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Application of Student and Weibull statistical distributions on experimental tensile test results of steel wires extracted from antigyratory wire rope (19x7).

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ABSTRACT

Throughout the life of a wire rope, the wires that make up this cable are subjected to high mechanical stress indicating a loss of the original force, which sometimes leads to very rapid deterioration leading to sudden rupture. Therefore, they must meet the strictest safety standards in their use because every failure causes material and immaterial damages. The interest of the present work is to apply two different statistical distributions; Student distribution to select the most reliable results and Weibull distribution to define probability of survival and the probability of failure (Reliability an damage of Weibull). As result of this study, confidence interval is determined for tensile test results and the superposition of the probability of survival and the probability of failure for both maximum stress and elastic stress curves allowed us to distinguish the elastic zone which is[0, 1850], the stable plastic zone [1850, 2250] and the unstable plastic zone [2240,2300] to intervene in time for a predictive maintenance.

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Introduction:

Wire rope solutions are utilized for wide industrial applications including mechanical, civil, electrical and ocean engineering structures.

A steel wire rope is characterized by a very complex architecture; the basic component is the drawn wire [1]. The wires are then twisted to form a strand; the wire rope is finally made with the strands, which describe helices around the core during the cabling operation [2].

The main purpose of this statistical study is first the selection of a confidence level for an interval to determine the probability that the confidence interval produced will contain the true value of maximum stress and elastic stress applied to steel wires extracted from wire rope. Thereafter and with the establishment of Weibull distribution, we could determine the probability of survival and the probability of failure for maximum and elastic stress and then extract the elastic zone, the stable plastic zone and the unstable plastic zone.

Test procedure and experimental implementation:

Tested material:

This study focuses on the behavior of steel wires extracted from wire rope of type 19x7 (The first refers to the number of strands in the rope and the second to the number of wires per strand) and antigyratory construction (1x7 + 6x7 + 12x7); such a structure is composed of a number of strands that are laid up in opposite directions to produce a non-rotating effect [3].
The studied steel wire is made of cold-drawn wires, this process is employed to improve mechanical properties; it is a metal-reducing process, in which a wire rod is pulled or drawn through a conical single die or a continuous series of dies, thereby reducing its section. This process is widely employed in industry for

producing high tensile strength that find widespread applications as structural reinforcements, such as prestressed concrete, mining and fishing cables and tire reinforcements. [4,5]

A. Chemical Composition:

The chemical composition is obtained by spectrometric analysis using a spectrometer peak spark. The result is summarized in Table 1:

Table1. Chemical composition of the material

Elements	C	Si	Mn	P	S	Cr	Mo
%	1,478	2,04	2	0,091	0,0144	0,182	0,208

Wire rope is made of plain carbon steel with high carbon content (about 1,478%) and a very fine grain structure achieved through isothermal transformation (patenting), and work hardening by successive drawing.

B. Mechanical properties:

The mechanical properties extracted from strength-elongation diagram of the wires specimens are reported in the table.2:

Table: 2. Mechanical properties of the material

Young's modulus	Poisson's ratio	Elastic limit (MPa)	Breaking stress (MPa)
E=198 GPa	ν=0,3	σe=1901	σr=2383

Experimental procedure

To obtain specimens of wires, a suitable length of the cable was cut and strands were de-wiring (wiring off). The minimum length of the samples wire is equal to the length of the test plus the necessary for the mooring. Therefore, a length of 300 mm is anticipated as the length of the test. The measurements tolerance in the length is ± a millimeter for all samples [6]. Dimensions of the wire are shown in Figure 1.

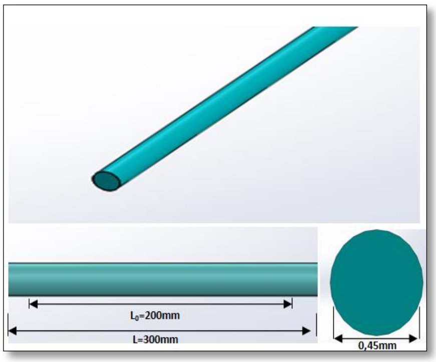

Figure: 1. Dimensions of the studied strand

Wires tensile test of diameter 0,45 mm was realized at 17 specimens by means of zwick roell testing machine (10 KN) (Figure 2).

Figure: 2. Zwick Roell testing machine (10 KN)

Statistical distributions:

Student distribution:

Student distribution is used for finding confidence intervals for the population mean when the sample size is small and the population standard deviation is unknown, in our case it is used to regulate the average distribution of the tensile tests.

