quantile regressions**. This type of regression is linear and may offer reliable upper and lower limits of lifetime once it has been correctly calibrated. For this work, **four explanatory variables** have been defined, based on the conductor's geometry, material and loading parameters. Hence, the predictive lifetime to failure can be expressed as follows:

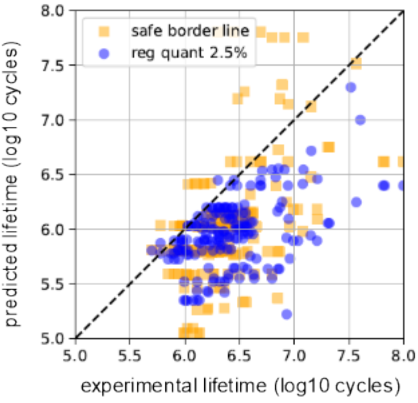
$$\log(N) = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_4 X_4$$

Where a_i are the model parameters and X_i the input variables. Compared to the Safe Border Line (SBL) available in the literature, the 2.5% quantile regression offers promising results that can be helpful for anyone working in this particular field.

Conclusion

The following points were developed in this study:

- More than **200 experimental tests were gathered** and listed to help willing TSOs to use such valuable data.
- Comparisons with the SBL showed that this limit may not always warranty the strength of conductors at least in experimental conditions
- A simple statistical model has been successfully applied and revealed that with only 4 explanatory variables, the 2.5% quantile regression offers **promising and conservative** results.



http://www.cigre.org

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2. Conductor fatigue and endurance limit

2.1. IEEE and EPRI approaches : endurance limit

Several tools were proposed to help TSOs to design their assets and define safe zones of operation. For instance, IEEE Transmission and Distribution Committee recommends to measure the deflection Yb located 89 mm away from the **Last Point of Contact (LPC)** between the conductor and its suspension clamp. If Yb is higher that the corresponding safe value available in the literature, then the conductor is expected to prematurely fail.

The EPRI proposed a similar approach but based on the bending stress σ_a rather than the sole deflection. This stress is related to Yb according to the Poffenberger-Swart equation:

$$\sigma_a = K.Yb \qquad (1)$$

with:

$$K = \frac{E.d.p^2}{4(e^{-p.xb} - 1 + p.xb)} \qquad (2)$$

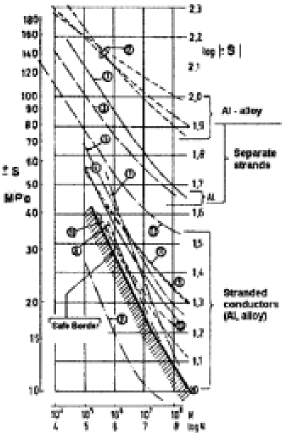
$$p = \sqrt{\frac{H}{(EI)_{min}}} \qquad (3)$$

Where σ_a is the maximum bending stress, H the mechanical tension of the conductor, E the Young's modulus of outer layers, d the diameter of the outer layer strands and finally EI_{min} the minimum bending stiffness.

2.2. CIGRE's Safe Border Line (SBL)

The recommandation of the CIGRE International Council relies on a cumulative damage approach based on various ''Cycles to failure'' curves, also called S-N or Wöhler curves. It is based on several sets of experimental data listed in [1] accounting for several types of conductors and material.

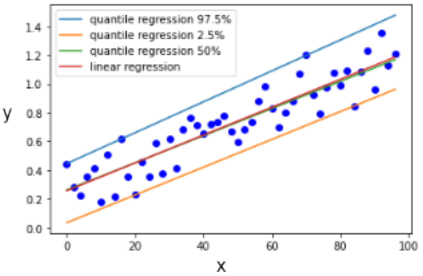
The Safe Border Line was then established according to Miner's law of cumulative damage. As displayed in this figure, this border is meant to be conservative and gives an estimate of the associated lifetime to failure. It is recommended to use this tool only when fatigue data are not directly available for a given conductor.



3.Statistical Regression Model

3.1. Definition of the quantile regression

The quantile regression is similar to the well-known linear but aims at different statistical values. Whereas the least square method used for linear regression estimates the mean value of the response variable, the quantile regression estimates the median or any other quantile of the response variable.



The 2.5% and 97.5% quantiles offer statistically accurate boundaries for any set of data. In the field of conductor's fatigue, both of these boundaries give an interesting estimate of the minimum and maximum expected lifetime for a test or an asset in use on the grid. This will be true providing that enough data is available to conduct such studies.

3.2. Quantile regression on conductor's fatigue data

Machine learning algorithms consider two main objects: a target vector and a feature vector. On the one hand, the target represents what the algorithm will try to predict (such as the lifetime to failure). On the other hand, the features are the input parameters contained in the initial dataset. For the current case of study, four features Xi are used to characterize the conductor's lifespan, depending on the boundary conditions and the conductor itself. These four features are:

- **The normalized mechanical tension**

$$X_1 = \frac{H}{RTS}$$

With H the mechanical tension and RTS the Rated Tensile Strength (i.e. the maximum tensile load that can be applied on the corresponding conductor).

- **The normalized vibration amplitude:**

$$X_2 = \log\left(\frac{Yb}{D}\right)$$

With D the conductor's nominal diameter.

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- **The normalized *self-weight* (sw) induced displacement :**

$$X_3 = \frac{U_{sw}}{D}$$

Such as:

$$\sigma_{sw} = K_{norm} \frac{U_{sw}}{D} E$$

With E the Young's modulus and σ_{sw} the self-weight induced stress.

- **The normalized stress coefficient K_{norm} :**

$$X_4 = K_{norm}$$

Knowing these four features, any linear regression will be expressed as follows:

$$\log(N) = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_4 X_4$$

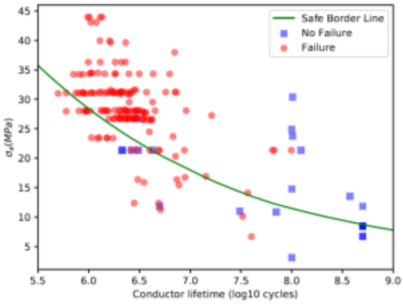
Where N represents the predicted lifetime to failure and a_i the coefficients defining the model. These values depend on the regression used. All these parameters are listed in the following table:

	2.5% quantile regression	97.5% quantile regression
a_0	6.15	6.01
a_1	1.37	-4.58
a_2	-2.06	-2.20
a_3	-2.45	-1.08
a_4	-165	-43.5

4. Comparisons with the SBL

4.1. SBL versus literature fatigue data

More than **200 experimental test data** were gathered from the literature in this work. These data can be directly compared with the Safe Border Line:



In order to be conservative, **all "failure" points should be located above the SBL**, while in fact some of them are located below. It reveals that the SBL may not be sufficient to always ensure the line integrity.

4.2. SBL versus quantile regressions

The following plots compare the SBL and both 2.5% and 97.5% quantile regression versus the same experimental data. These were divided according to the conductor type for a better clarity. It shows how the 2.5% regression provides a safest design zone compared to the SBL, for both ACSR and AAAC.