

Verification of High Cycle Fatigue Analyses from the Literature by using Finite Element Software

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Accumulation.

Abstract— This work compares fatigue analysis results presented in the literature with computational simulations performed using finite element software. To this end, two fatigue cases with distinct geometric configurations and loading conditions are analyzed. In the first case, the loading is multiaxial, with sinusoidal variation and the presence of a non-zero mean stress. In the second case, the loading presents alternating and mean stresses that vary over time, and is analyzed by counting load cycles using the Rainflow method. The results found in the literature for both cases, obtained through conventional theoretical fatigue approaches, are compared with the results of the computational simulations performed in this work using finite element software. It can be noticed that the use of numerical simulation computational tools offers great flexibility for the analysis of fatigue problems with complex geometries and loadings. Furthermore, the use of computational tools provides greater ease and speed in obtaining results, contributing to the development of more efficient designs.

I. INTRODUCTION

Material fatigue is a process caused by alternating load amplitude, resulting in local mechanical failure, and generally occurs at a much lower value than that required for a static load to cause rupture. Mechanical failure can be characterized by the appearance of one or more cracks or the complete rupture of the material after a certain number of fluctuations. Fatigue can be described as local, progressive, and cumulative, and its progression depends on material characteristics and geometry, [1]. To obtain this information, much effort, investment, time, and extensive research with testing have been dedicated to this area, aiming to prevent and understand mechanical and structural failures caused by material fatigue, [2].

Fatigue resistance is the ability of a material to withstand a sequence of cyclic stresses without breaking, and is a determining factor in ensuring the durability and safety of structural components. Materials respond quite differently when subjected to loads that vary over time compared to

static loads, [3]. Most machine designs involve the development of parts that will be exposed to variable stresses, making it essential to know the fatigue resistance of materials under these loading conditions. Fatigue resistance for a single cycle is equivalent to static tensile strength, showing a linear decrease in the log-log graph with increasing number of cycles. This trend continues until a stress level is reached, starting a horizontal line around $1E6$ cycles. This fatigue resistance plateau is observed only in certain metals, especially in steels and cast irons, and is called the fatigue strength limit. In contrast, for other materials, fatigue resistance continues to decrease beyond this point, [4].

Problems that previously could only be solved through small-scale models or costly experimentation are now largely addressed in computational environments. This is partly due to limitations in physical resources and the need to optimize solutions, which often requires a complete redesign of the project. These issues become even more

critical when various engineering fields are involved in modeling, such as in the analysis of structures subjected to loads resulting from interaction with fluids or applied dynamic forces, as in the case of buildings exposed to seismic tremors or equipment that experiences thermal stresses and static and dynamic forces simultaneously.

Mechanical simulation software allows engineers and designers to analyze the performance of their designs before manufacturing, saving time and resources by identifying potential problems and testing various solutions. Achieving more efficient processes and safer products is directly linked to the software's simulation capabilities, [5].

The overall objective of this work is to analyze the difference between the results obtained in software simulations compared to the results obtained using the established mechanical structural fatigue theory found in [2,6]. For this purpose, two fatigue cases with distinct geometric configurations and loading conditions are analyzed. In the first case, the loading is multiaxial, with sinusoidal variation and the presence of a non-zero mean stress. In the second case, the loading presents alternating and mean stresses that vary over time, and is analyzed by counting load cycles using the Rainflow method, [7].

The importance of building knowledge about the tools available for calculation and their level of confidence, that is, their proximity to reality, is very high, since the applications are diverse and for numerous purposes and work areas, such as engineering structures, medical equipment, tools and installations for agriculture and industry. The improvement of equipment leads to a reduction in dimensions and even greater safety for users, [8]. It can be considered that everything is subject to stress and, during its useful life, there are variations in load, even of small amplitude, which generate everything from tolerable wear and tear to defects that render them unusable for a given application. The possibility of building a simulation close to reality brings much better results and more efficient projects. Confidence in these simulations is essential to lay the foundation for future concepts.

