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# Energy's Method for Experimental Life Prediction of a 1 + 6 Strand

Amal Tijani[1], Meryam MEKNASSI[2], Hassan CHAFFOUI[3], Mohamed El Ghorba[4]

[1]*Laboratory Of Atmosphere's Physics and Modeling, FST Mohammedia, Hassan II University Of Casablanca, BP 146 - Mohammedia, Morocco*
[2]*Laboratory Of Control And Mechanical Characterization Of Materials And Structures, National Higher School Of Electricity And Mechanics (ENSEM), Hassan II University Of Casablanca, B.P 8118 Oasis - Casablanca, Morocco*
[3]*Laboratory Of Atmosphere's Physics And Modeling, FST Mohammedia, Hassan II University Of Casablanca, BP 146 - Mohammedia, Morocco*
[4]*Laboratory Of Control And Mechanical Characterization Of Materials And Structures, National Higher School Of Electricity And Mechanics (ENSEM), Hassan II University Of Casablanca, B.P 8118 Oasis - Casablanca, Morocco*

**ABSTRACT**
*A method to calculate damage evolution during the life of a strand was developed in this paper. Based on simple tensile tests, it has the advantage of being time and money saving. The residual energy damage calculation was compared to the unified theory for different loading levels. The correlation between the two methods was found for a loading level of 1.49.*
*The energy calculation method is verified comparing with another paper where the correlation was found for a loading level of 1.68 and the damage stages were the same.*

***Keywords:*** *damage, energy, steel wire rope, strand, tensile test.*

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## I. INTRODUCTION

Since their invention by Oberbergrat Wilhelm August Julius Albert in 1834 [1], the use of wire ropes is more than ever wider. We find them in mining industries, electrical lines, lifting systems and lifts, anchors of offshore platforms, cable stayed bridges and pre-stressed concrete structures.
Used in severe environment conditions (urban, industrial, marine…), there is different degradation mechanisms on wire ropes that we can classify into 4 categories [2]:
- Reduction of the wire area by wear, corrosion or abrasion;
- breaking of steel wires;
- Strains such as bird cages, shell, crush;
- Fatigue.

For this purpose, well defined inspection procedures exist [3] to quantify the wire rope degradation and ensure a safe use. New methods of non-destructive control are used, such as acoustic emission [4] [5].
Siegert [6] studied wire ruptures in steel wire ropes caused by fatigue. He elaborated a criterion to predict the initiation and endurance of fatigue cracks in the inter-wires contact of wire ropes. This criterion is based on the concept of critical facet amplitude maximum shear.
The objective of our research is to predict the damage of a strand according to its fraction of life which is defined as the number of wire breaks divided by the total wires number. During the tensile tests, drop of the strength is observed at each wire break. In this paper, we will use the loss of energy stored in the material as a criterion to define the damage.

## II. EXPERIMENTATION

### *2.1 Material*

Tests are carried on the constitutive strands of a wire rope of type 19 * 7 (1 * 7 + 6 * 7 + 12 * 7), rotation resistant construction and 10 mm diameter, made of stainless steel, with independent wire rope core (IWRC), right hand lay and preformed.

The rotation resistance is obtained by laying the strands of external layer and internal layer of the wire rope in opposite directions. This way, the wire ropes do not require guiding and rotation of the suspended load can be avoided. This type of cable is used especially in tower cranes and suspended bridges [7].
The Table below shows the geometrical characteristics of the wire rope used in our study. Data in bold are provided by constructor, the other were obtained by laboratory measurements.

**Table 1.** Wire rope 19x7, 10 mm diameter geometric information

| | |
|---|---|
| Strand diameter | 1,9 mm |
| Wire rope core diameter | 2,4 mm |
| Strand wire diameter | 0,58 mm |
| Wire core diameter | 0,68 mm |

Tensile tests are carried out on a universal machine "Zwick ROELL" (Fig. 1) in LPEE laboratory of Tit Mellil, with 10 KN maximum load.

