Accelerated Fatigue Test in Mechanical Components

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Additional information is available at the end of the chapter

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Abstract

The reduced time available for product development has forced original equipment manufacturers and their suppliers to develop new components and subsystems efficiently, to release it to the market with lightweight and innovate designs, guaranteeing non-failure on the service life. In order to reach these goals, accelerated tests are developed to evaluate its durability with different design proposals. Although durability is nowadays improved through virtual testing, it is mandatory to perform experimental tests before the final release of the product. The tests are done not only to reproduce the same loads; it has to be modified to reproduce the failures that are found on the roads under normal use conditions. The component can be evaluated as itself, in subassembly or in the assembly; the result among these possibilities have to be the same. To reach this aim, devices are designed to reproduce a specific stiffness, combining its mechanical behavior with the modified loads also known as spectrum. Accelerated test can be developed to increase its severity, reducing test time. The spectrum to perform the durability test was built with service loads and different profiles or users and different roads including weather conditions.

Keywords: accelerated tests, durability, spectrum, extrapolated tests, statistical analysis

1. Introduction

To release new or optimized component, it is mandatory to evaluate it under fatigue load conditions to prevent any kind of unexpected failure on the product life. To reduce the time of the development process, accelerated tests can be performed to obtain the mechanical strength feedback to improve its fatigue performance, thereby reducing the excessive material or reinforcing critical areas as stress concentrators. Nowadays, this information directly influences the component with physical optimization or analyzes it in a virtual way, in order to reduce the number of physical prototypes. The importance of implementing accelerated tests in the early stages of design is to evaluate components developed in the concept stage or to modify it, for changes in design during its production life act as facelift. **Figure 1** shows the time development reduction when accelerated tests are implemented. Most improvements have to be made prior to mass production and in the early manufacturing process of the tooling [1].

To perform this kind of test, it is necessary to evaluate the critical failures on the component related with the major probability of occurrence. All the load cases are evaluated; however, the target of this kind of a test is to evaluate the component in an easier way, with uniaxial test, where it is possible.

In other cases, the test is developed depending on the part or the process that has to be evaluated, for example, a new stamped part, or the weld cordon or the sequence of the welding. In those cases, a localized damage is developed with a correlation to its use in normal load conditions, but the important thing is to find the direction and load amplitude generated by use conditions, to get a correlation between the number of load repetitions and how many kilometers or time of use represent it.

The way to develop this kind of test starts with the instrumentation of a car with displacement transducers, accelerometers, force-moment transducers and strain gauges where it is necessary. The instrumented car is measured on different roads, used by different drivers in all the markets and under different weather conditions to acquire loads to measure the changes on the responses of the wheels.

These responses are acquired as signals, which are analyzed to synthetize it in one signal representing all of these driving and use conditions. The new signal used for the durability test is known as spectrum. The reproduction of this spectrum in labs reaches the same damage on the component as in the roads, but the target of this kind of test is to reduce the time of evaluation in a controlled manner to detect the location of failure, the moment of occurrence and its propagation. To accelerate the test, the spectrum is extrapolated and proving grounds are developed. These are faster than duration cars on the roads, but it is possible to reduce the evaluation time developing accelerated test on test benches through extrapolating the loads; to perform this, the component can be mounted as assembly, subassembly or component as itself. Test reduction is reached due to the loads that represent more damage by their amplitude and severity, than that applied on the component in normal-use conditions.

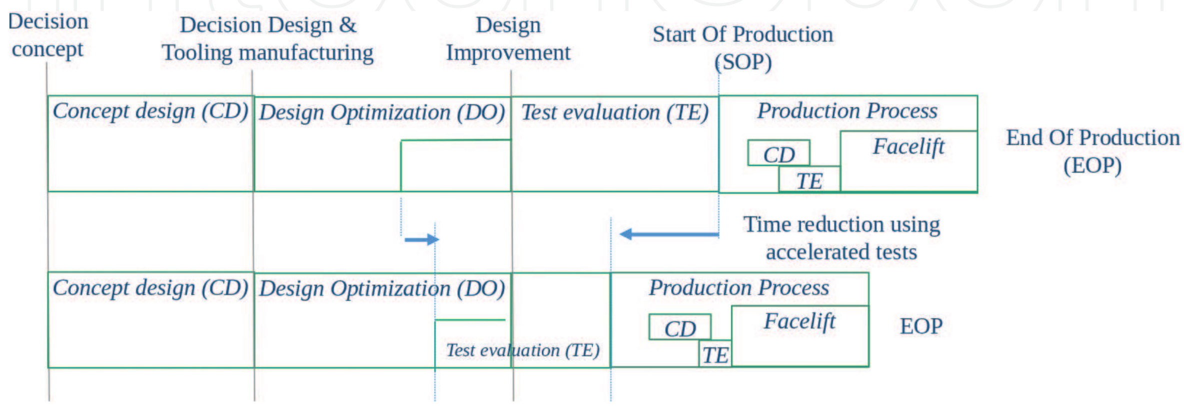

Figure 1. Development time reduction using accelerated tests.

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Test responses and desired signals have to be evaluated through statistical analysis. The correlation of results in lab and on roads is essential as the main target of accelerated tests is to reproduce the same failures as on the road so as to take steps to prevent them. The component´s load spectrum is made more aggressive by including all the variables in load conditions as in the case of drivers on roads, and the spectrum is also modified to build test requirements to include the safety factor.

In this chapter, a review of durability test has been performed, describing the process to develop a fatigue test and also the development of accelerated test. A general overview is done on the product evolution process (PEP) to define where the evaluation of the component is applied and how it affects the development process, the general process of the fatigue life evaluation of the component, a description of the finite element analysis and its application on fatigue life prediction to evaluate an automotive component and develop stiffness devices necessary for the test that are used with the modified loads to reproduce the failures.

2. Fatigue tests

It is important to evaluate components in experimental tests because fatigue strength has its inherent scatter due to four main factors: the loading, design, manufacturing and material (**Figure 2**). Experimental results under variable loads differ from analytical predictions owing to the effect of sequence loads [2, 3], Jimenez et al. [4] proposed a modification in Linear Damage Rule to include the effect of sequence in fatigue life prediction.

While manufacturing generally determines the strength and scatter, the geometry can modify the effect of mechanical properties [5, 6] due to the material that has variations on its properties. Loads have the major variability due to the diversity of drivers and factors such as number of passengers, weight on the car and its distribution, weather and its effects on the interchange of the loads between the non-suspended mass and the pave and the loads generated by bumpy ways and maneuvers.

Fatigue strength at the endurance limit is affected by the type of load and the size, reliability and surface roughness of the component [7]. The surface roughness can be improved with

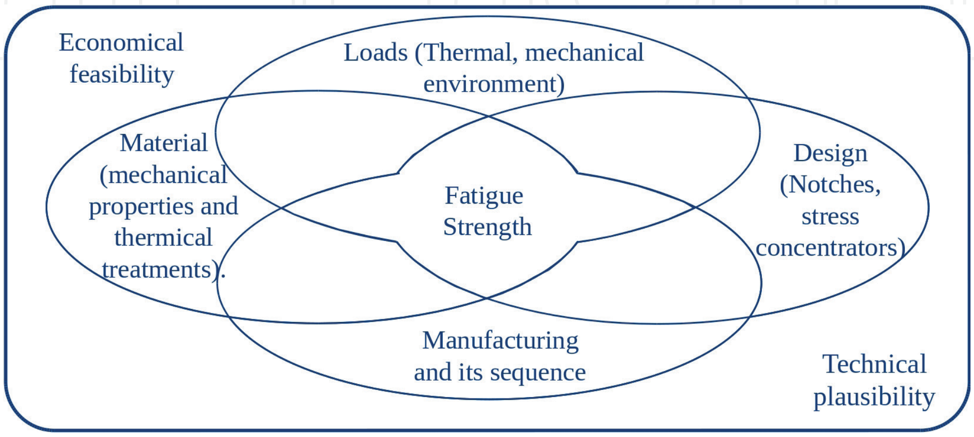

Figure 2. Parameters influencing the structural durability of components.

processes such as shot peening, which is important because fatigue cracks usually initiate at the surface in homogeneous materials [8, 9].

