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LIFE TIME PREDICTION USING ACCELERATED TEST DATA OF THE SPECIMENS FROM MECHANICAL ELEMENT

PROGNOZOWANIE CZASU PRACY ELEMENTU MECHANICZNEGO Z WYKORZYSTANIEM DANYCH Z BADAŃ PRZYSPIESZONYCH

In accelerated life testing, products are exposed to stress levels higher than those at normal use in order to obtain information in a short time. In this paper ,we expand the limits of performing accelerated life tests to an aerospace product (supple platinum). Specimens from the IAR 330 Puma helicopter structure, made of supple platinum, were subjected to accelerated life testing, and a significant reduction of the testing time was obtained. A simulation of the accelerated life testing data from the same case study was performed using the Monte Carlo method, with the purpose of comparing the data resulting from the experimental study (accelerated life tests) with the simulated data.

Keywords: *reliability, lifetime, accelerated life tests, acceleration model, Monte Carlo simulation.*

W przyspieszonych badaniach cyklu życia, produkty poddaje się naprężeniom o wartościach wyższych niż występujące w normalnych warunkach użytkowania, w celu szybszego uzyskania informacji. W przedstawionym artykule poszerzamy granice zastosowań badań przyspieszonych o produkt przemysłu lotniczego (giętka platyna, ang. supple platinum). Próbki z giętkiej platyny pochodzące z elementu konstrukcji śmigłowca IAR 330 Puma poddano badaniom przyspieszonym otrzymując znaczne skrócenie czasu badania. Dla otrzymanych danych z badań przyspieszonych przeprowadzono symulację metodą Monte Carlo, w celu porównania danych eksperymentalnych (z badań przyspieszonych) z danymi symulacyjnymi.

Słowa kluczowe: *: niezawodność, cykl życia, badania przyspieszone, model przyspieszenia, symulacja Monte Carlo.*

1. Introduction

The obtaining information regarding the reliability of mechanical products is usually done either by following the behaviour of the products during operation or during the reliability tests. In the real time operation we carefully record all the phenomena that occur during the product's use. A study based on this information represents only a "historical" study, its value being only that of collection experimental data or screening factors that can lead to a low reliability of the products. The information gathered from the operation usually refers to products or equipments suffering from the wear process, so that at the moment of the conclusions they might not be that important for the improvement of some aspects regarding the design and manufacturing of products, as a requirement of reliability [1, 10]. Considering the main requirement of reliability - the increase of performance of the industrial products, in direct connection with the scope of the study - it is necessary to extend a significant importance to reliability tests. A reliability test is represented by an experiment performed to determine the parameters of reliability for a well-defined product. The main reliability parameters during reliability tests is mean time to failure (MTTF), knowing that, based on the existing relations between reliability parameters, they can be easily deduced from one in other. It is required to specify that in order to apply the statistical methods of estimation of the reliability parameters, is recommended to know the low of distribution for the mean time to failure [21].

Many of the mechanical products produced today for complex technical systems have very high reliability under normal use conditions. The questions then arise of how to make the optimal choice between several types or designs of a device and how to collect information about the corresponding life distributions under normal use conditions. A common way of tackling these problems is to expose the products to sufficient overstress to bring the mean time to failure down to an acceptable level. Thereafter, one tries to "extrapolate" from the information obtained under over stress to normal use conditions. This approach is called Accelerated Life Testing (ALT) or overstress testing [1, 5, 6, 12, 13, 15, 19, 21]. In these tests, reliability practitioners may force the product to fail more quickly than it would under normal use conditions. Accelerated failure time modelling is one part of the quantitative accelerated life testing. The interest of this theory is to know the influence of any given stress on the life duration of an item. The technique of accelerated life testing enjoys both intuitive appeal and objective support from the physics of failure, and can be implemented in various ways; experimental aims are, however, usually phrased in statistical terms. For instance, the practitioner may wish to estimate a specified percentile of life or the probability of failure within a given warranty period of an item operating under design stress.