And we have:

$$P\left[-t_{(\alpha,\mu)}\,;\,\alpha \leq \frac{X-\mu}{s/\sqrt{n}} < +t_{(\alpha,\mu)}\,;\,\alpha\right] = 1-\alpha \quad (1)$$

Where:

X: The sample mean ;

n : sample size;

μ : n-1;

s : Standard deviation;

α : Risk threshold;

t(α,μ) : value drawn from Student's distribution with n-1 degrees of freedom;

X distribution with mean μ is defined as:

$$P\left[X - t_{(\alpha,\mu)}\,;\,\alpha.\frac{s}{\sqrt{n}} < \mu < X + t_{(\alpha,\mu)}\,;\,\alpha.\frac{s}{\sqrt{n}}\right] = 1-\alpha \quad (2)$$

Weibull distribution:

The purpose of this statistical method is to definite the relationship between mechanical load and the failure probability of a part if the distribution parameters are known. Using a level of stress at which the failure probability becomes $\sigma 0$ the Weibull modulus (m) becomes a measure of the distribution of stress. The higher the Weibull modulus is, the more consistent the material (which means that uniform "defects" are evenly distributed throughout the entire volume) and also the narrower the probability curve of the stress distribution. Today, values between 10 < m < 20 are typically achieved.

The survival probability of specimen undergoing stress could be modeled using the following Weibull distribution:

$$Ps = e^{-(\frac{\sigma}{\sigma 0})^m} \quad (3)$$

Where :

Ps : the Probability of survival;

σ : the applied stress;

σ0 : a constant scale parameter with the same dimensions as used for the stress;

m : dimensionless and called the weibull modulus.

Results and discussion:

To make a statistical study of the test results on the studied wires, we conducted a tensile test of 17 specimens. Results of these tests are presented in figure 3.

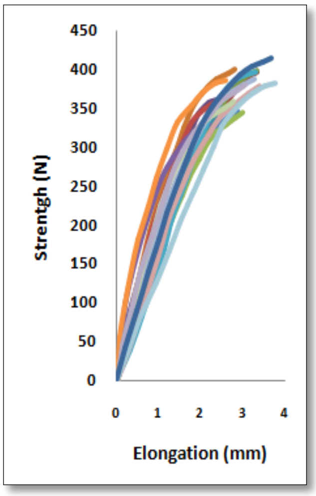

Figure: 3. strength-elongation diagram of the steel wire (17 specimens)

Applicability of student distribution for steel wires:

The average and standard deviation estimated of maximum stress that correspond at 17 specimens subjected to static tests are:

- **For elastic stress**

X = 1901.98MPa ; s =59.39; n = 17 specimens; α = 0.01; $t\,(\frac{\alpha}{2}; 16)$ =2.921 (value from STUDENT table)

Resulting:

$$\mu = 1901.98 \pm 2.921\sqrt{\frac{3527.1}{17}} = [1829.9; 1901.9]$$

The confidence interval (CI) at 90% is an interval of values which have 90% chance to contain the true value of the estimated elastic stress.

- **For maximum stress**

X = 2205.7 MPa ; s =124.01; n = 17 specimens; α = 0.01; $t\,(\frac{\alpha}{2}; 16) = 2.921$ (value from STUDENT table)

Resulting:

$$\mu = 2205.7 \pm 2.921\sqrt{\frac{3527.1}{17}} = [2117.9; 2205.7]$$

Applicability of Weibull distribution for steel wires:

The main of this statistical study is to provide a statistical processing to derive the maximum stress and the elastic stress that can be applied on the material so that the failure probability (damage) is less than 1% ,and then estimate the survival probability (reliability) and the probability of failure.

The Weibull plot has special scales that are designed so that if the data do in fact follow a Weibull distribution, the points will be linear (or nearly linear) such that:

$$\mathbf{\ln\ln(\frac{1}{PS}) = m(\ln\sigma - \ln\sigma 0)} \qquad (4)$$

This line yields estimates for the both parameters of the Weibull distribution. Specifically, the parameter m is the slope of the fitted line and the parameter $\sigma 0$ is the exponent of the intercept of the fitted line.

- **For elastic stress**

Ln(Ln(1/Ps)) versus Ln (σ) is ploted in figure 4.

