Civil and Environmental Research www.iiste.org
ISSN 2224-5790 (Paper) ISSN 2225-0514 (Online)
Vol.8, No.11, 2016

Assessment of Strand Damage under Combined Degradation Modes

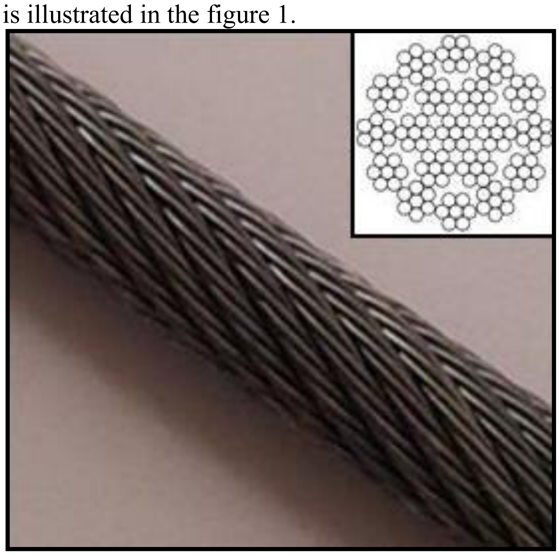
Amal TIJANI[1*] Meryam Meknassi[2] Hassan Chaffoui[1] Mohamed El Ghorba[2]
1.Laboratory of Atmosphere's Physics and modeling, FST Mohammedia, Hassan II University of Casablanca, BP 146 - Mohammedia, Morocco
2.Laboratory of Control and Mechanical Characterization of Materials and Structures, National Higher School of Electricity and Mechanics (ENSEM), Hassan II University of Casablanca, B.P 8118 Oasis – Casablanca, Morocco

Abstract
This paper deals with the influence of broken wires and the combination of broken wires and corrosion on the damage of constitutive strands of a wire rope. It was set that the damage is linear with broken wires. In the case of combined damage, after the first stage where it is nearly linear, it becomes more aggressive in the progressive damage stage. The increment from the artificial damage is about 25%. The brutal damage beguines at 4/7 broken wire when damage is combined against a brutal damage limit at 5/7 broken wire for the artificial damage. The critical life time of the strands was established at 55% in the combined damage, at 60% in the artificial damage, and depending on the loading level, from 70% to 85% with the unified theory.
Keywords: Wire rope, damage, reliability, corrosion, broken wire.

1. Introduction

Cables used in suspension bridges and cable stayed bridges, during their life time, are subject to aggression of the environment (urban, industrial, marine, etc.) and ageing. These effects lead to their loading capacity and reliability reduction. Thus, to insure an optimal use of these structures, the analysis of their security is connected to specific inspection procedures (Zhang, Ge, et Qiang 2003; SIEGERT et BREVET 2005). Due to their complex construction and non-linearity, the models for wire rope behavior are statistical (Elachachi et al. 2006) (Cremona 2003). Indeed, the behavior of wire ropes is multi-level: wire's scale, strand's scale and entire rope scale. In the one hand, in corrosion case, the physic-chemical process expands differently depending on the rope construction and the wires position. For example, the external layer are more exposed to corrosion than the inner layers. On the other hand, a wire rope with broken components can recover its strength in a specific length (Raoof et Kraincanic 1998).

The multi-level behavior of cable incites us to investigate, as a first stage, the strand scale. This work aims at the damage prediction of strands subject to combined degradation: artificial damage by breaking wires and corrosion. The wire rope used is illustrated in the figure 1.



Wire rope picture and cross section

2. Experimental procedure

2.1. Material and equipment

The wire ropes components are mechanically high strength and chemically low alloy steel wires. The wires are manufactured by cold drawing process. The wire's section is reduced by passing through decreasing section dies. Thus, the hardened wires obtain high resistance (LEFORT 2016).

In this work, we took wire ropes of type 19 * 7 (1 * 7 + 6 * 7 + 12 * 7), rotation resistant and 10 mm diameter, made of stainless steel, with independent wire rope core (IWRC), right hand lay and preformed.