II. BASIC CONCEPTS

The fatigue failure process can be divided into three main stages: crack nucleation, crack propagation, and final failure. Crack nucleation generally occurs at stress concentration sites, such as discontinuities, surface imperfections, or inclusions in the material. These points are vulnerable to local stresses that can exceed the material's strength, initiating the failure process.

Furthermore, mechanical structural fatigue can be classified into different types, such as low-cycle fatigue and

high-cycle fatigue, depending on the number of load cycles the material can withstand before failure. Low-cycle fatigue generally occurs in components subjected to high stresses and a reduced number of cycles ($<1E3$), while high-cycle fatigue refers to lower stresses and a high number of cycles ($>1E3$). Understanding these differences is vital for the design and analysis of components in various applications.

An important aspect of high-cycle fatigue is the influence of the material's microstructure on fatigue properties. Materials with refined microstructures, such as heat-treated steels, tend to exhibit better fatigue resistance compared to materials with coarser microstructures. The presence of inclusions, porosity, and surface discontinuities can also significantly affect fatigue resistance, as these defects can act as crack nucleation points. Figure 1(a) shows an example of fatigue fracture with the corresponding beach sand marks. Figure 1(b) shows the striations caused in the material related to the applied load.

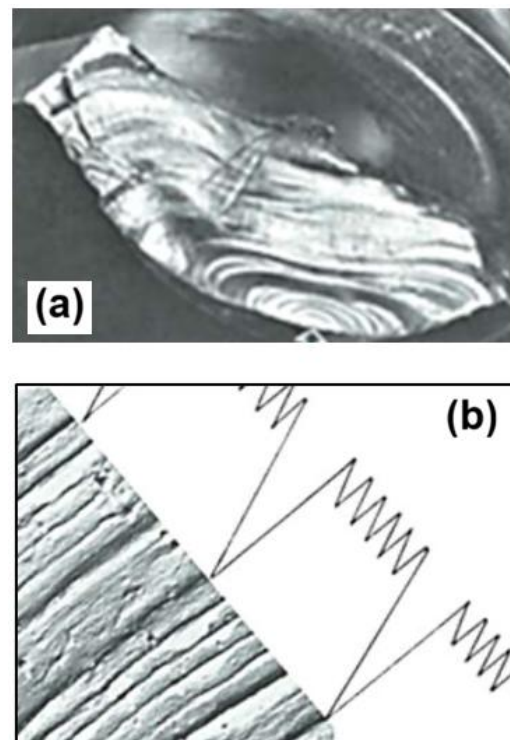


Fig.1. Adapted from [6]: (a) example of fatigue fracture; and, (b) load striations.

Furthermore, temperature and loading frequency are critical factors influencing fatigue behavior. Elevated temperature can reduce the fatigue resistance of materials, while loading frequency can affect the crack growth rate.

It is also valuable to consider the effect of the environment in which the material is operated. Factors such as humidity and corrosion can significantly influence fatigue resistance. For example, corrosion can accelerate the

crack nucleation and propagation process, reducing the component's service life. Therefore, infinite life analysis must take into account not only the material properties but also the environmental conditions in which it will be used.

Ultrasound and thermography methods have stood out as essential tools in detecting flaws in materials subject to mechanical fatigue, especially due to their ability to perform non-destructive inspections with high precision. Ultrasound, based on the propagation of high-frequency acoustic waves, allows the identification of internal discontinuities, such as cracks and delaminations, even in the early stages of formation. This technique is particularly useful in metallic and composite materials used in critical structures such as bridges, aircraft, and turbines. The application of ultrasound significantly contributes to the continuous monitoring of structural integrity, enabling preventive actions before a catastrophic failure occurs. Thermography, in turn, uses thermal images to identify temperature variations on the surface of a material, which may be associated with internal damage, excessive friction, or the onset of cracks. In components subject to fatigue, these thermal anomalies often precede visible signs of failure, making thermography an effective technique for early diagnosis.