In durability tests, the aim is to minimize the likelihood of failure applied for the more aggressive driver using the weakest component. **Figure 3** shows a strength-load interference model [10], which helps to manage the likelihood of failure of a component. As described in **Figure 2**, the component has different sources of scatter and its structural strength is determined on a bell-shaped curve. On the other side is evaluated the scatter for the loads applied to the component. The safety factor is defined by the difference between the central value of applied loads and its difference with the central value of the component's structural strength.

Jimenez et al. [7] reported that the advantage of component testing is that the effects of the material, manufacturing process and geometry are inherently accounted for. Although with controlled process as in test laboratory, fatigue test results have scatter, the main sources of scatter are summarized in **Table 1** [11].

Fatigue evaluation is not simple to predict by analytical methods, and to perform durability assessment and to predict the component´s life, it is necessary to measure the most precise information, and to do this, the loads in service are acquired and analyzed, to reproduce them as shown in **Figure 4**.

To build a track to perform a durability test, it is necessary to get information from the customers through a data acquisition with strain gauges, accelerometers and displacement transducers; then this information is analyzed. The output of this analysis is to get the desired signal that is known as spectrum. The importance of getting the spectrum is to compare the loads with the S-N curve in order to predict the component life through damage accumulated rule. Every step of the development process is evaluated to improve its mechanical response, and after the design is released, tests are performed to monitor the quality of the product to prevent failures in its service life.

To reduce the time required for testing on public roads, accelerated tests are performed on proving grounds. This simulates road damage for different maneuvers, different vertical loads of frames and different longitudinal dynamics for accelerating and braking, lateral dynamics and vibrations [12], combining all the events (normal roads, rough roads, emergency braking, high speed, city and country roads). In addition, the tests can be performed in the laboratory [5]. It is possible to increase the number of repetitions at high or medium loads, avoiding inadmissible stresses that satisfy the test results. Although some proposals [13] have included

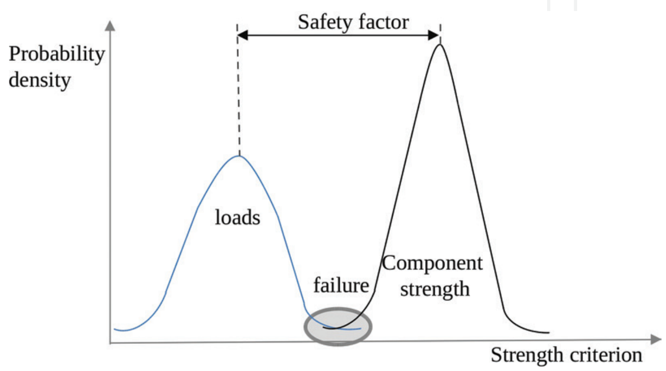

Figure 3. Failure likelihood in components subjected to cyclic loads.

the omission of low loads, they depend on the type of material and the application (**Figure 5**). The main objective is to develop an accelerated spectrum to get a test track.

Variable	Fatigue in components	
	In laboratory	**In service**
Production and materials.	Production samples and different lots	Material from different lots and suppliers processed in different facilities.
	Quality on the specimen Surface.	Quality on Surface in critical areas as in notches.
Loads including environment	Type of load (CA, VA)*	Loads in service from different users
	Accuracy of test equipment	Residual fatigue life
Environment	Temperature, humidity in laboratory	Temperature, snow, rain.
Human	Skills and expertise of lab staff to perform and evaluate the test.	Different users and styles of use, overloads not expected, abuse loads. Responses changed for the environment.

*CA-Constant amplitude; VA-Variable Amplitude.

Table 1. Main sources of scatter in mechanical fatigue.

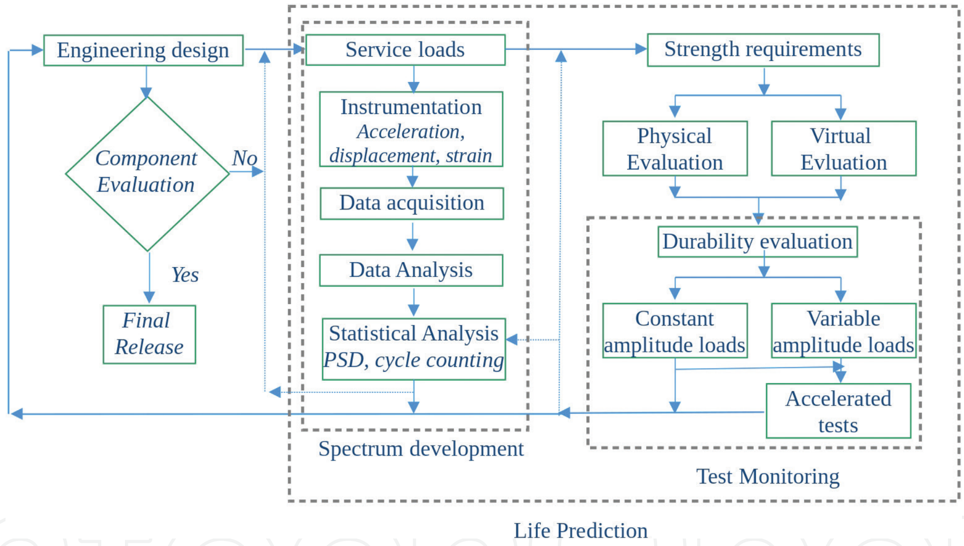

Figure 4. Parameters influencing the structural durability of components.

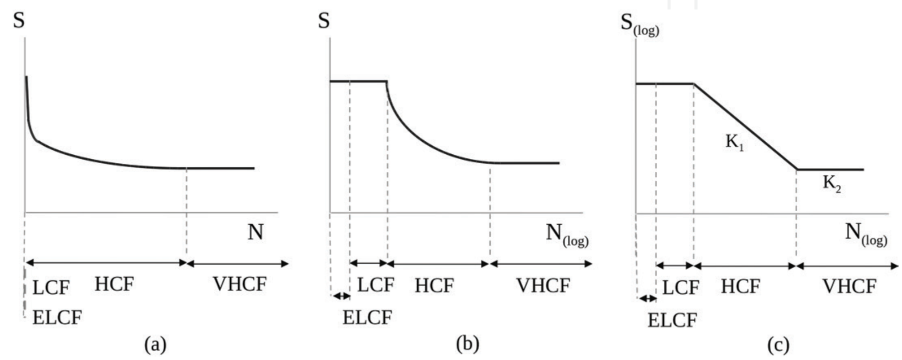

Figure 5. Schematic S-N curve: (a) linear-linear, (b) semi-log, and (c) log–log.

3. Statistical analysis

The loads acquired are compared with S-N curves. The S-N curves are often expressed on semi-log, normal and log–log coordinates. **Figure 5** shows a schematic curve on different coordinates, linear, semi-log and log–log. The most common representation is log-log since it becomes linear (**Figure 5c**).

The S-N curve represents the material or component fatigue strength, and is split into regions depending on its cycles. Extremely low cycle fatigue (ELCF) is defined from 0 until 100 cycles, between this limit and until 1000 cycles is low cycle fatigue (LCF), and between 1000 cycles and until 1 × 106 for steel and 5 × 107 for nodular cast iron is defined as high cycle fatigue (HCF). Anything beyond this point is defined as very high cycle fatigue (VHCF) [7].

To compare the S-N curve with loads, the time history is analyzed. **Figure 6** shows a schematic waveform. The main characteristic is the stress amplitude S_a. If it has constant amplitude, the stress range S_R is constant and is defined by the difference of the maximum stress (S_{max}) and minimum (S_{min}) in a cycle (Eqs. (1)–(3)).

$$S_R = S_{max} - S_{min} \tag{1}$$

$$S_a = \frac{S_R}{2} = \frac{S_{max} - S_{min}}{2} \tag{2}$$

The mean stress S_m is defined as

$$S_m = \frac{S_{max} - S_{min}}{2} \tag{3}$$

A fully alternating stress $S_m = S_a$.