External and internal layers being laid in opposite direction, the wire rope gets some rotation resistance. This type of cable is used especially in tower cranes and suspended bridges where the wire rope doesn't require guiding and rotation of the suspended load can be avoided (BRIDON STEEL WIRE ROPES AND FITTINGS, s. d.).

Table 1 shows the wire rope geometrical characteristics. 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
Strand construction	**6/1**
Coating	**Stainless steel**
Core	**IWRC**
Approximate mass	**40.4 kg/100 m**
Lubrication	**A2/W-3**
Breaking force	**68,6 KN**

A "Zwick ROELL" with 10 KN maximum load is used for the strands tensile tests (Fig. 2).

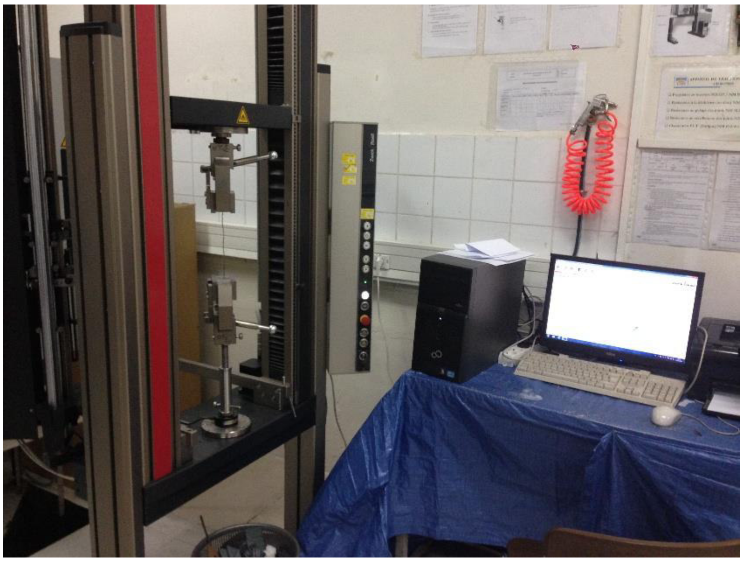


Figure 1. ''ZWICK ROELL'' testing machine

2.2. Chemical composition

A peak spark spectrometer was used for the chemical composition. Homogeneous wire rope section of 20 mm diameter were obtained by compressing mechanically the cleaned wires. Results are represented in Table 2.

Table 2. Wire rope chemical composition

Composition	**Fe (Iron)**	**C (Carbon)**	**Si (Silicon)**	**Mn (Manganese)**	**S (Sulphur)**	**P (Phosphor)**
Percentage	Balance	0,8 %	0,22 %	0,52 %	0,018 %	0,019 %

2.3. Mechanical characterization

Samples are 300 mm length (200 mm over 100 mm required for mooring) (ISO 1974). The strands are extracted from the outer layer of the wire rope. Screwed wedges are fixed on the strands terminations during the tensile test in order to avoid slipping. The elongation speed is 1.5 mm / min (Tijani et al. 2016).

Tensile test results on the virgin strand are illustrated on figure 3 by a representative curve, with the stress on ordinates and the strain on abscissa.

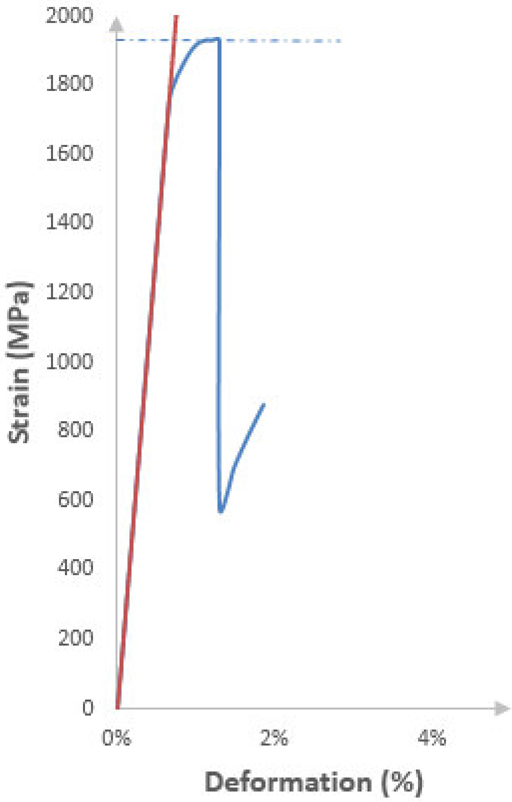


Figure 2. Tensile test on virgin strand

Strand mechanical characteristics are summarized in the Table 3. They represent the average values out of three tensile tests. The standard deviation is less than 4 %.