III. THEORETICAL ASPECTS

To estimate the fatigue life of a structure, we can follow four possible paths:

- A) Alternating stress tests over time with real assemblies or with prototypes of devices from a real project;
- B) Fatigue tests on specimens obtained from the same material and manufacturing process as the part, such as casting, machining, forging, among others;
- C) Use fatigue strength data that may be available in the literature or provided by the manufacturer or material supplier. However, these represent tests in environments different from the application and with polished specimens of a different size than the real ones. Therefore, correction factors should be applied;
- D) Estimate the fatigue strength limit of the material based on available data from static tests, that is, estimate using the ultimate strength S_{ut} and the yield strength S_y .

If the actual conditions and those applied in tests are different, it is necessary to apply factors to correct the theoretical fatigue resistance values. These factors take into account the physical differences between the test specimens and the actual part, temperature differences, environmental conditions such as humidity and corrosion effects, the test conditions and the conditions to which the part will be subjected in the future after a period of operation, and also

the differences in the way the load is applied. For a specific application, there are several correction factors that must be applied, according to [6]:

$$S_e = C_{load} C_{size} C_{surf} C_{temp} C_{conf} S_{e'} \quad (1)$$

$$S_f = C_{load} C_{size} C_{surf} C_{temp} C_{conf} S_{f'} \quad (2)$$

where S_f and S_e are the new corrected fatigue strength and fatigue limit values, respectively. according to test rig. C_{load} is the correction due to the loading mode, C_{size} is the correction due to the dimensions of the part, C_{surf} is the correction due to the type of surface finish, C_{temp} is the correction due to the working temperature, C_{conf} is the correction according to the desired degree of confidence, and finally, $S_{e'}$ and $S_{f'}$ are the values obtained by the theory without correction. The index e refers to a fatigue strength limit that provides infinite life, while the index f refers to a fatigue strength limit for a given number of cycles. To calculate each of the factors mentioned above, we can use the equations and tabulated values to plot the S-N diagram according to [6].

The notch sensitivity equation is a relationship that describes how the presence of a notch in a material can affect its fracture resistance. This equation is frequently used in failure analysis of materials and structures, especially in materials engineering and mechanics. The equation is expressed as:

$$K_f = 1 + q(K_t - 1) \quad (3)$$

Where K_t is the theoretical stress concentration factor for the particular geometry and K_f is the fatigue stress concentration factor. The notch sensitivity q indicates how much the presence of the notch reduces the material's resistance to fracture, and varies from 0 to 1. Finally, we can obtain the normal σ or shear stress τ by multiplying the nominal stress by the fatigue stress concentration factors related to normal and shear stresses:

$$\sigma = K_{f\sigma} \sigma_{nom} \quad \text{or} \quad \tau = K_{f\tau} \tau_{nom} \quad (4)$$

Due to the wide range of real-world load conditions during a structure's lifespan, a good design requires evaluating the cumulative damage. The linear cumulative damage hypothesis serves to predict the behavior of elements subjected to different loading conditions, such as, alternating and mean stresses varying with time. The total accumulation is the sum of the consumed life fraction, and when it reaches 1 (one unit), the structure's lifespan is considered complete according to Miner's Damage equation

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \quad (5)$$

where D is the damage, malfunction, or partial loss of functionality, ranging from 0 to 1, with $D = 0$ being a virgin part and $D = 1$ being a material failure; k is the number of blocks considered; n_i is the number of cycles or time in a block, and N_i is the number of cycles or time until failure.

Alternating loads cause fatigue damage that is cumulative and irreversible. We can consider that real-world situations almost always present complex loads that vary over time, even randomly. Over time, loads tend to completely alter their amplitude and frequency; for example, in equipment such as cargo vehicles, they can assume a random nature. Due to the nature of rotating machines, fluctuating stresses often take the form of a sinusoidal pattern; however, other very irregular patterns can occur with random alternating and mean stresses. Figure 2 shows several failure curves (Gerber, Goodman and Soderberg) considering the relationship between alternating stress σ_a and mean stress σ_m . S_y is the yield stress and S_{ut} is the ultimate stress of the material.