The stress ratio *(R)* is defined as the ratio of minimum to maximum stress as is shown in Eq. (4).

$$R = \frac{S_{min}}{S_{max}} \tag{4}$$

The fatigue damage of a component is influenced in high cycle region by the mean stress expressed by its stress ratio. In normal $R \geq 0$, open microcracks accelerate the propagation of stress, while $R = \infty$ or >1 closes the microcrack that is beneficial for fatigue strength. In low cycle fatigue region, the plastic deformation eliminates the effect of mean stress to improve or detriment the fatigue strength. The schematic stress ratio is shown in **Figure 7**.

The amplitude ratio is the ratio of the stress amplitude to mean stress as show in Eq. (5).

$$A = \frac{S_a}{S_m} = \frac{1 - R}{1 + R} \tag{5}$$

The loads are monitored with cycle counting that is used to summarize variable amplitude time histories, providing the repetitions of the load during the time history. There are different

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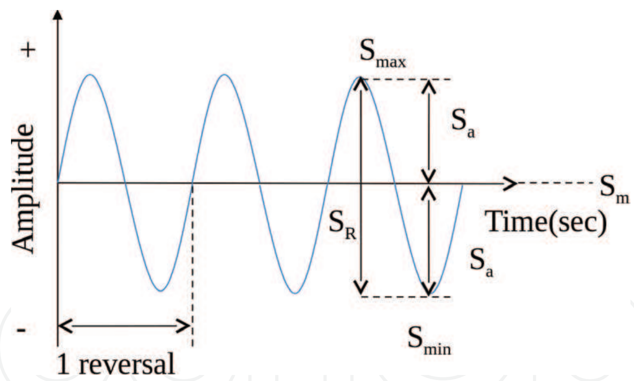

Figure 6. Signal characteristics.

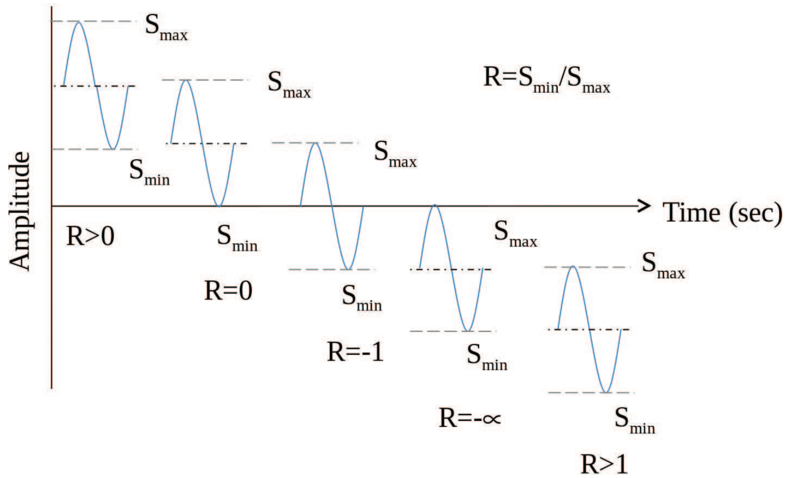

Figure 7. Stress ratio.

cycle counting methods such as the Rainflow used to extract cycles from random histories in the time domain [13, 14], based on the analogy of raindrops falling on a roof. **Figure 8** shows Rainflow counting process.

The cycle counting is represented in a matrix based on **Figure 5**. The signal has 2 cycles from 5 to 3, 1 cycle from 6 to 3, 1 cycle from 1 to 5, 1 cycle from 2 to 4 (**Figure 5a**), 2 cycles from 1 to 6 (**Figure 5b**), and it has residue. In **Figure 5c**, these cycles are tabulated on a matrix, which depending on its counting can be represented by colors.

It is possible to evaluate time histories with other types of cycle counting methods, such as the level crossing method [15] where the amplitudes of the loads are split into a number of levels based on ranges, and the load is counted when it has peak at a different level, changing its slope from positive to negative or negative to positive; the cycle counting is shown in **Figure 9**.

In the range pair counting method, the magnitude of loads is split into a number of levels. The result of the extracted number of reversals is shown tabulated in **Figure 10b**. **Table 2** summarizes the events counted in **Figure 10**.

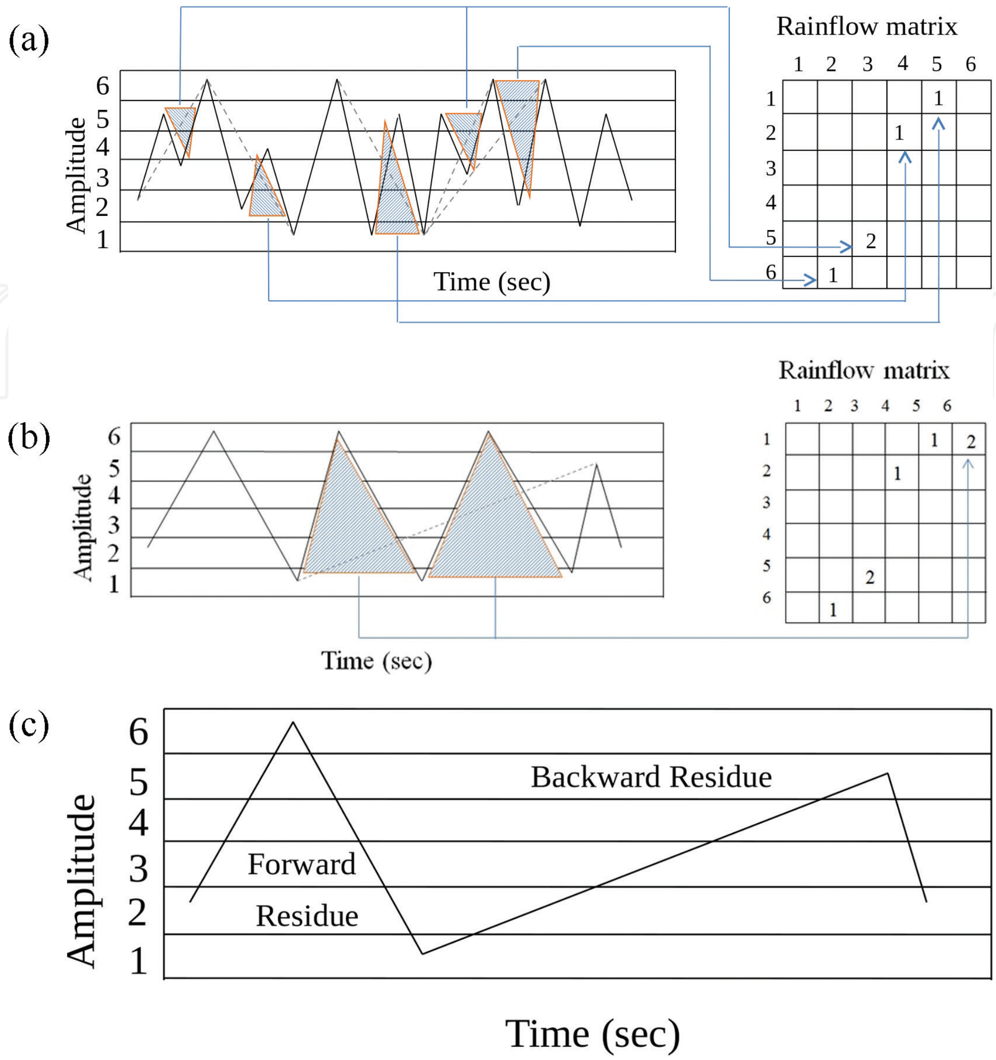

Figure 8. Rainflow counting process: (a) initial counting, (b) continue counting, and (c) residue.

The signals can be seen in time domain and frequency domain. A transfer function can be used in the frequency domain to relate the power spectral density (PSD) of the input desired load to the PSD of the output stress (Eq. (6)) [16]:

$$\sigma_{PSD}(w) = |h(w)|^2 F_{PSD}(w) \tag{6}$$

here the squaring process is required to get the transfer function in the correct units of PSD stress [17]. In this equation, σ_{PSD} (w) is the PSD of the stress at frequency w (N^2/Hz); h (W) is the linear transfer function at frequency w; and F_{PSD} (w) is the PSD of the input amplitude at frequency w (N^2/Hz). The advantage of analyzing the responses with PSD is that it helps us represent the energy of the time signal at each frequency.