Table 3. Strand mechanical properties

Modulus of elasticity	Yield strength (σ_e)	Breaking strength (σ_u)	Stress at breaking
183 GPa	1800 MPa	1935 MPa	880 MPa

2.4. Strands damage

2.4.1. Stands mechanical damage

A default is initiated by cutting the sample's wires. A tip is inserted through a strand wire and turned in the wiring direction. Cutting is then performed by using a cutting plier. Thus, mechanically damaged samples are obtained with several damage levels (from 1 to 6 broken wires).

2.4.2. Stands combined damage

A combined damage is made by accelerated corrosion on the mechanically damaged strands. 100 mm length at the middle of the strands is immersed in a 30% H_2SO_4 solution at room temperature as indicated on figure 4. The choice of acid concentration is determined as the critical value from Meknassi et al work (Meknassi et al. 2015). Immersion time is 4 hours. The picture on figure 5 shows strands after combined damage (fig. 5).

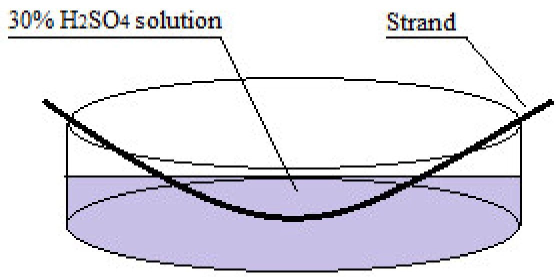


Figure 3. Corrosion procedure

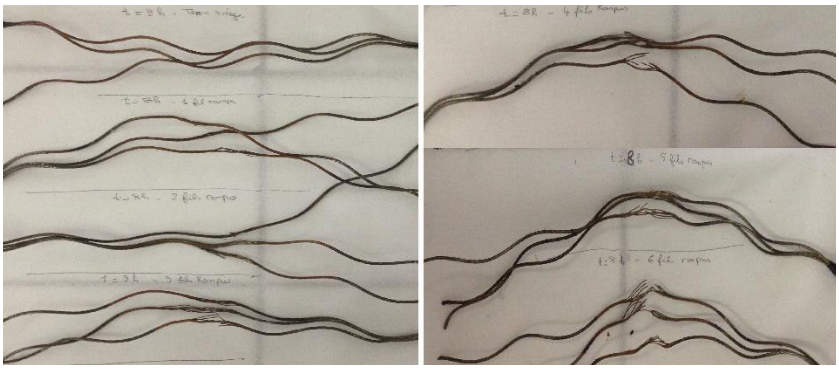


Figure 4. Combined damaged strands

3. Test results

Table 4 indicates the resulting ultimate forces on mechanically damaged strands. Residual ultimate forces obtained for combined damage are indicated on table 5. The forces indicated are average values.

Table 4. Residual ultimate strength of the mechanically damaged strands

Number of broken wires	0	1	2	3	4	5	6
Residual ultimate force	3770	3300	2800	2430	1970	1620	797

Table 5. Residual ultimate strength of combined damaged strands – 4 hours corrosion

Number of broken wires	0	1	2	3	4	5	6
Residual ultimate force	3397	2838	2350	1944	1153	842	396

4. Damage calculation

4.1. Normalized static damage

The damage calculation adopted in this paper uses a relation derived from the unified theory, it is normalized for the static results. The normalized static damage is expressed as:

$$\boldsymbol{D_S = \frac{1 - \frac{F_{ur}}{F_u}}{1 - \frac{F_a}{F_u}}} \qquad (1)$$

Where:

F_{ur} is the experimental ultimate tensile strength. Each value corresponds to the number of broken wires

F_u is the original material ultimate strength

F_a is the critical strength corresponding to the residual strength just before breaking of the last wire

$\boldsymbol{\beta}$ is the fraction of life ; $\beta = \frac{\text{number of broken wire}}{\text{number of wires}}$

For $\beta = 0$ (undamaged strand) we have $F_{ur} = F_u$ so $D = 0$

For $\beta = 1$ (last wire cutted) we have $F_{ur} = F_a$ so $D = 1$

The curve below (fig. n°6) represents the obtained damage by the strength residual method in the case of artificial broken wires.