The primary purpose of an ALT is to estimate the life distribution and quantities of interest at a use condition. This estimation involves extrapolation from higher stress levels by using an acceleration model, and thus includes the model error and statistical uncertainty. Sometimes, the model error outweighs the statistical one. The model error may be reduced or eliminated only by better understanding the failure mechanisms and using a more accurate model, whereas the statistical uncertainty can be reduced by carefully selecting a good test plan. A typical test plan is characterized by the stress levels, the number of test units allocated to each level, and their censoring times. The most commonly used ALT in modern manufacturing industry is the constant-stress ALT (CSALT) where stress applied to a sample of units is constant. A typical parametric model of CSALT consists of two components: (1) a lifetime distribution that models the time-to-failure at a constant-stress level; and (2) a stress-life model that quantifies the manner in which the lifetime distribution changes a cross different stress levels. There are different types of ALT plans in use, which include subjective, traditional, best traditional, statistically optimum and compromise plans [4, 6, 8, 9, 17, 19, 20].

Pursuing the previously stated main purpose of the accelerated life tests, we need a model that relates life to accelerating stress, such as temperature, humidity, and voltage. Such models, usually called acceleration models, can be classified into the following three types: physical models; quasiphysical models; empirical models. Among the most important acceleration models (life-stress) we can mention the following: Arrhenius, Eyring, Inverse Power Law; Life - Thermal Cycling, Life - Voltage, Life - Vibration, Life - Humidity, Life - Temperature - Humidity [2, 5, 8, 13, 15, 21].

Accelerated life testing [7,11, 13, 16, 21] is used in electronics, (resistors, lasers, liquid crystal displays, electronic bounds, switches, circuit breakers, relays, cells and batteries) in the study of metals and composite materials, but also for certain components and mechanical assemblies (automobile parts, hydraulic components, tools, bearings). In aerospace industry, the accelerated life testing is used to test certain components: the engine, the oil pumps, the landing gear, onboard electronic equipment and stiffening components (strips, spear).

As a result of the critical study above on the accelerated life tests, the scope of the paper becomes evident, which is: the theoretical and experimental study regarding the management of accelerated life tests for a product from the field of aviation (supple platinum), in order to reduce the testing time and obviously of the material costs related to this kinds of tests.

2. Case study

In this paper, accelerated life tests will be implemented and performed on a vital component from the structure of the IAR 330 Puma helicopter, following all the stages that are necessary to the execution of such tests. Starting from the constructive and functional analysis of the tested product and of the experimental bench, then proceeding with the optimization and the design of the accelerated life test plans and finalizing with the statistical processing of the experimental data using software that is specific to accelerated life tests. For a validation of the accelerated life tests we used the Monte Carlo simulation method for the data in accelerated conditions. The purpose of using this method is to make a comparison between the data from accelerated conditions that resulted from the Monte Carlo simulation and the experimental data.

2.1. The necessity of implementation of accelerated life tests in the mechanical product's testing

If a mechanical product requires, for example, 10^8 cycles to cause a failure from fatigue in normal use condition, by using an accelerated life test we can obtain the same result in 10^5 cycles. The design of the accelerated life test and the interpretation of data require the understanding of the relation, in the course of the destructive process considered, between the level of stress and the failure rate. The result of these accelerated life tests is the reliability estimated by statistical and mathematical means, using specific software. Thus, for the design of the accelerated life tests plans and for the processing of statistical data obtained from the quantitative accelerated life test in this paper we used the ALTA 7 (Accelerated Life Testing Data Analysis) software.

In the case study of this paper, we applied a cyclical mechanical stress. During the cyclical stress the most frequently used are the metallic components and systems and the phenomenon is fatigue. The degradation by fatigue involves a variety of aspects regarding to: the type of stress; the shape of the part; the quality of the part that will be processed; the environment of the part's operation. The accelerated life tests where the main degradation phenomenon is fatigue are very important in the industrial field and especially in the aerospace industry [7, 11, 14, 18], with application on the components in the structure of airplanes and helicopters.