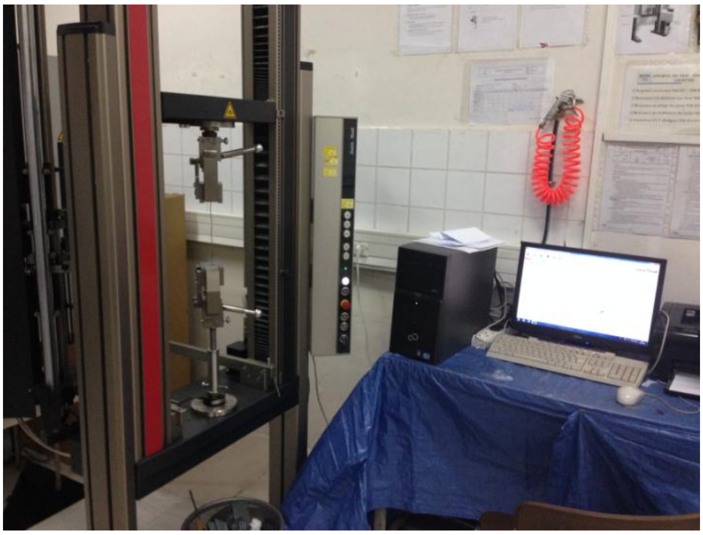


**Figure 1.** ''ZWICK ROELL'' testing machine

### *2.2 Chemical composition*

The chemical composition is obtained by a peak spark spectrometer in the "LPEE" (Public laboratory of experimentation and studies) laboratories of Tit Mellil. Homogeneous wire rope section of 20 mm diameter were obtained by compressing mechanically the cleaned wires. Results are summarized in Table 2.

**Table 2.** Wire rope chemical composition

| **Elément** | **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Mo** |
|---|---|---|---|---|---|---|---|
| % | 1,368 | 1,946 | 2,06 | 0,07 | 0,02 | 0,23 | 0,197 |

From the chemical analysis, we note the low alloy nature of this steel with a high Carbon content conferring to the wire rope high resistance [8].

### *2.3 Mechanical characterization*

Samples are made from 300 mm wire rope length (200 mm over 100 mm required for mooring) [9]. Then, the strands are extracted from the outer layer of the wire rope.
Tensile tests are made on the strands with screwed wedges fixed on terminations. The elongation speed is 1.5 mm / min [10].
This operation allows us to determine the ultimate strength of the strands and other mechanical characteristics.
The curve below shows the tensile test results on the virgin strand with the stress on ordinates and the strain on abscissa.

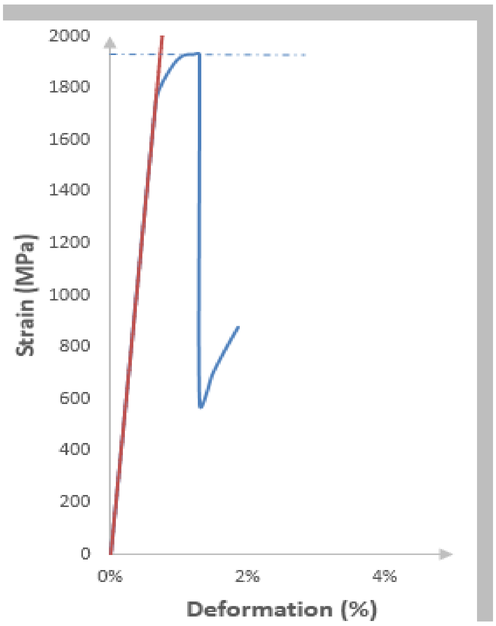



**Figure 2.** Tensile test on virgin strand

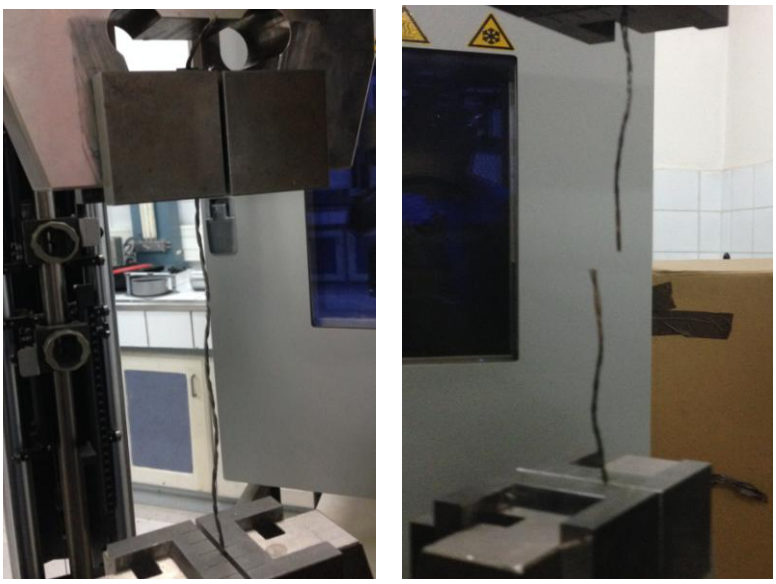
Mechanical characteristics defined from this test are summarized in the Table 3:

**Table 3.** Strand mechanical properties

| **Modulus of elasticity** | **Yield strength ($\sigma_e$)** | **Breaking strength ($\sigma_u$)** | **Stress at breaking** |
|---|---|---|---|
| **183 GPa** | **1800 MPa** | **1935 MPa** | **880 MPa** |

Next, a strand default is initiated by cutting two wires. The damage is obtained by inserting a tip through a strand wire and turning it in the wiring direction. Cutting is then performed by using a cutting plier. The same operation is repeated for the second wire.

Figure 3 shows pictures of strand before and after tensile test. With a default initiated, we can observe the fracture at the middle of the sample.



Before tensile test After tensile test

**Figure 3.** Illustration of sample before and after tensile test

## III. RESULTS AND DISCUSSION

***3.1 Test results***

Test resulting curve is represented below (Fig. 4) with strength on ordinates and strain on abscissa.

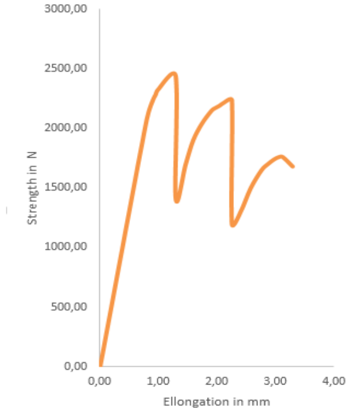
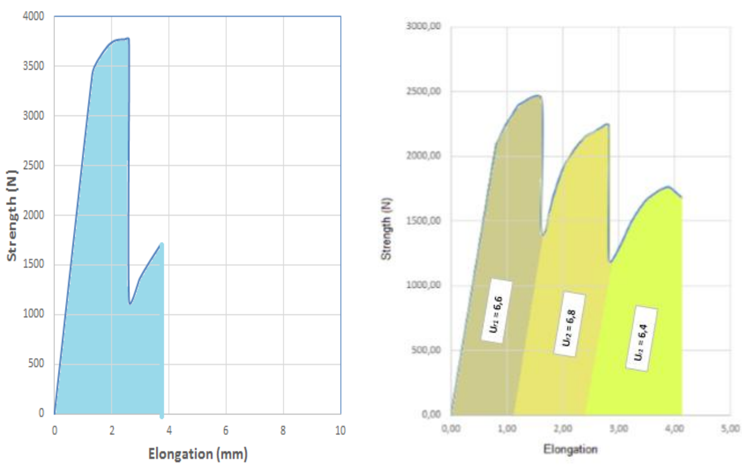



**Figure 4.** Tensile test of 2 wires damaged strand (2/7)

From tensile curves of virgin and 2/7 wires damaged strands, the energy needed to break each wire during the test is calculated. It corresponds to the area under the stress-strain curve.




Strength- elongation diagram of virgin strand | Strength – elongation diagram of 2 wires damaged strand

**Figure 5.** Ultimate and residual ultimate energy derived from tensile curves

We point a total stored energy of **22.09 J.m$^{-3}$** from the tensile test on virgin strand. Then, from the tensile test on 2 wires damaged strand we calculate a total residual energy of **19.8 J.m$^{-3}$**. At every wire break correspond a loss of residual energy as indicated on the diagram (Fig.5).

Last energy stored just before strand total breaking is derived from tensile test of a six wires damaged strand. We obtain the last residual energy (**$E_a$**) equal to **1.54 J.m$^{-3}$** (Fig.6).