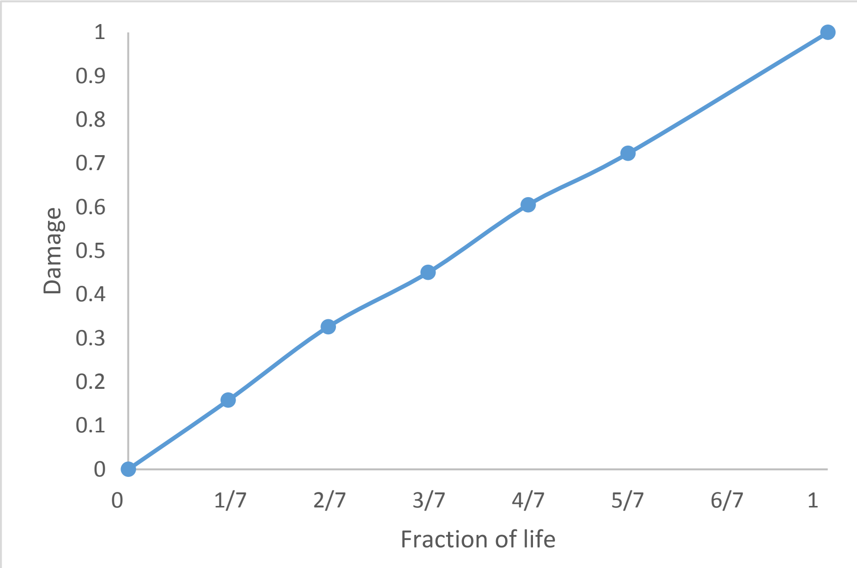


Figure 5. Normalized damage of strands with artificial broken wires

The damage obtained is near the linear damage of Miner. Next, the influence of a second deterioration mean which is corrosion will be investigated by extracting the damage curve of strands artificially damaged with broken wires and immerged in acid solution during 4 hours. The resulting damage curve in function of the fraction of life is represented in figure 7.

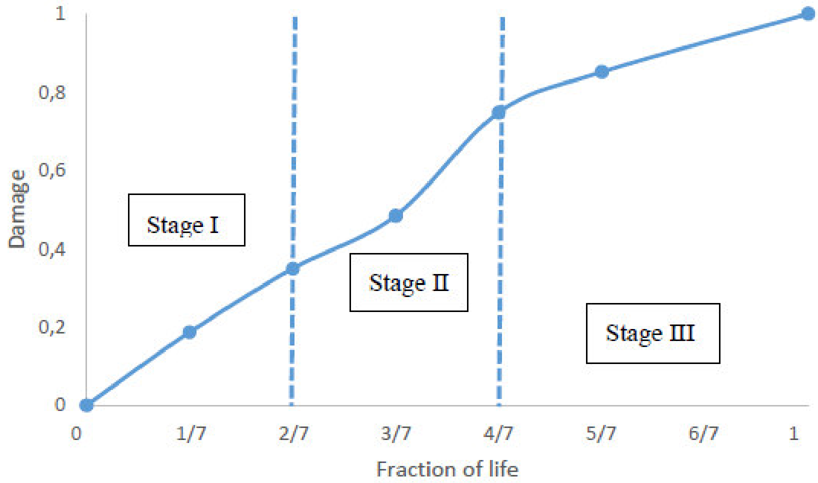


Figure 6. Normalized damage of strands with combined artificial damage

In the figure, are also represented the three stages of damage:

- 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.

Comparatively to the case of artificial damage (Tijani et al. 2016), the stage I limit is the same. However, the brutal damage beguines at 4/7 broken wire when damage is combined against a brutal damage limit at 5/7 broken wire for the artificial damage.