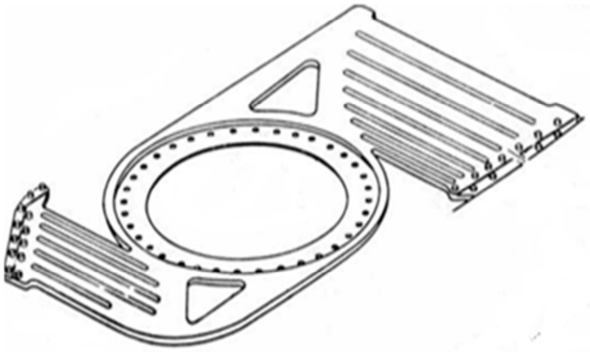
The introduction of accelerated life tests in the aviation is necessary, because the fatigue tests can have the operating time of millions of cycles until the failing of components occurs (the helicopter blade, the supple platinum, command rods, the wing and the landing gear). That is the reason why the accelerated life tests represent a method by which the testing time of components from the aerospace field is shortened and thus leading to optimizing of the testing system.

2.2. Constructive and functional of supple platinum

The french helicopter constructors introduced the system for reducing the vibrations like supple platinum. Supple platinum (Fig. 1) is made of a titanium alloy and is placed between the inferior part of the main transmission box and the mechanical board at the Puma IAR 330 helicopter. Supple platinum is a vital part and has the role to reduce the vertical vibrations produced by the main rotor's blade.

2.3. The structure of the test bench

Due to its configuration, supple platinum cannot be subjected to stress tests. That's why the tests are being made on specimens, with standardized shapes and dimensions, made of the same material as supple platinum (a titanium alloy known in the aviation as TA 10).



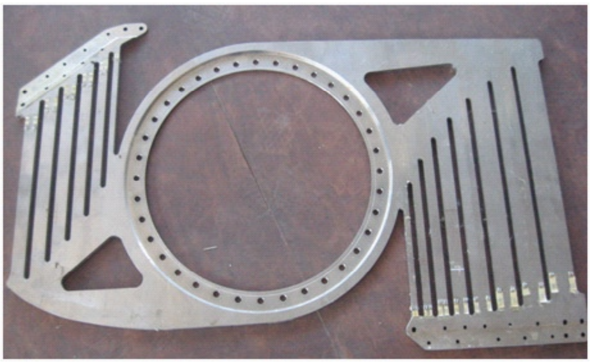


Fig. 1. Supple platinum

The tests of the specimen made of supple platinum consists of the repeated stress using a bending force, on a test bench that includes: a fixation device for the specimen - the specimen is embedded at one end, and at the other end we apply a displacement (arrow) on vertical; the device for the tensioning of the specimen - the main function of the device is to introduce a displacement at the free end of the specimen; the energy installation - that is composed of an engine which produces the mechanical energy for production at displacement at the free end of the specimen; the command installation - has the role to turn off and on the engine during the testing of the specimen; the electronic installation - is composed of an apparatus that reads frequencies and a cycle counter. The test bench used for the fatigue testing of specimens is presented in figure 2.

Fig. 2. The test bench for the fatigue testing of specimens

The data acquisition system is composed of: Hottinger measuring device with 6 channels, Hottinger LC 11 strain gauges, apparatus that show the frequency of stresses and a cycle counter.

2.4. Plan and accelerated test conditions of test specimens

The experimental research has been performed on specimens made out of supple platinum, specifically from removed portions that result from the technological processing. Figure 3.a shows the constructive model of the specimen used in accelerated life tests and, also, the placement of strain gages. On the specimens are mounted and connected in half-bridge 2 strain gages used to measure the specific strain. The placement of this strain gages is described in figure 3b.

Poor accelerated life test plans waste time, effort and money and may not even yield the desired information. Before starting an accelerated life test, it is advisable to have a plan that helps in accurately estimating reliability at operating conditions while minimizing test time and costs. To design the plan for the accelerated life tests of the specimen made out of supple platinum it is necessary to establish the following parameters:

A) The acceleration model: for accelerated life tests where the failure mechanism is a mechanical one (the fatigue in the case of accelerated life tests for the specimens made out of supple platinum), the most adequate one is the IPL model; The inverse power law (IPL) model is commonly used for non-thermal accelerated stresses and is given by:

$$L(V) = \frac{1}{KV^n} \tag{1}$$

where L represents a quantifiable life measure, such as mean life, characteristic life, median life, B(x) life, etc; V represents the stress level; K is one of the model parameters to be determined, ($K > 0$); n is another model parameter to be determined.