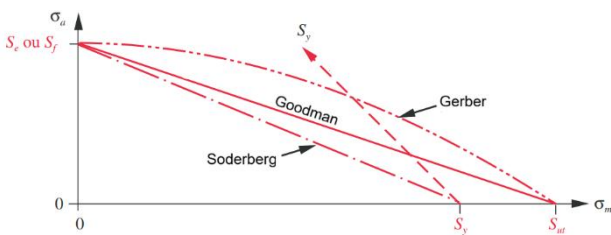


Fig. 2. Adapted from [6]: Failure curves taken into account the relationship between σ_a and σ_m .

When we have well-defined and constant σ_a and σ_m throughout the loading, it is possible to predict fatigue life in a simpler and more effective way. However, when the stress-time patterns are more complex, it is necessary to account for the damage due to the various existing stress-time modes. This could be, for example, a load with zero mean stress but with amplitude variation, or with variation in mean stress and also in the amplitude of the alternating stress. In this way, it is necessary to characterize the load in blocks of alternating stresses, and for this, cycle counting methods are used, which convert a random load into blocks of alternating stresses associated with the number of cycles. The Rainflow method is one of the most used in the industry and can represent a variable load in a very approximate way.

In the Rainflow method, the historical stress-time spectrum is plotted to scale on a coordinate system resembling a series of sloping roofs. Some rules are defined to describe the behavior of imaginary “raindrops” descending through these sloping roofs (stress) in such a way that this rainwater runoff can be used to define stress cycles. The cycle count begins with the first “raindrop”

either in the most negative valley or the most positive peak, and continues numbering sequentially until all cycles of a complete block have been counted in sequence. Then, the raindrops are successively positioned on the inside of each peak or valley. Peaks and valleys are considered sources of water. Water flows according to the following rules:

1. A path starting from a valley and continuing through the sections of the “roof” until it encounters a valley more negative than the original;
2. A flow path ceases when it encounters a flow from a previous path;
3. A new path should not be started until a previous path stops;
4. There will then be half-cycles generated by the valleys all along the path;
5. The process is repeated on the other side of the time axis, with a path starting at a peak.

For sufficiently long loads, each valley generating a half-cycle will have a corresponding half-cycle generating peak, thus forming a complete cycle. At the end of the application of the Rainflow Method, a list is obtained with the values of the variations of the alternating and mean stress cycles obtained and their respective number of occurrences. These alternating and mean stresses are then transformed into equivalent alternating stresses. With this data, fatigue damage can be calculated using Miner's Damage equation.

IV. RESULTS

The first case study falls into the category of fluctuating stress in which maximum stress, minimum stress and mean stress have a value different from zero. Figure 3 shows the case studied, extracted from [6], which consists of a tubular rod fixed to the wall and an arm parallel to the support plane, made of 2024-T4 aluminum alloy which has a yield strength $S_y = 47000$ psi and a ultimate strength $S_{ut} = 68000$ psi.

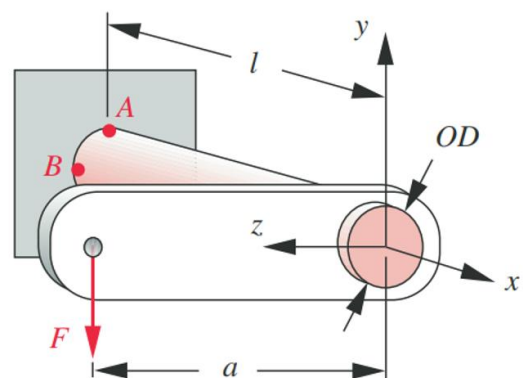


Fig.3. Adapted from [6]: Geometry and dimensions of the first case study.

The tube length is $l = 6$ in and the arm length is $a = 8$ in. The outer diameter of the tube is $OD = 2$ in and the inner diameter is $ID = 1.5$ in. The applied load varies sinusoidally from $F = 340$ lb to -200 lb. The temperature is 20°C . The notch radius in the wall is 0.25 in. The stress concentration factors are: for normal stress 1.7 ; and, for shear, 1.35 . The desired service life is $6E7$ cycles. Since aluminum does not have a fatigue limit plateau, the fatigue strength is estimated to be $S_f = 19$ kpsi in $5E8$ cycles. Using the appropriate correction factors and calculating for the required number of cycles, $S_f = 14846$ psi. Since bending and torsional moments are both caused by the same force, they are synchronous and in phase, and any change in one will have a constant relationship with the other. Thus, for this situation, the safety factor at point A can be calculated by:

$$SF = \frac{S_f S_{ut}}{\sigma'_a S_{ut} + \sigma'_m S_f} \quad (6)$$

$$SF = \frac{14846(68000)}{6419(68000) + 1664(14846)}$$

$$SF = 2.2$$

where SF is the safety factor, σ'_a is the von Mises alternating stress and σ'_m is the von Mises mean stress.