The time histories for constant amplitude test spectrum is linear (**Figure 11a**), and for variable amplitude, it is a curve (**Figure 11b**) generated by the cycle counting. Although a theoretical fatigue limit has been proposed, with the introduction of new test equipment for high frequency, the prediction has been improved at low load levels. Although this stress couldn't damage the components by itself, the accumulated damage induced by high loads can be propagated by such small loads. The correction factors for the slope depend on the material [18].

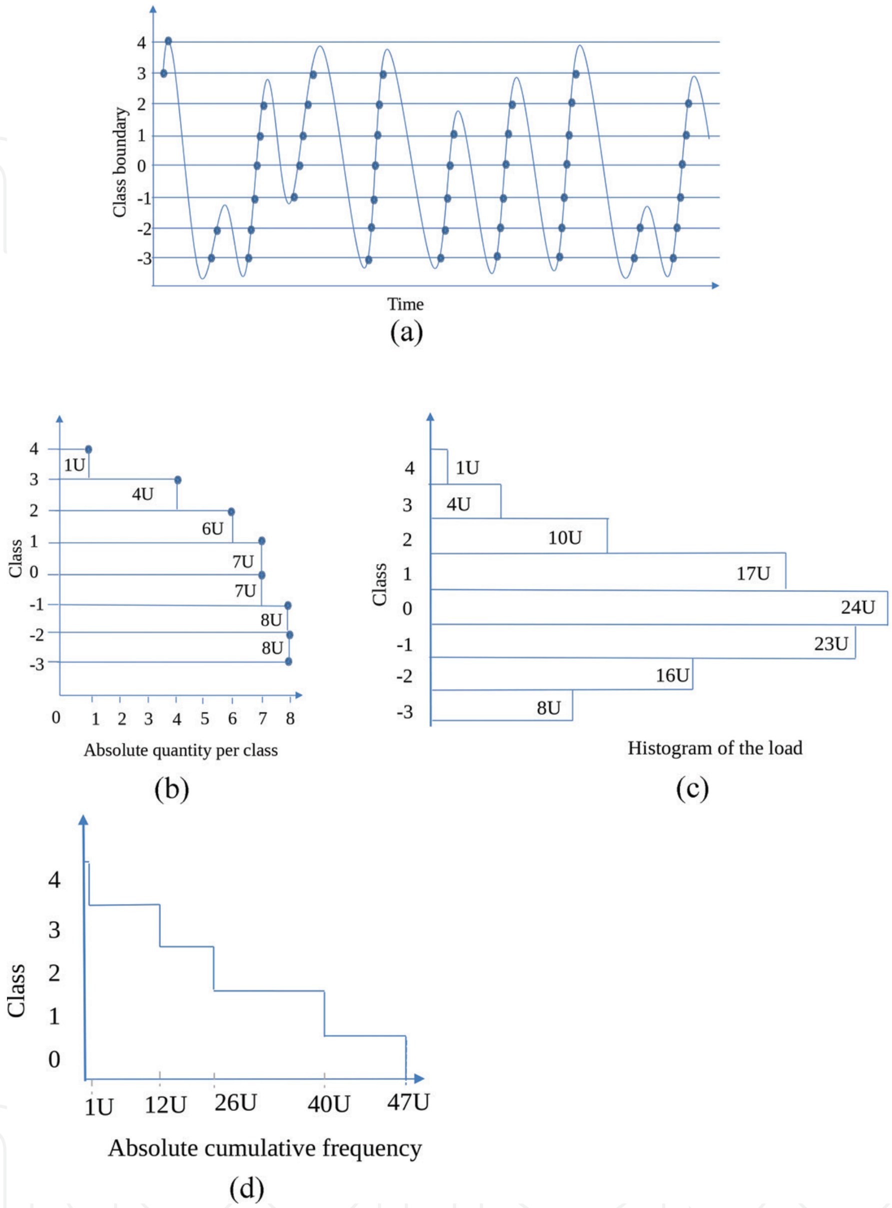

Figure 9. Level crossing counting process: (a) time history, (b) quantity per class, (c) histogram, and (d) absolute cumulative frequency.

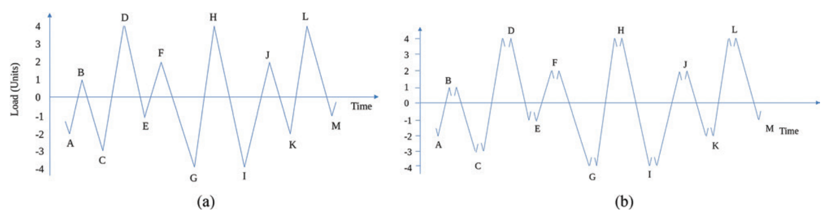

Figure 10. Range pair counting process, (a) time signal and (b) events.

Range (Units)	Cycle counts	Events
8	1.0	G-H,H-I
7	0.5	C-D
6	1.5	F-G, I-J,K-L
5	1.0	D-E,L-M
4	1.0	B-C,J-K
3	1.0	A-B,E-F
2	0	
1	0	

Table 2. Range pair counting.

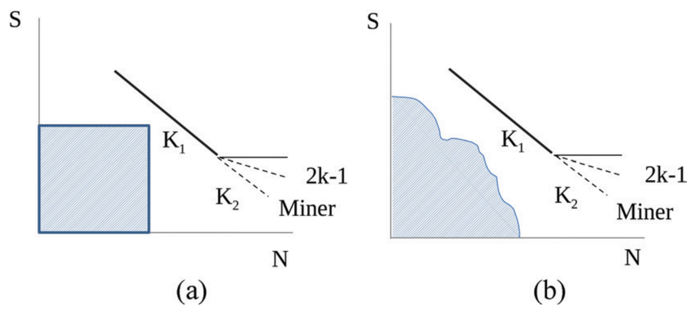

Figure 11. Schematic spectrums versus components S-N curves: (a) constant amplitude, (b) variable amplitude.

4. Accelerated tests

Component life testing is commonly designed to validate fatigue strength of a component based on a target customer usage and is based on loads acting on components. The measurement period is usually not long enough to be used directly in a test. The main target for extrapolated signals is based on time measurement restrictions and problems such as synchronicity, spikes, drifts observed on measurement devices. For this reason, the most representative road or proving ground is determined and that is extrapolated to reach the kilometers of the total life.

The advantages of finite element simulation are mainly in the early stages of design where the prototypes are not yet available, and also to improve its design without physical components. But also in this case, the loads for variable or spectrum as well as constant amplitude are developed to correlate with the accelerated tests. All the factors are evaluated in physical tests, and the results are analyzed through statistical results.

The load measures are extrapolated to the requirement. These spectrums are evaluated to include all the behaviors, as is shown in **Figure 12**. Spectrum test is developed using different

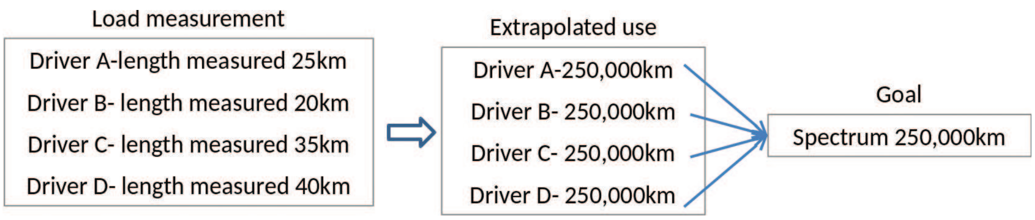

Figure 12. Spectrum development target.