The failure rate under normal operating conditions is:

$$\lambda(t, V) = \beta KV^n \cdot (KV^n t)^{\beta-1} \tag{2}$$

B) The number of specimens subjected to accelerated life tests: for accelerated life testing we used 20 specimens made from supple platinum;

C) The distribution law of the number of cycles until failure used in accelerated life testing: the Weibull distribution was chosen to test the specimens;

D) The stress under normal condition and in accelerated condition: the bending force in normal testing conditions is 50 daN and the maximum bending force is 70 daN (according to the specimens' test chart).

E) The accelerated life test plan: for the accelerated life testing of the specimens made from supple platinum we chose 3 levels best compromise plan. The test plan was realised using the ALTA software, introducing the aforementioned parameters.

The ALTA 7 software generates an optimum testing report, where the levels of accelerated life testing and the number of specimens tested at every accelerated stress level are specified. The testing parameters resulted from the design of the accelerated life testing plan for the specimens made from supple platinum are as follows: 3 levels of testing: 60, 64, 70 daN;

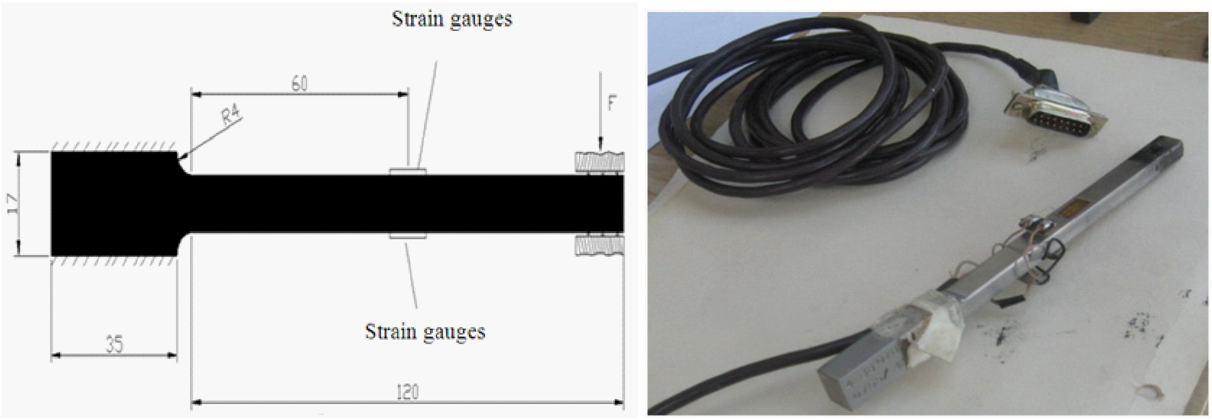


Fig. 3. The specimen made of supple platinum: a) the specimen's constructive model, b) the experimental model

the number of tested specimens corresponding to the level of acceleration: 9, 5 and 6 specimens.

2.5. The statistical processing of experimental data

For the results obtained from the accelerated life testing of the specimens for the 3 levels of accelerated stress we verified the hypothesis that the distribution law of the number of cycles until failure is Weibull (the Kolmogorov - Smirnov test was used). For this verification, we measured the spacing between empirical distribution function of the sample and the cumulative distribution function of the reference distribution. We compared these results with a level of confidence of the Kolmogorov – Smirnov test. Following the statistical processing of the experimental data for the 3 levels of stress the Weibull distribution was accepted.

For the determination of the mean number of cycles to failure and of the reliability parameters under normal testing conditions (F=50 daN) for the specimens made from supple platinum, the experimental data resulted from accelerated conditions have been processed using the ALTA7 software. We calculated the three parameters corresponding to the IPL-Weibull model using the maximum likelihood estimation method for the data from the accelerated regime introduced in the ALTA7 software. The following values of parameters resulted: β=7.283; k=4.04267E-18; n=6.788. We determined the acceleration factor corresponding to the IPL model. This is determined for every level of acceleration of the bending force. The accelerated levels are: La1=60 daN, La2=64 daN, La3=70 daN, and the normal testing level is Lu=50 daN. By calculating the product of the calculated values of the acceleration factors and the number of cycles to

Tab. 1. The determination of the number of cycles to failure in normal conditions