Figures 4(a) and 4(b) show the corresponding three-dimensional analysis performed using the finite element software. As shown in the figures, the maximum stress in the most stressed region of the part is 6930.2 psi and the calculated safety factor is 2.24 .

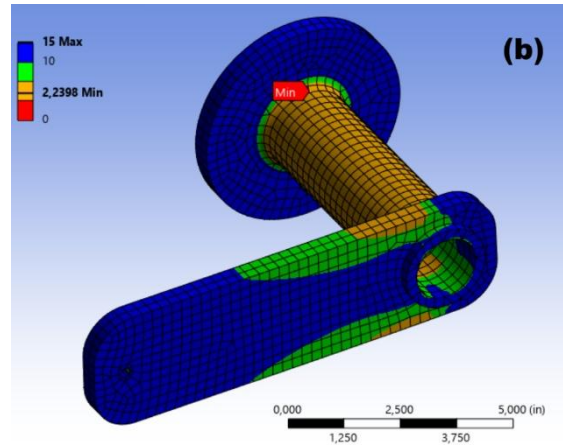


Figure 4. (a) von Mises stress analysis; and, (b) safety factor analysis.

For the second case study, the load presents both mean stresses and alternating stresses variable in time. The objective is to find how many hours the structure will withstand until failure occurs. For this, we can use the S-N curve provided for the application. The load is presented divided into blocks with a duration of 1 minute, as shown in Figure 5. The S-N curve is provided and represents the fatigue behavior with respect to fully reversible and purely alternating stresses, Figure 6.

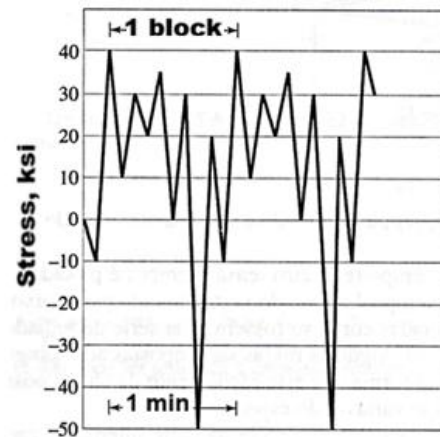
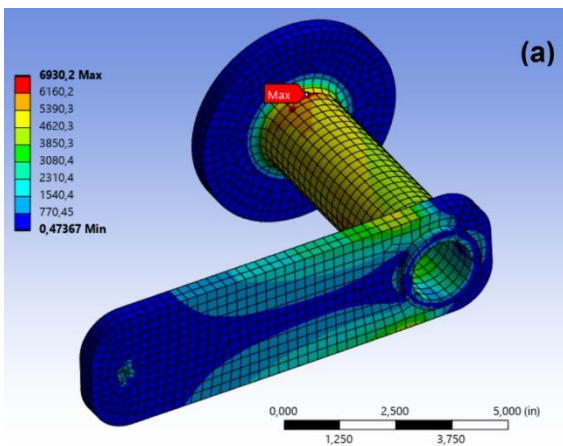


Fig.5. Adapted from [2]: History load data applied to the second case study.

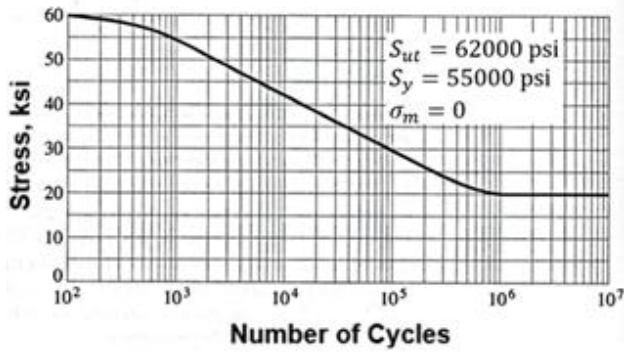


Fig.6. Adapted from [2]: S-N curve of the second case study with respect to fully reversible stresses.