4.2. Unified theory damage calculation

The unified theory for calculating damage is a synthesis by T. Bui Quoc and al (Bui Quoc et al. 1971) of different theories taking into account the applied stress level. Normalized damage is thus written as:

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

With $\gamma_u = \frac{F_u}{F_o}$; $\gamma = \frac{\Delta F}{F_o}$ and $\beta = \frac{number\ of\ broken\ wire}{number\ of\ wires}$

Where

F_o is the original material enduring strength. It is obtained by applying a safety factor on the breaking strength equal to 2.5 (MEKSEM 2010).

ΔF is the applied load.

The resulting damages by the unified theory for three loading levels are represented below.

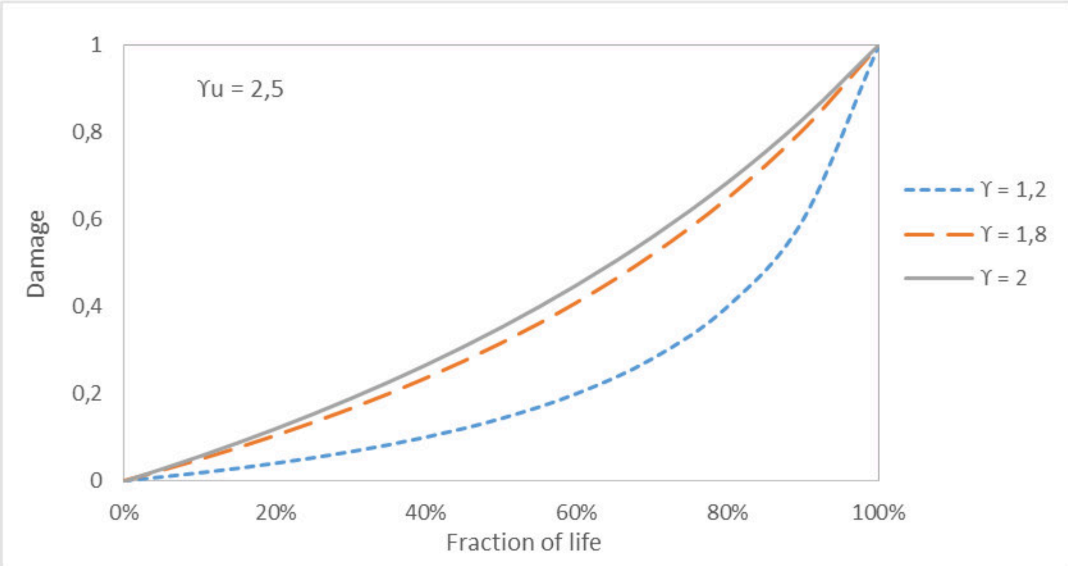


Figure 7. Damage by the unified theory for different leading level

We can note the progressive damage in the case of low loading. With the increasing load, the damage approaches the linearity.

4.3. Reliability in function of the fraction of life

In the purpose of monitoring the material's deterioration from the beginning of its life until its total ruin, there is the continue variable which is damage D and there is the statistical parameter which is reliability R(t), it represents the probability of the material survival. Considering the Weibull distribution as the most convenient to wires behavior (Chapouille et al. 1968), it can be expressed as:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\lambda}} \quad (3)$$

Reliability associated to Weibull distribution (Eq. 3) is an explicit function of time. Considering time as a series of sequences whose period is τ, we have: $t = n * \tau$ and $\eta = N_f * \tau$.

Where:

n : instant number of cycles;

τ: time between two loading cycles;

η: Spreading of the distribution;

N_f: Total number of cycles until breaking.

So replacing t and η in equation 3, we obtain the expression of reliability in function of the fraction of life:

$$R(\beta) = e^{-\beta^{\lambda}} \quad (4)$$

Then, in the linearized weibull equation (5), the shape parameter λ appears as the slope of a straight line:

$$ln\left[ln\left(\frac{1}{1-F(t)}\right)\right] = \lambda * [ln(t) - ln(\eta)] \quad (5)$$

The regression line is numerically defined using the least squares. It can be noticed that the experimental values are all near the straight line, which confirm the validity of Weibull distribution.