Num.	The number of cycles to failure in accelerated conditions	Acceleration factor	The number of cycles to failure in normal conditions
1	141453	3.447	487711
2	157243		542153
3	169634		584875
4	182723		630005
5	201634		695207
6	206256		711143
7	219634		757269
8	231238		797278
9	247234		852430
10	112787	5.343	388874
11	119462		411889
12	123300		658866
13	139498		745421
14	152087		812692
15	50231	9.818	268414
16	56922		304168
17	67037		658200
18	73008		716826
19	78025		766085
20	85341		837917

Table 2. The dependence between the numbers of cycles in normal conditions – Reliability - Unreliability – Failure Rate

The number of cycles to failure in normal conditions	Reliability R(t)	Unreliability F(t)	Failure Rate $\lambda(t)\cdot10^{-6}$
268414	0.999	0.001	0.020
304168	0.998	0.002	0.044
388874	0.989	0.011	0.204
411889	0.984	0.016	0.293
487711	0.945	0.055	0.847
542153	0.885	0.115	1.648
584875	0.808	0.192	2.654
630005	0.693	0.307	4.233
658200	0.604	0.396	5.573
658866	0.602	0.398	5.609
695207	0.472	0.528	7.859
711143	0.413	0.587	9.062
716826	0.392	0.608	9.527
745421	0.287	0.713	12.181
757269	0.247	0.753	13.450
766085	0.218	0.782	14.465
797278	0.131	0.869	18.587
812692	0.096	0.904	20.964
837917	0.054	0.946	25.403
852430	0.036	0.964	28.297

failure in accelerated conditions we determined the number of cycles to failure in normal testing conditions (Table 1) for the specimens made from supple platinum from the structure of the IAR 330 Puma helicopter.

We determined the reliability parameters (the reliability function, unreliability and the rate of failure) depending on the number of cycles to failure in normal testing condition (Table 2).

Using the calculated values (the number of cycles in normal testing conditions), the reliability function 3D (Fig. 4a) and the failure rate 3D (Fig. 4b) were plotted.

The main purpose of accelerated quantitative tests is to determine the life time in normal testing conditions. Using the data resulted from accelerated life tests we can determine the mean number of cycles to failure of the specimens made from supple