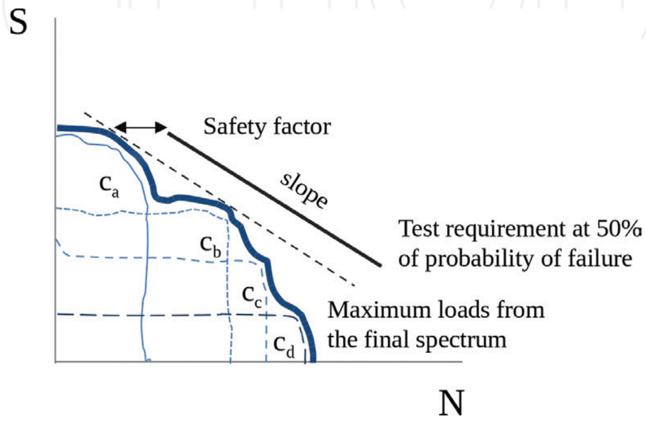

Figure 13. Schematic spectrum development.

loads from the users and different responses are taken into account. C_a is the driver A, the most aggressive driver, C_b is the average driver, and C_c and C_d are the drivers that use less aggressive components but for more time. After having extrapolated the goal use, the spectrum is built considering all these measurements. **Figure 13** shows a schematic spectrum development. For variable amplitude test, the spectrum is reproduced and monitored with statistical analysis.

The repetitions of the cycles are found using the linear damage rule of Miner (Eq. (7)), and damage is evaluated using the ratio of the loads *(n)* with the number of repetitions *(N)* tolerated at *i* load level.

$$D = \sum \frac{n_i}{N_i} \tag{7}$$

The damage could be reached when the summation is 1 and there is an effect of sequence load. Depending on sequence effect loads, the damage can be reached too with values above or below 1 [4]. The failure is observed when there is a physical crack.

5. Instrumentation

Figure 2 shows that the first point to acquire information is to install measurement devices on the component or in its vicinity, to obtain the responses of the components that induce stress. To obtain the most important information we install the measurement devices at the main stress points. To do this, it is necessary to perform a finite element simulation in order to get the point and the direction of the stresses. **Figure 14** shows the typical process used to perform this kind of simulation.

The components evaluated can be from different materials and built with different manufacturing process. In the next figure are shown instrumented components with a point selection from finite element evaluation [7]. Then to find the point and direction of the main stresses, components are instrumented with strain gauges. Its nominal resistance is 120 or 350 ohms. Higher resistance can be used for base material with low heat conductivity and higher voltage excitation than 10 Volts can be mainly used in environments with high electrical noise [18]. **Figure 15** shows chassis components instrumented, **Figure 15a** the rear subframe for a rigid axle, **Figure 15b** a front axle steering knuckle and **Figure 15c** a frontal axle track control arm.

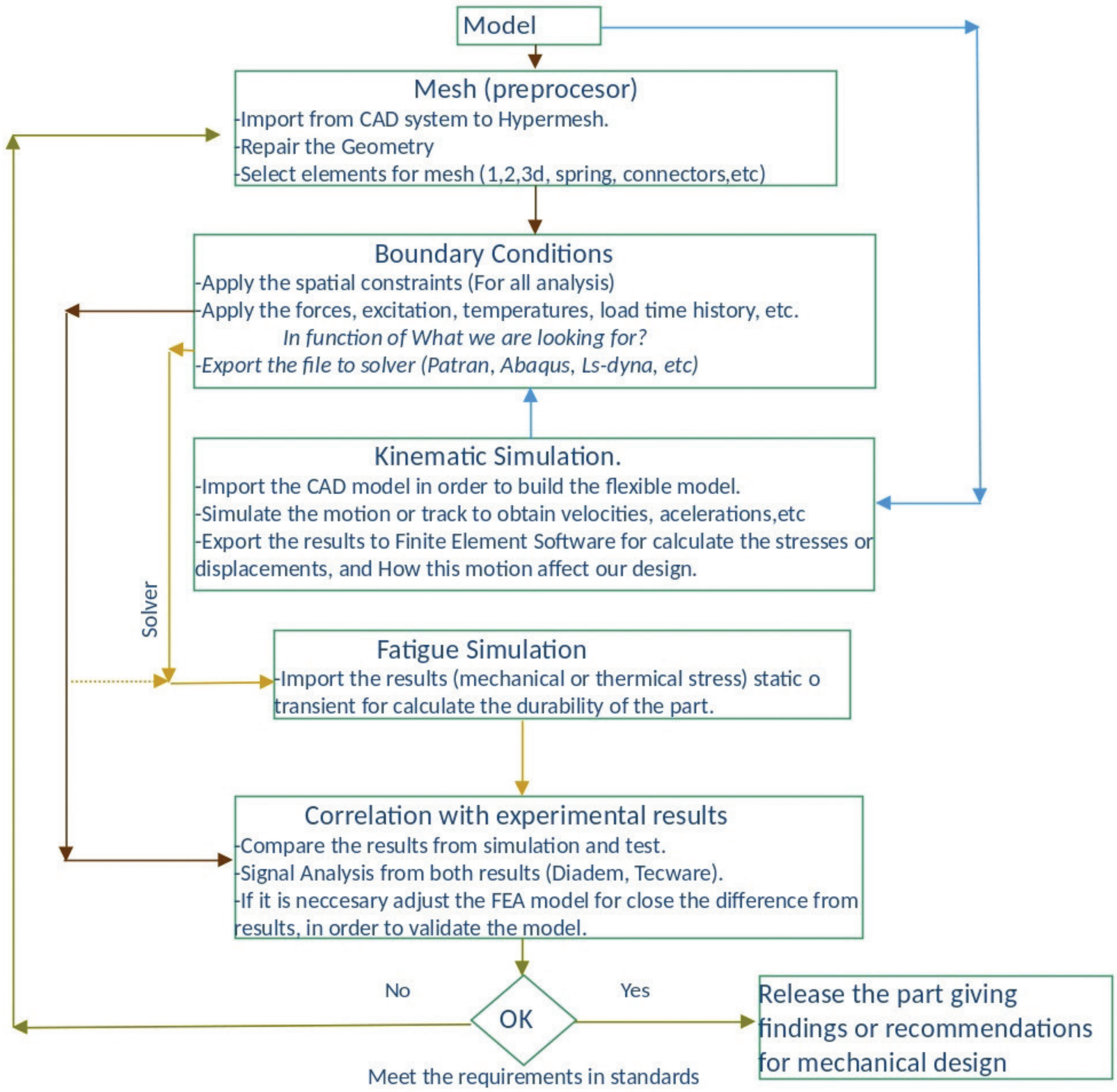

Figure 14. General procedure for simulation.

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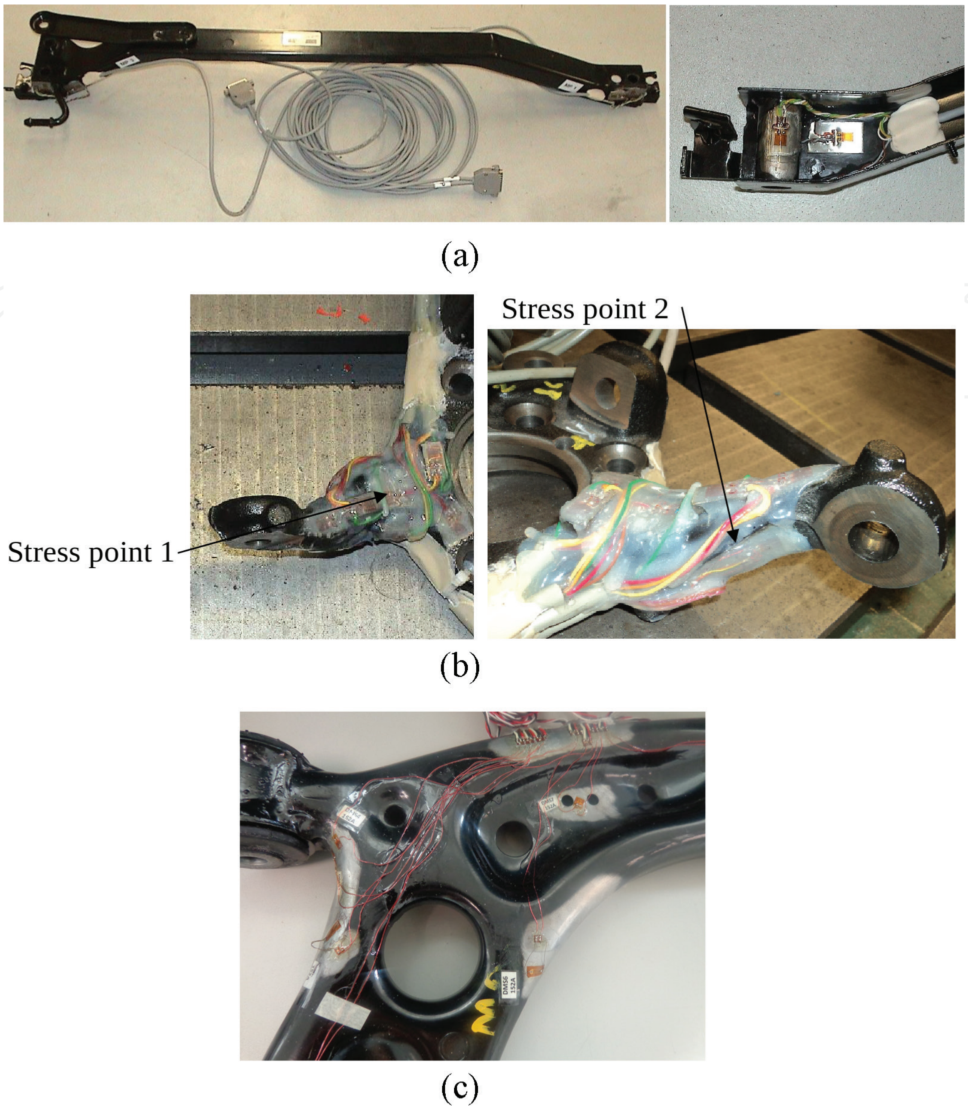