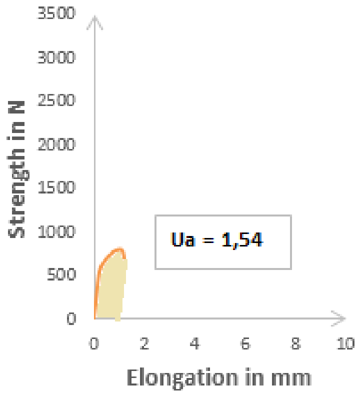



**Figure 6.** Last residual energy

Calculated values are indicated on the Table below:

**Table 4.** Residual ultimate energy

| $U_u$ | $U_{ur1}$ (3/7) | $U_{ur2}$ (5/7) | $U_{ur3}$ (6/7) | $U_a$ (7/7) |
|---|---|---|---|---|
| 22.09 $J.m^{-3}$ | 19.80 $J.m^{-3}$ | 13.20 $J.m^{-3}$ | 6.40 $J.m^{-3}$ | 1.54 $J.m^{-3}$ |

***3.2 Damage calculation***

***3.2.1 Residual energy damage calculation***

Initially used with the strength values [11], the formula indicating the loss of residual energy strength through the tensile test (1) can be developed as:

$$D_S = \frac{1 - \frac{U_{ur}}{U_u}}{1 - \frac{U_a}{U_u}} \quad (1)$$

With:

$U_{ur}$ is the experimental ultimate residual energy. Each value correspond to a number of broken wires

$U_u$ is the original material ultimate energy stored

$U_a$ is the critical residual energy corresponding to the energy released just before breaking of the last wire.

We draw the curve of the static damage in function of the strand fraction of life β witch correspond to the number of broken wire divided by the total number of wires (Fig.7).

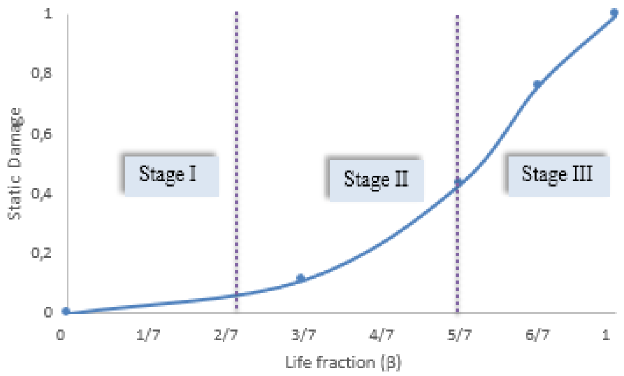



**Figure 7.** Static damage diagram by residual energy

The damage stages indicated on the diagram (Fig. 7) represent:

- Stage I: damage initiation ;
- Stage II: progressive damage. It is placed after the change of the damage curve's slope ;
- Stage III: brutal damage. In this stage, the curve becomes more steep and the element out of control.

It is observed that the stage of damage initiation ends at the life fraction of 2/7. The critical life fraction where brutal damage begins is located at 5/7 (71% of broken wires).

1.1.1. UNIFIED THEORY DAMAGE CALCULATION

As a method to evaluate the damage taking into account the loading level, the unified theory developed by T. Bui Quoc and al [12] establish a relationship between damage and the loading level. Here, replacing loads by the residual energy, normalized damage is thus written as:

$$\mathbf{D_u} = \frac{\boldsymbol{\beta}}{\boldsymbol{\beta} + (\mathbf{1} - \boldsymbol{\beta})\,\mathbf{x}\,\dfrac{\boldsymbol{\Upsilon} - (\frac{\boldsymbol{\Upsilon}}{\boldsymbol{\Upsilon u}})^{8}}{\boldsymbol{\Upsilon} - \mathbf{1}}} \qquad (2)$$

With $\Upsilon = \frac{U_{ur}}{U_o}$ ; $\Upsilon_u = \frac{U_u}{U_o}$ and $\beta = \frac{\text{number of broken wire}}{\text{number of wires}}$

Where $U_o$ is the original material enduring energy. It is obtained by applying a safety factor on the total energy stored equal to 2,5 [13].