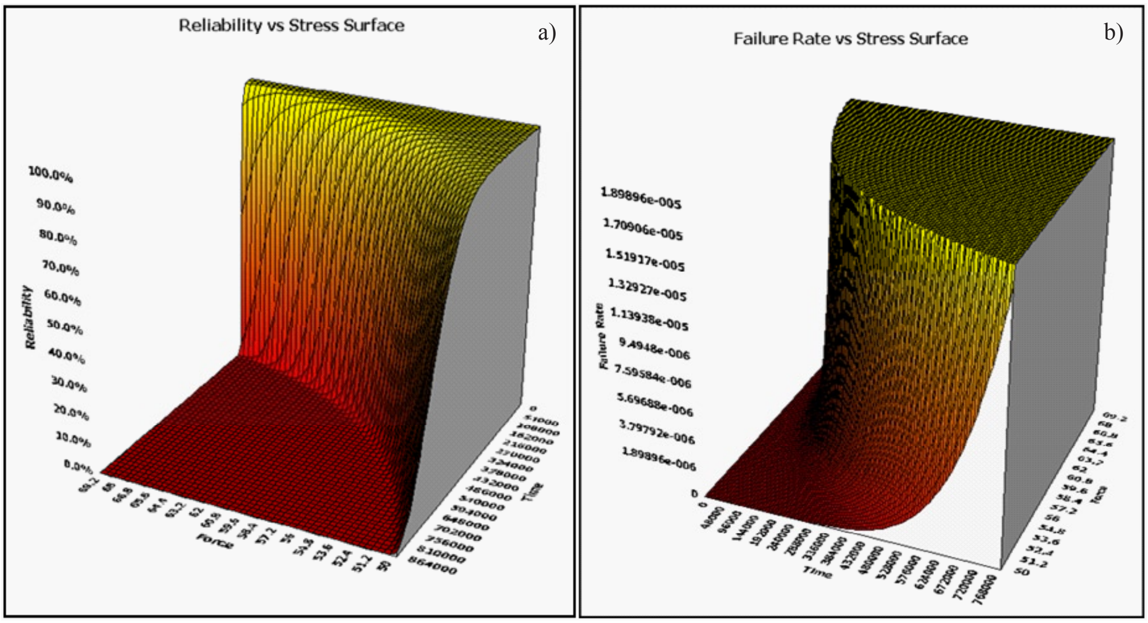


Fig. 4. Reliability parameters: a) reliability function, b) failure rate

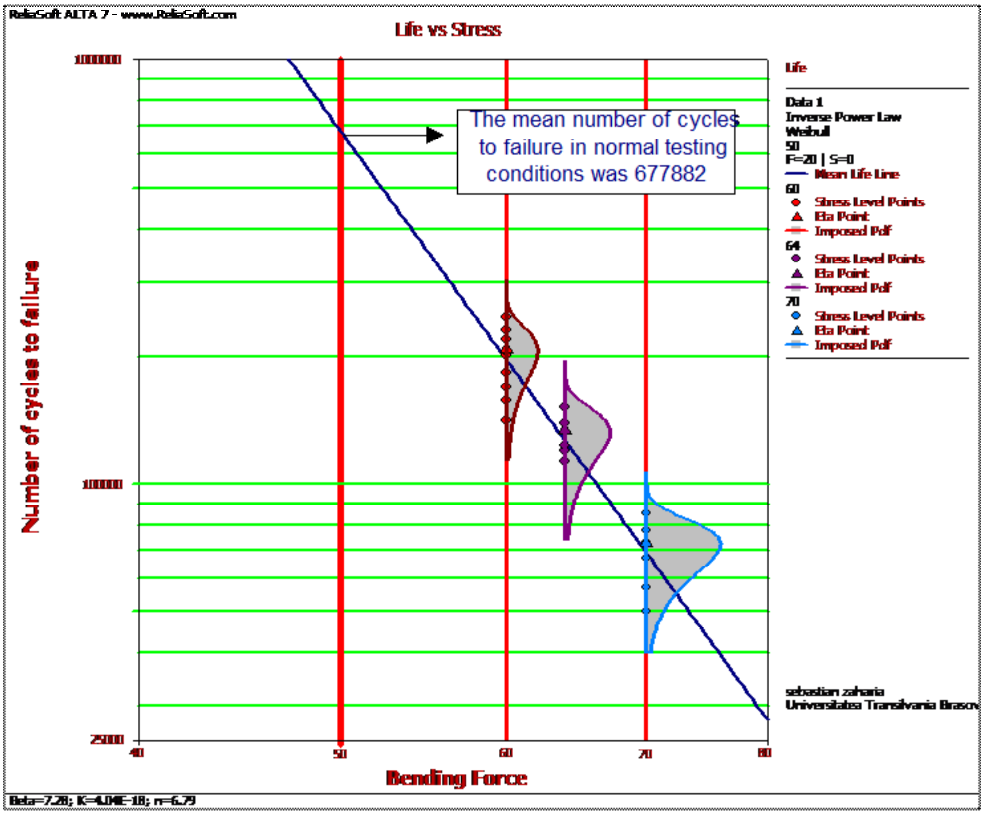


Fig. 5. The determination of the number of cycles to failure of the specimens in normal testing conditionst

platinum in normal testing conditions. The mean number of cycles to failure is determined using the relation of the mean time to failure from table 1.

The mean number of cycles to failure for the tested specimens was of 677882. Life versus stress plots is the most important plot type in accelerated life testing analysis. Life versus stress plots are widely used for estimating the parameters of life-stress relationships. Any life measure can be plotted versus stress in the life vs. stress plots available in ALTA 7. In figure 5, by drawing a line through the mean number of cycles to failure for the 3 levels of acceleration (60 daN, 64 daN and 70 daN) and marking the point of intersection of this line with the vertical line at the normal level of stress of 50 daN, we found out the mean number of cycles to failure in normal testing conditions.