Figure 15. Instrumented components with strain gauges, (a) rear rigid axle subframe, (b) steering knuckle, and (c) track control arm.

6. Case study

The accelerated tests are developed to reduce the time and complexity of the test in order to have faster results. **Figure 16** shows a test stand to evaluate a frontal axle track control arm.

The information collected from the strain gauges can be used to evaluate the component, perform a correlation with virtual or analytical tools and build a spectrum. In not all the cases, can we directly measure the microstrain to validate the virtual simulation. The acceleration can be used to validate the finite element model with experimental acceleration results. With this validation, the stresses are found in a virtual way and can be used to perform the real-life prediction [4].

In the next part, the process to develop an accelerated test is shown. The time history in **Figure 17** shows the raw data time history to evaluate a track control arm, its main characteristics is a range of 42,354 N, maximum value of 21,473.6 N and minimum value of −20,880.8 N and the time length is 249.9 s.

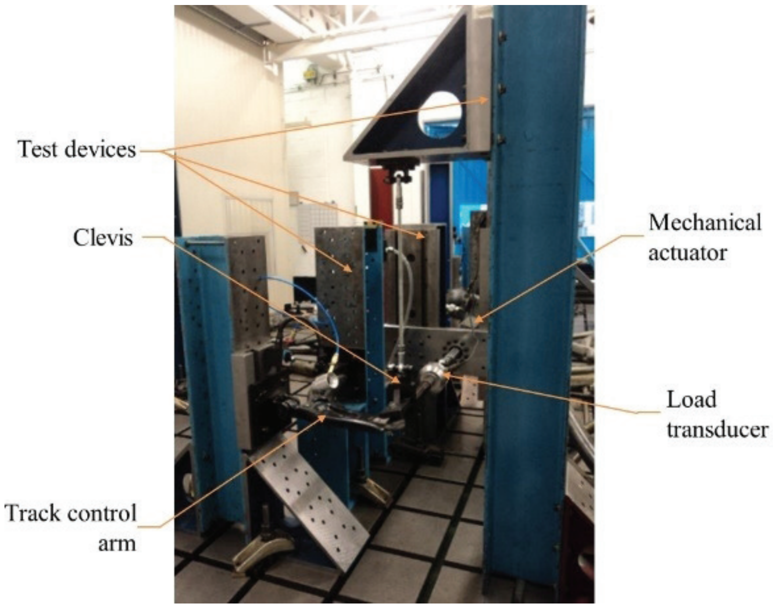

Figure 16. Durability test stand for frontal track control arm.

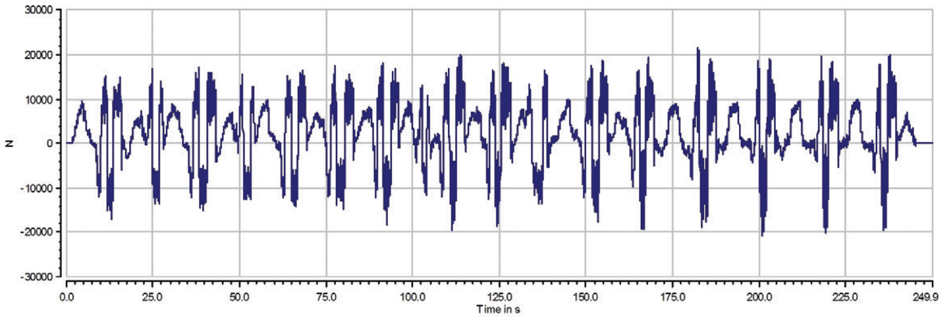

Figure 17. Raw data time history for uniaxial test of track control arm.

The information acquired is then analyzed to eliminate unnecessary information such a noise. To do this, we apply filters, and perform statistical analyses. For a structural analysis it is necessary to have a low pass filter of 100 Hz [19]. To evaluate the changes after applying the filter, it is necessary to perform the statistical analysis using cycle counting tools and evaluate the pseudodamage using the linear damage rule [4]. The results of this evaluation are shown in **Figure 18**.

After applying the filter, the time history obtained has the next characteristics: range of 41,715.3 N, maximum value of 21,283.5 N and minimum of −20,433.6 N; the time length keeps its length of 249.9 s. The pseudodamage was reduced from 4.55 to 4.41, it means a reduction of 3.07% of damage, taking as a reference the raw signal.

There are many ways to accelerate the test. One of them is to eliminate the loads amplitude that do not apply a high amount of damage. To do this, in the time history, we eliminate the amplitude below 5000 N. **Figure 19** shows the process to show the selected areas and the final time history.

The cut signal and the raw data and the filtered raw data were compared using statistical analysis as it is shown in **Figure 20**.

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After eliminating the amplitudes below 5kN, the new time history has the next characteristics: range of 41,717 N, maximum value of 21,283.5 N and minimum value of −20,433.6 N and the time length is 208.4 s. The pseudodamage has not been modified, while the time has been compressed from 249.9 to 208.4 s (16.6%). This is our target signal to generate the test spectrum, in order to develop the durability test.

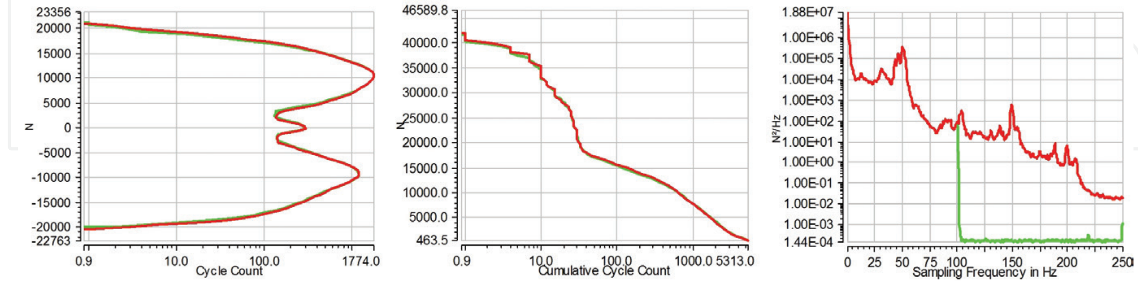

Figure 18. Statistical analysis of the raw data compared with the filtered signal (a) cycle counting, (b) cumulative cycle count, and (c)PSD.