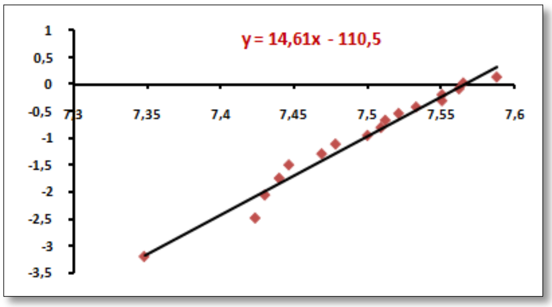

Figure: 4. $\ln\ln(\frac{1}{PS})$ in function of $\ln\sigma_e$

The equation of this line is:

y = 14.61x - 110.5

Which mean:

m =14.61 and σ0 = 1926.2 MPa

The probability of survival and the probability of failure curves in function of elastic stress according to equation (3) are presented in figure 5.

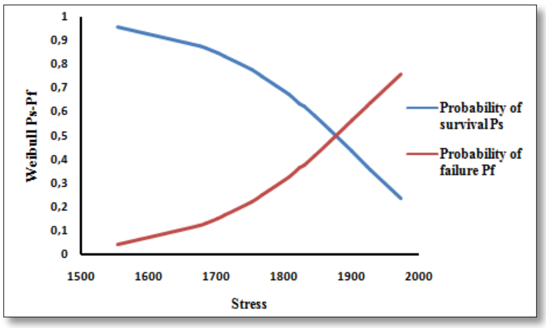

Figure: 5. The probability of survival and the probability of failure curves in function of elastic stress

- **For maximum stress**

Ln(Ln(1/ Ps)) versus Ln (**σ**) is ploted in figure 6

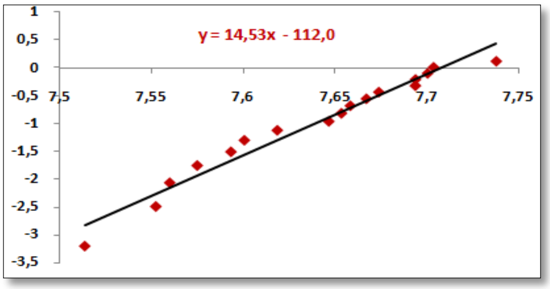

Figure: 6. $\ln\ln(\frac{1}{PS})$ in function of $\ln\sigma_{max}$

The equation of this line is:

$$y = 14.538x - 112.05$$

Which mean:

$$m = 14.53 \text{ and } \sigma 0 = 2304.45 \text{ MPa}$$

The probability of survival and the probability of failure curve in function of maximum stress are presented in figure 7.

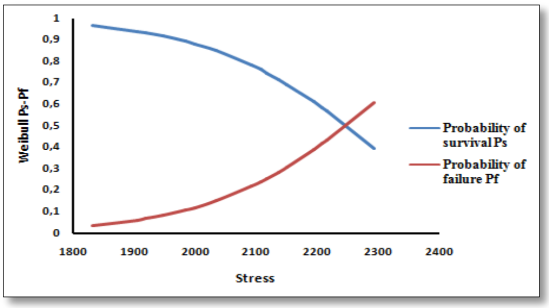

Figure: 7. The probability of survival and the probability of failure curves in function of maximum stress

The value of maximum stress obtained that could be applied on the material so that the failure probability is less than 1% is:

$$\sigma = 1679 \text{ MPa}$$

- **Superposition of elastic stress and maximum stress curves**

The probability of survival and the probability of failure curves in function of stress for both maximum and elastic stress are presented in figure 8

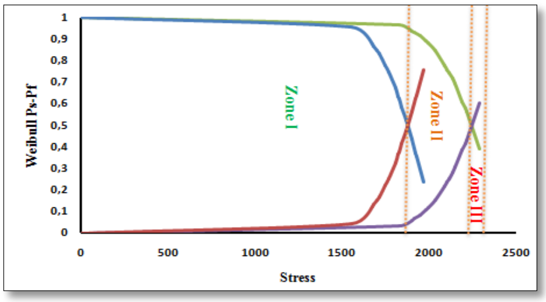

Figure: 8. probability of survival and the probability of failure curves in function of stress for both maximum and elastic stress

According to the curve in figure 8, we could distinguish three zones: elastic zone [0, 1850], stable plastic zone [1850, 2250] and unstable plastic zone [2240,2300].

Conclusion:

Using Student distribution, a confidence interval of [1829.9; 1901.9] is determined for elastic stress and [2117.9; 2205.7] for maximum stress.

On the other hand, Weibull distribution allows us to define the appearance of probability of survival and probability of failure for elastic stress and maximum stress and therefore distinguish the elastic zone, the stable plastic zone and the unstable plastic zone for a predictive maintenance in order to ensure the efficiency of steel wires and wire rope in general.

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