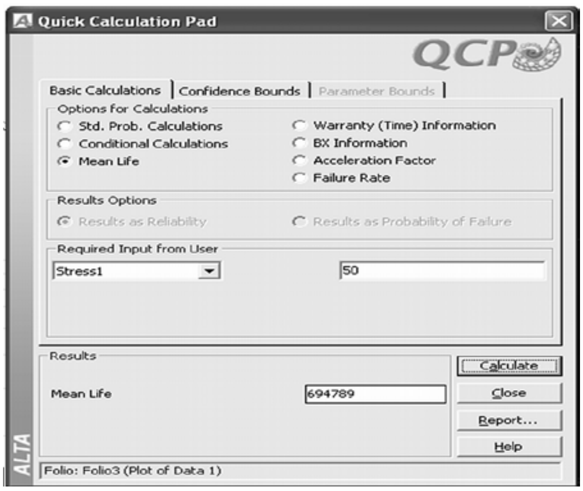


Fig. 6. The calculation of the mean number of cycles to failure in normal testing conditions for the specimens of supple platinum with the Monte Carlo method using QCP

The mean number of cycles to failure of the specimens in normal testing conditions given by the manufacturer at the approval of the vital element supple platinum is 700000 cycles, whereas the mean number of cycles to failure obtained from the accelerated life tests was of 677882 cycles. By adding the number of cycles to failure resulted from the accelerated life tests, this is of 2814747. The total number of cycles to failure in normal testing conditions is 12627432. The main purpose of the accelerated life tests on the specimens made from supple platinum from the structure of the IAR 330 Puma helicopter, to reduce the number of cycles using the accelerated life tests, was validated. Using the accelerated life tests on the specimens made from supple platinum from the structure of the IAR 330 Puma helicopter, the number of cycles to failure has been reduced by 4.5 times, making this result responsible for significant reductions of the material costs.

2.6. The application of the Monte Carlo method for the simulation of data in accelerated conditions (for supple platinum - a component of the IAR 330 Puma helicopter)

Using the Monte Carlo method we simulated N stages of a product with the help of an acceleration model (Inverse Power Law) and statistical distribution (Weibull) which are suited to the analyzed case study. Using the previously determined parameters (β=7.283; k=4.04267E-18; n=6.788) and the three accelerated levels (60, 64 and 70 daN), we simulated with the help of ALTA7 software the values for the number of cycles to failure in accelerated conditions.

Following the simulation of accelerated data using the Monte Carlo method for the specimens from supple platinum from the structure of the IAR 330 Puma helicopter, we obtained the value of 694789, which represents the mean number of cycles until failure (Fig. 6), which is close to the value of 677882, which represents the mean number of cycles to failure of the specimens tested in accelerated conditions in the previously presented abovementioned experiment. The Quick Calculation Pad (QCP) provides you with a quick and accurate way of gaining access to some of the most frequently requested reliability results.

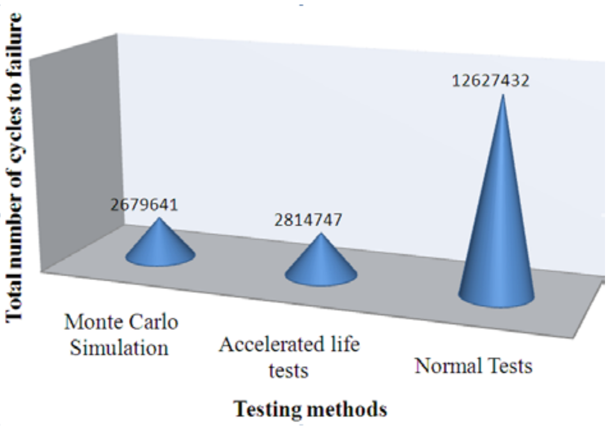


Fig. 7. Significant reduction of time using accelerated life tests

3. Conclusion

At some industrial products (from the aviation, nuclear and electronic fields), for which a high reliability is estimated, the determination of the life time and of the reliability parameters, under normal stress conditions, implies a long testing period. For this reason we opted for the accelerated life testing methods. These are tests being performed at more intense stress conditions, compared to the normal stress conditions, with the purpose of intensifying the degradation processes and, as an economic result, the shortening of the period and costs related to the testing, while preserving the same failure modes and mechanisms.

The implementation of accelerated life tests on the products from the aviation field has produced a significant reduction of the testing time. For the case study under analysis, figure 7 shows the number of cycles to failure from: accelerated life tests, the simulation with the Monte Carlo method and the data from the normal testing conditions. We can observe that, by using the accelerated life tests, the testing time has been reduced by 4.5 times. Given the fierce competition existing on the aviation industry market and considering the reduction in testing time and therefore the optimizing of the products' life cycle, many companies will implement and develop various methods of obtaining data as fast as possible regarding the reliability and quality of the products.

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