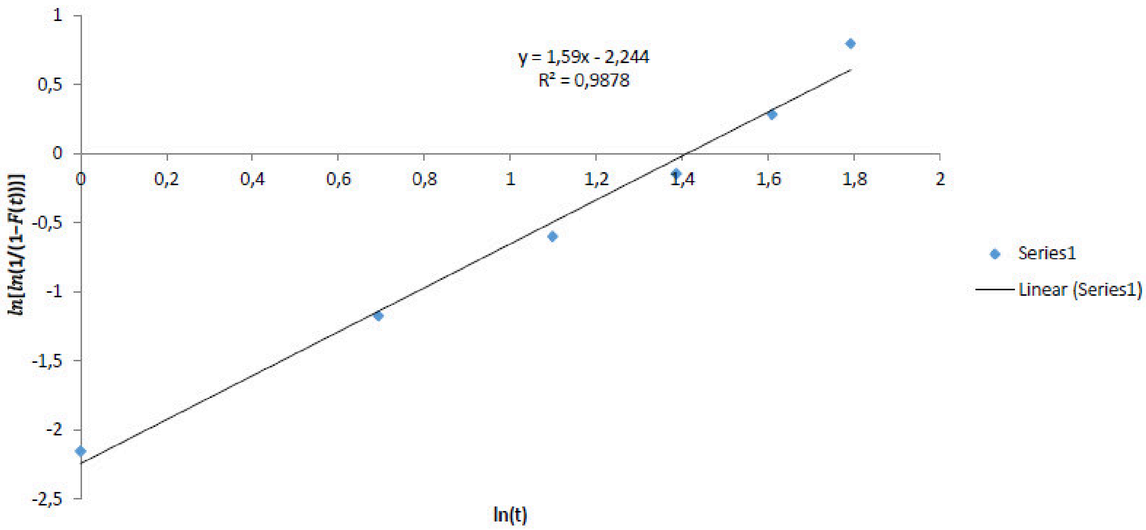


Figure 8. Evolution of ln(ln(1/(1-F(t)))in function of ln(t)

Replacing λ by its value, the reliability in function of the fraction of life is written as:

$$R(\beta) = e^{-\beta^{1,59}} \quad (6)$$

In figure 10, the reliability and damage curves detailed before are represented for the case of artificial and combined damage.

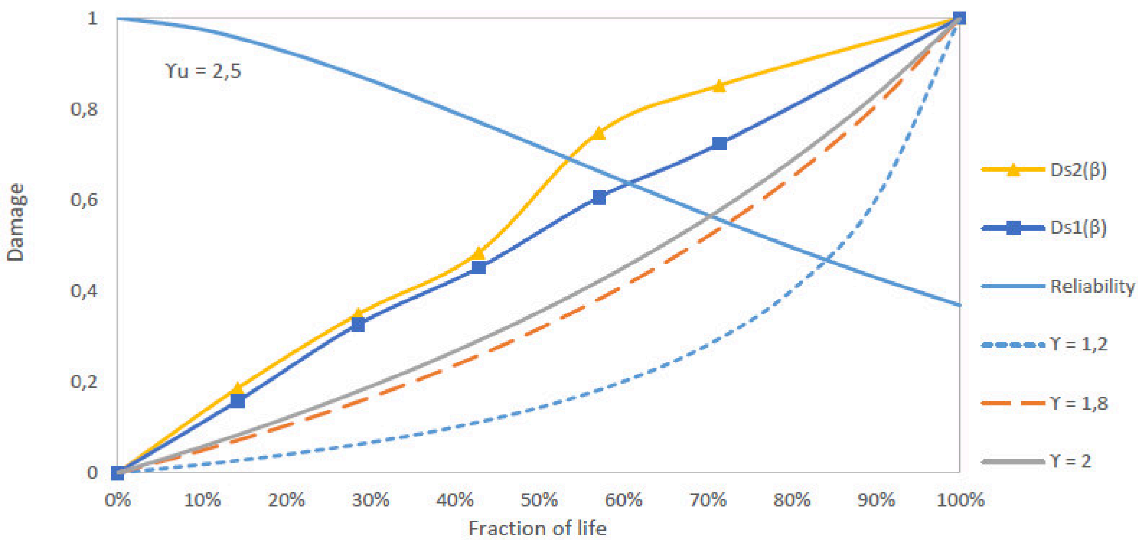


Figure 9. Damage reliability curves in function of the fraction of life

It is noticed that at the end of the fraction of life, where damage is equal to 1, the reliability is not zero value. It can be explained by the residual reliability before complete deterioration of the material.