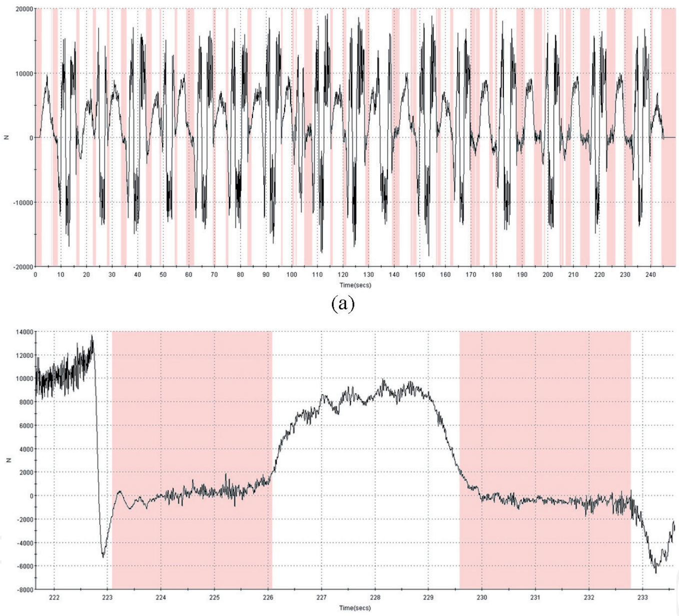

Figure 19. Cutting load damage areas from the raw data time history filtered, (a) 0–249.9 s, (b) zoom between 221.7 and 233.6 s.

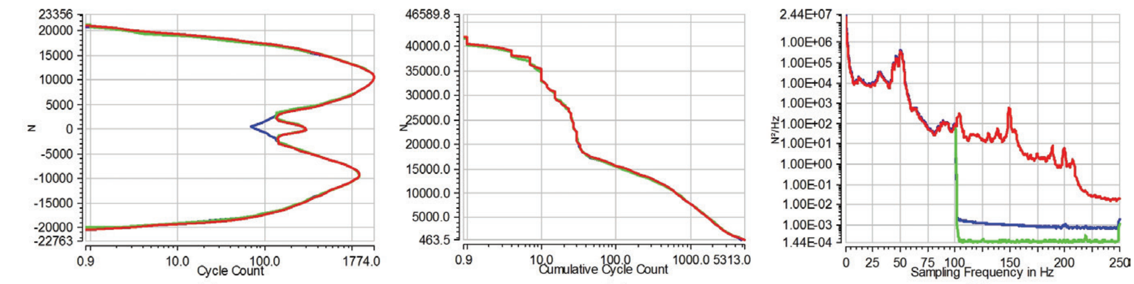

Figure 20. Statistical analysis after cutting loads below 5000 N, (a) cycle counting, (b) cumulative cycle count, and (c) PSD.

To accelerate the test, we can increase the number of repetitions of loads with amplitude high and medium. **Figure 21** shows the statistical analysis increasing the medium loads. The time history obtained has the next characteristics: range of 42,340.9 N, maximum value of 21,906.9 N and minimum value of −20,433.9 N; time length of 135.1 s. The damage was increased from 4.55 to 8.52, which means that it was increased by a factor of 1.87, reducing the time by 45.93% with respect to the raw data.

Figure 22 shows the statistical analysis increasing the amplitude of high loads and the number of repetitions of high and medium loads. The time history obtained has the next characteristics: range of 59,124.4 N, maximum amplitude of 30,670.6 N and minimum of −28,543.8 N; time length of 167.7 s. The damage was increased from 4.55 to 39.6. This means that it was increased by a factor of 8.7, reducing the time by 32.89% with respect to the raw data.

Figure 23a summarizes the spectrums of the all strategies extrapolated to the time histories, the raw filtered data could be cut at below load levels to reduce the time; the medium and high loads in the signal can be increased, reducing the original time and increasing the damage. **Figure 23b** shows the schematic techniques to accelerate the test.

An alternative option to represent the spectrum instead of time history is with Matrix Rainflow. **Figure 24** shows the four analyzed signals: original (**Figure 24a**), filtered (**Figure 24b**), increasing the medium loads (**Figure 24c**), and increasing the number of reversals in high loads inclusive of above the maximum loads of the raw data (**Figure 24d**). The major differences are shown in **Figure 24c** and **d** for medium and high loads, respectively, and the ranges for medium-to-high loads and its number of repetitions have been increased.

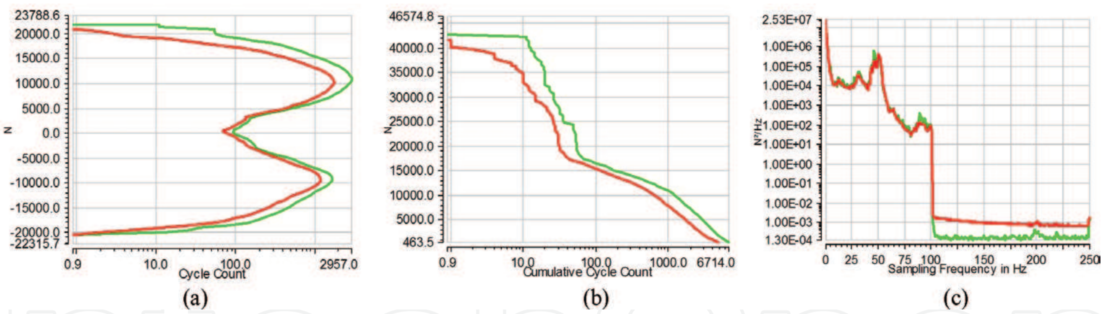

Figure 21. Statistical analysis increasing medium loads, (a) cycle counting, (b) cumulative cycle count, and (c) PSD.

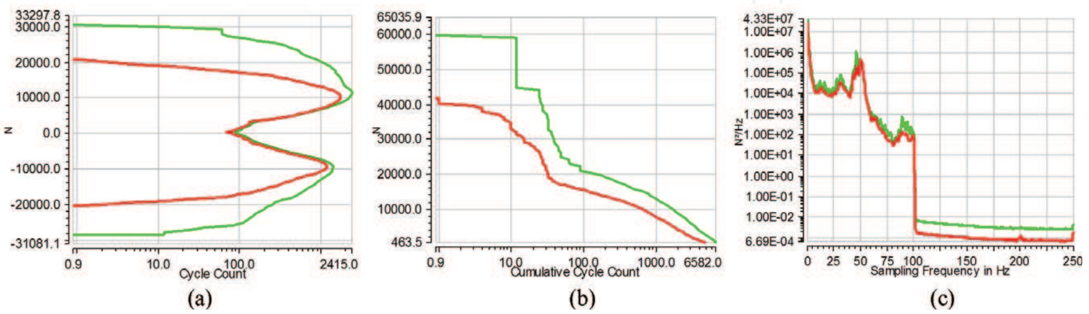

Figure 22. Statistical analysis increasing high loads: (a) cycle counting, (b) cumulative cycle count, and (c) PSD.

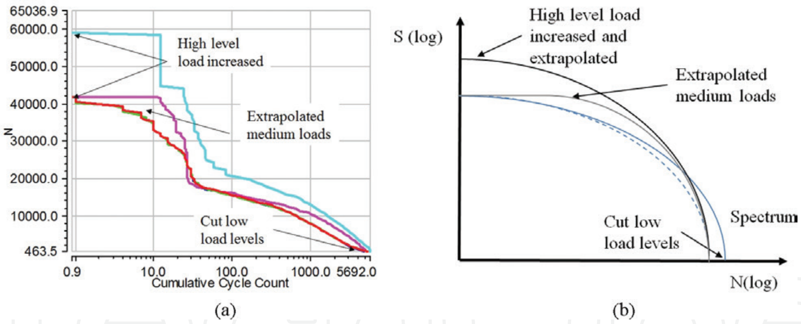

Figure 23. Spectrum of the time histories, (a) summary of time test reduction and (b) schematic accelerated test.