Analyzing the S-N curve and grouping the raindrops, Table 1 can be obtained, where the maximum stress (σ_{max}), the minimum stress (σ_{min}), the mean stress (σ_m), the alternating stress (σ_a), the equivalent alternating stress (σ_{eq-CA}), the number of cycles of occurrence (n), and the number of cycles supported by the application according to the S-N curve (N) can be obtained:

Table 1: Raindrops data for the second case study.

σ_{max}	σ_{min}	σ_m	σ_a	σ_{eq-CA}	n	N
40	-50	-5	45	45	1	6E3
20	-10	5	15	16.3	1	∞
35	10	22.5	12.5	19.6	1	∞
30	20	25	5	8.4	1	∞
30	0	15	15	19.8	1	∞

With the non-zero mean stress cycles already converted to equivalent fully alternating cycles (σ_{eq-CA}), the damage is totaled using the Palmgren-Miner linear damage rule. z is the number of blocks and the repetition will occur 6,000 blocks before failure. Since each block lasts 1 minute, the duration will be 6,000 minutes, totaling 100 hours of operation until failure.

$$D = z \left[\sum_{i=1}^k \frac{n_i}{N_i} \right] \rightarrow z = 6,000 \text{ blocks} \rightarrow 100 \text{ h} \quad (7)$$

The problem was modeled in finite element software encompassing all the information presented in terms of loads and material data. An arbitrary simple geometry in the form of a parallelepiped was assumed to represent the problem. The software predicts the lifespan of the part as 6139 cycles equivalent to 102.5 hours, Figure 7.

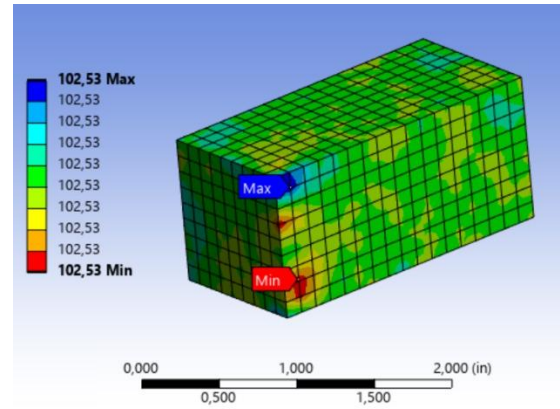


Fig.7. Computational simulation of lifespan of the second case study.

Table 2 shows the differences found for the two case studies considering the conventional theoretical approach from the literature and the computer simulations using finite element software. An excellent agreement can be observed between the calculated results.

Table 2: Summary of the results.

Case study #	Conventional theory from the literature	Numerical computational simulation (this work)	Variation %
1	SF = 2.2	SF = 2.24	1.8
2	100 h	102.5 h	2.5

V. CONCLUSIONS

Analyzing the simulation results, it is possible to conclude that the Finite Element Method using computational software can be a good tool for addressing structural fatigue problems. In the first case study, simpler with alternating and mean constant stresses over time, the difference between the values calculated by the conventional fatigue theory from the literature and the finite element software simulation is 1.8%. In the second case study, more complex because it presented alternating and mean stresses varying with time, which required cycle counting using the Rainflow method and accounting for the damage, the difference between the values calculated by the conventional fatigue theory from the literature and the finite element software simulation is 2.5%. Thus, the differences found for both cases are very low, which is quite acceptable for engineering problems of this nature that contain high statistical variations that can influence the results. Of particular importance is the fact that systems with a large amount of load information or complex geometries can, as can be realized by this work, be better modeled and handled using finite element software than by using a conventional

approach advocated in literature, reinforcing the importance of computational tools in the analysis of engineering problems.

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