The damage curves superposition shows to stages: in the first one, combined damage is linearly higher than the artificial damage about 6%, in the second stage, damage is harder in the combined case, it is about 25% higher than the case of artificial damage.

Theoretical fatigue damage calculated by the unified theory is far more progressive. The intersection of the damage curves with the reliability curve indicates the critical fraction of life β_c, it is determined at 55% in the combined damage, at 60% in the artificial damage, and depend on the loading level, from 70% to 85% with the unified theory.

5. Conclusion

In this work, we investigated the influence of broken wires and the combination of broken wires and corrosion on the damage of constitutive strands of a wire rope. It was found that the damage caused by broken wires can be estimated by the linear rule of Miner. Damage is more aggressive, comparatively to the case of artificial damage. Damage stages were defined, the stage I limit is the same in the two cases of deterioration. However, the brutal damage beguines at 4/7 broken wire when damage is combined against a brutal damage limit at 5/7 broken wire for the artificial damage. Damage due to a combined degradation is nearly linear in the stage of damage initiation, an acceleration is noted in the stages of progressive and brutal damage. The increase with respect to the artificial damage reaches 25%. Theoretical fatigue damage was calculated using the unified theory. Damage curves in function of the fraction of life and according to the loading level were drawn. A relationship of the reliability in function of the fraction of life was established. Using the intersection of the reliability curve and damage curves, critical life time was established. This critical point, when damage becomes higher than the material reliability, defines the removal time for a safe material use. The critical life time was established at 55% in the combined damage, at 60% in the artificial damage, and depending on the loading level, from 70% to 85% with the unified theory.

References

BRIDON STEEL WIRE ROPES AND FITTINGS. s. d. « The Blue Pocket Catalogue ».

Bui Quoc, Thang, J. Dubuc, A. Bazergui, et A. Biron. 1971. « Cumulative Fatigue Damage Under Stress-Controlled Conditions ». Journal of Basic Engineering 93 (4): 691. doi:10.1115/1.3425328.

Chapouille, Pierre, Roger de Pazzis, J.-J. Baron, et Pierre Davous. 1968. Fiabilité des systèmes. Les techniques de base de l'informatique. Paris: Masson.

Elachachi, S.M., D. Breysse, S. Yotte, et C. Cremona. 2006. « A Probabilistic Multi-Scale Time Dependent Model for Corroded Structural Suspension Cables ». Probabilistic Engineering Mechanics 21 (3): 235‑45. doi:10.1016/j.probengmech.2005.10.006.

LEFORT, André. 2016. « Tréfilage de l'acier ». Techniques de l'ingénieur Mise en forme des aciers, aluminium, autres métaux et alliages base documentaire : TIB356DUO (m3125).

Meknassi, M, MOUHIB, N, TIJANI, A. and M EL GHORBA. 2015. « Experimental study of wires extracted from steel wire rope and exposed to sulfuric acid ». IPASJ INTERNATIONAL JOURNAL OF MECHANICAL ENGINEERING (IIJME) 3 (11): 47‑53.

MEKSEM, Aziz. 2010. « Probabilistic approach and experimental characterization of the behavior of wire rope hoist ». ENSEM, University Hassan 2.

SIEGERT, D, and BREVET, P. 2005. « Fatigue of stay cables inside end fittings high frequencies of wind induced vibrations » OIPEEC Bulletin (89): 43‑51.

Tijani, Amal, El Ghorba, Mohamed, Chaffoui, Hassan, Mouhib, Nadia, and Boudlal, El Mostapha. 2016. « Experimental life prediction of a 1+6 strand extracted from a 19x7 wire rope ». IPASJ INTERNATIONAL JOURNAL OF MECHANICAL ENGINEERING (IIJME) 4 (3): 23‑29.

Zhang, D.K., S.R. Ge, et Y.H. Qiang. 2003. « Research on the Fatigue and Fracture Behavior due to the Fretting Wear of Steel Wire in Hoisting Rope ». Wear 255 (7‑12): 1233‑37. doi:10.1016/S0043-1648(03)00161-3.