The resulting curves are represented on the figure below (Fig. 8):

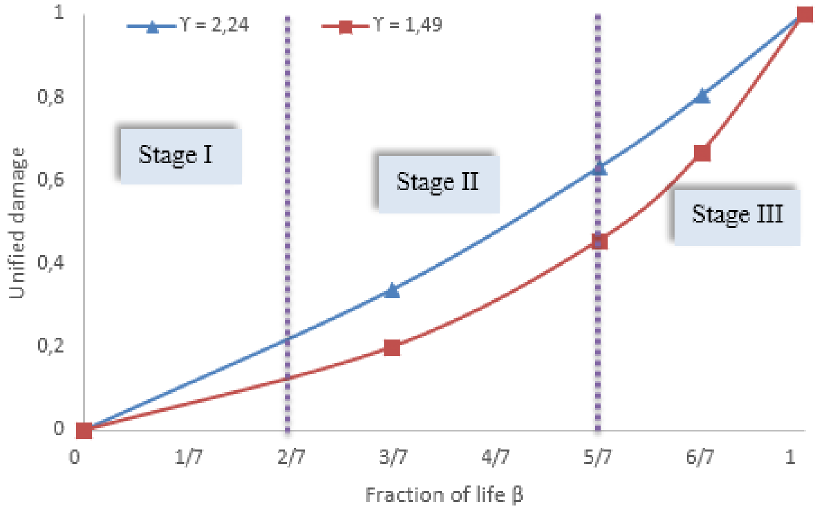



**Figure 8.** Unified theory damage diagram by residual energy

From this diagram, we can note that the limits of damage stages are similar to those obtained by the experimental static method. With the unified theory, the curves approach the bisectrix as the loading level increases. The bisectrix represents Miner damage with is calculated regardless of the loading.

### *3.3 Results discussion*

As we can see in Figure 9, damage evolution depends on the calculation method. Miner linear damage gives the most important damage. Then, depending on the loading level, the damage obtained by the unified theory goes increasingly toward the Miner damage line when high loading levels. Static damage curve is nearby the unified theory damage with a loading level of 1,49.

As a comparison, the correlation between the two methods were obtained for a loading level of 1,68 when the residual strength were used.

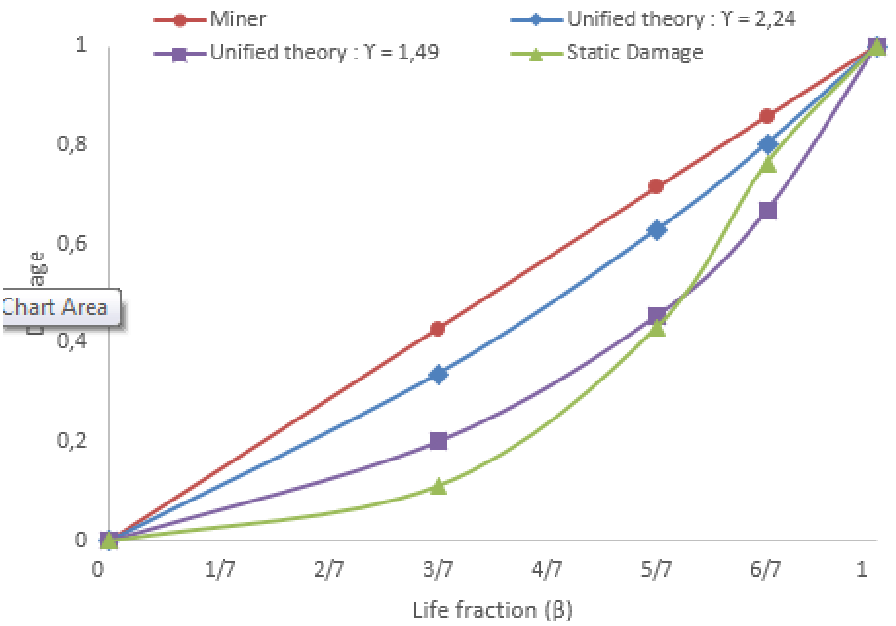



**Figure 9.** Damage curves by Miner, Unified theory and experimental residual energy

## IV. CONCLUSION

The strand's damage evolution according to the fraction of life were determined in this research. A new method to calculate the damage using residual energy was developed.

Different damage stages were identified. The initiation damage stage finish at the second wire breaking. Then, it enters in the progressive damage stage where intervention for predictive maintenance is required. The limit of this stage is at the $5^{th}$ wire's breaking and then, we enter in the fraction of life of brutal damage.

The residual energy damage calculation was compared to the unified theory for different loading levels. The correlation between the two methods was found for a loading level of 1.49.

In conclusion, the energy calculation method can be confirmed taking in consideration the previous work where the correlation was found for a loading level of 1.68 and the damage stages were the same.

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