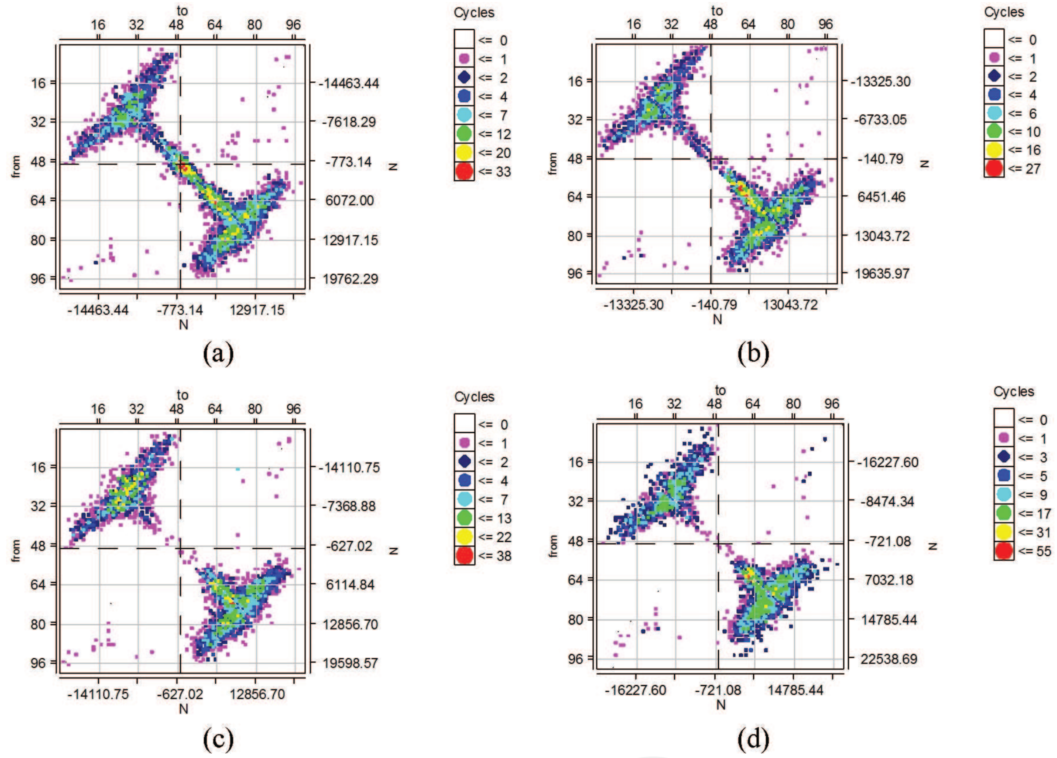

Figure 24. Rainflow matrix (a) raw data, (b) cut filtered signal, (c) medium loads increased, and (d) high loads increased.

For variable amplitude loads, this statistical analysis is used to monitor and guarantee that the loads have been applied correctly. Because it is necessary to build a drive used for the actuators to test the applied loads, the feedback through loads are measured and compared with the desired spectrum, and the drive to control the test actuators is developed through an iteration process [20]. Another way to perform an accelerated test based on the spectrum is using two load levels with a constant amplitude load for each load level. Then these results are plotted in an S-N component curve, and the specimen results are evaluated to predict the fatigue strength and different load levels [21]. **Figure 25** shows the experimental results of uniaxial constant amplitude loads of steering knuckle.

In an S-N curve, the percent replication *(PR)* is found by using the number of stress levels *(L)* and a sample size *(n_s)* as is shown in Eq. (8).

$$P_R = 100\left(1 - \frac{L}{n_s}\right) \quad (8)$$

This value represents the portion of specimens that may be used in the variability to replicate the tests. The recommended values by Lee et al. [18] are as follows:

17–33 for preliminary and exploratory tests,

33–50 for research and development tests,

50–75 for design allowable data tests and

75–88 for reliability tests.

Steering knuckle results shown in **Figure 25** have 7 level of loads, and 90 Specimens using Eq. (4) get a percent replication of 92.2. These high values obtained from these results are evaluated to analyze a proposal to estimate an S-N curve. For a component test, recommended samples used depend on the target, for research and development tests 6–12, and for reliability tests 12–24 samples. The minimum samples for two load levels are three specimens for each load level.

The median is the central value of results at each load level, and the tendency is considered at 50% of reliability and is necessary to evaluate it to know the scatter of the factors described in **Figure 1** (Eq. (8)).

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (9)$$

To evaluate the scatter of the components based on its fatigue results, the standard deviation is evaluated using Eq. (10). To take into consideration, its results have to be between 0.05 and 0.15; for samples without notches, the range is between 0.1 and 0.2, for uniaxial tests the range is between 0.2 and 0.3, while in complex tests, it can reach values between 0.3 and 0.6 [22].

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \mu)^2 \quad (10)$$

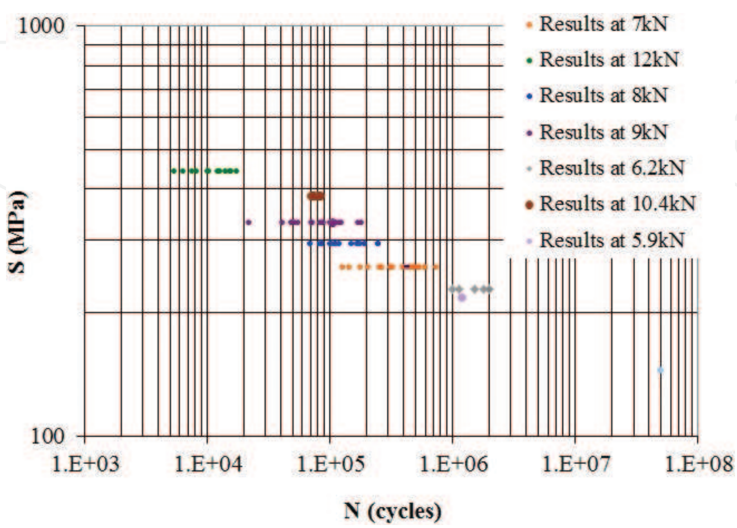

Figure 25. Test results in steering knuckle analysis.

http://dx.doi.org/10.5772/intechopen.72640

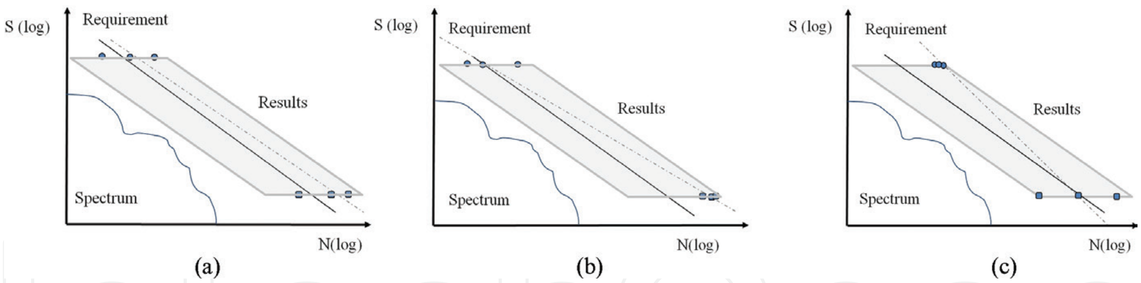

Figure 26. Evaluation results (a) slope test k_{test} = slope requirement k_{req}, (b) $k_{test} < k_{req}$, (c) $k_{test} > k_{req}$.

Results of the slope found in tests are compared with the requirement, and changes on the slope affect the behavior at low or high load levels. **Figure 26** shows the evaluation of the results with constant amplitude loads.

7. Conclusions

Accelerated tests are used to reduce cost and time in the development process. It can also be used to monitor the quality of the components during its manufacturing life. Experimental evaluation is mandatory prior to final release and start of production to analyze the scatter of the manufacturing process and prevent failures in service life. The importance of performing variable amplitude loads tests is because the prediction of fatigue life under the complex spectrum loads is not possible by any damage hypothesis. The spectrum to evaluate the components in the tests is developed with the loads from different customers and markets and use conditions. Experimental results show discrepancies even within the same batch of production, and the statistical value to evaluate the reliability of the lot under test is the standard deviation that shows the influence of the factors described in **Figure 1**. Although the tests are performed under controlled conditions in a laboratory, in specimens with notches, the batch of production is released if the standard deviation of its fatigue results has a maximum value of 0.2. For samples without notches in uniaxial tests, the maximum scatter allowed is 0.3 and 0.6 for complex test [22]. To evaluate the fatigue strength as well as the scatter, it is necessary to perform durability tests, to prevent failures on the service life.

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