The use of the Ansys computational tool in the initial study of the fatigue phenomenon

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Abstract. The fatigue phenomenon in structural elements is a major concern. Most of the structures, even when projected in the elastic regime, are subject to failures after a certain time of exposure of the load. These failures can lead to collapse and affect not only the target element, but also compromise the integrity of everything around it. Experimental and numerical analysis are tools used to evaluate this phenomenon and its implications, contributing to offer subsidies to guarantee a long life to the structural element. The purpose of this study is to validate the use of the fatigue tool in the Ansys Student software. For this purpose, a cantilever beam subjected to a harmonic force at its free end was studied. The numerical values extracted, such as stress, fatigue life, safety coefficient and fatigue damage, were compared with those obtained by the analytical procedure. The achieved values converged, demonstrating in addition to the correct conduction in the use of the computational tool, the understanding of the basic theoretical concepts of the study of fatigue.

Keywords: fatigue, numerical analysis, beam.

1 Introduction

Within the elastic domain, if a specimen is subjected to a load that generates a maximum stress lower than the material's yield stress, it returns to its initial conditions when the load is removed, that is, there is no plastic deformation. However, if subjected to this same load, but in a cyclical way, the specimen may fail due to the fatigue phenomenon at a lower stress than expected for the yielding [1,2].

Fatigue failures have been the subject of study for over 150 years. W. A. J. Albert conducted an initial study that tested mine lifting chains under cyclic loading in Germany around 1828. The fatigue phenomenon was further studied in the mid-1800s by researchers in several countries in response to the recurrent failure of components such as beams, gears and ducts [3]. The German August Wöhler tested in laboratory the application of alternating stresses until failure, and his findings, published in 1870, identified the number of cycles as responsible for the collapse. Furthermore, he discovered the existence of a fatigue strength limit [4].

Despite the discoveries, this phenomenon continues to be the cause of several accidents. In 1954 a Havilland Comet commercial jet exploded in the air and investigations indicated that wear on the fuselage cracked one of the windows and caused the tragedy. A door lock failure resulted in a Jumbo 747 fuselage leaking in 2015, after eighteen years of use [5]. In 2018, the collapse of the Morandi bridge in Genoa, Italy, killed 43 people, also caused by structural fatigue [6].

Numerical and experimental fatigue tests are tools used to understand the phenomenon in order to prevent and eliminate resulting problems. This paper will introduce assessments in this field by exploring the features of the *Ansys Student* fatigue package. The analysis will be validated by comparing analytical results, this will induce the need to comment and present analytical and practical methods that will be used to extract the fatigue life, safety factor and damage parameters.

2 General Objectif

The objective of this study is to explore some functionalities of the *fatigue tool* module available in the *Ansys Student* 2020 R2 software and to validate the conduction of the analysis of the parameters associated with fatigue life of the evaluated structural element.

2.1 Specific objectives

- Plot the main coordinates to reproduce the numerical analysis in *Ansys*;
- Evaluate the influence of cyclic stress on the chosen structural element;
- Discuss and compare the fatigue life, safety factor and damage values obtained with those resulting from the analytical calculation.

3 Applied methodology and description of the object of study

The applied methodology concerns a comparative procedure in order to evaluate the correct use of a computational package available for fatigue analysis. Thus, *Ansys Workbench* was used in the 2020 R2 student version, which, through the fatigue tool, provides fatigue data discussed here. The results of this analysis were compared with those obtained by the consolidated analytical procedure in classical literatures, such as *Budynas and Nisbett* [2] and *Dowling* [3].

For this, a fatigue life analysis was carried out on an ASTM 36 steel cantilever beam element. It is 20 mm wide, 100 mm height and 500 mm long. A harmonic load with amplitude equal to 10 kN is applied at the free end. The mechanical properties of the steel are shown in Tab. 1.

Table 1. Properties of ASTM A36 steel [7]

Yield stress	250 MPa
Ultimate tensile strength (S_{ut})	460 MPa
Young's modulus	2.0E+5 MPa
Poisson's ratio	0.3
Density	7850 kg/m^3

The beam was discretized in 1000 finite elements. The hex dominant method was used, with hexahedral elements with 6 degrees of freedom in each node. It was necessary to provide an S-N curve of the material to obain the fatigue results.

Figure 1 illustrates a flowchart of steps describing the simulation process in *Ansys Workbench*.

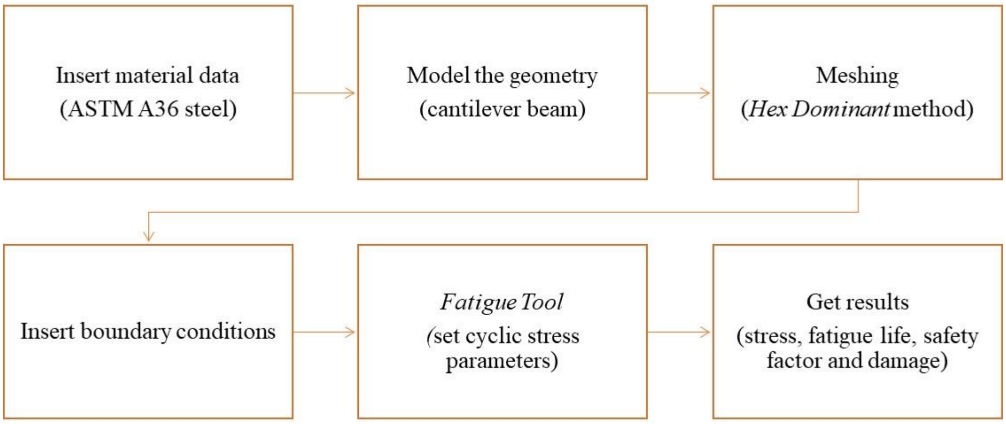

Figure 1. Numerical simulation flowchart

4 Results and discussion

4.1 S-N Diagram

The fatigue regime is based on the number of stress or strain cycles a material is subected to. There is the low-cycle fatigue regime, with number of cycles, *N*, less than 10^3 , and the high-cycle fatigue regime, tith number of cycles, *N*, greater than 10^3 cycles [2, 4].

Three approaches are used to calculate fatigue: the strain-number of cycles (ε-N) model, the linear-elastic fracture mechanics model and the stress-number of cycles (S-N) model [3]. Although the S-N model is the least accurate, particularly for the low cycling region, it is the most used. Its application is easier and represents with satisfaction the data from the high cycling region [2].

The test results of a specimen at different stress values are used to obtain the S-N curve of a certain material, which describes the stress, *S*, over the number of cycles, *N*. The number of cycles changes rapidly with stress level and, for this reason, they are usually plotted on a logarithmic scale [3].

When plotting the S-N, curve, it is possible to notice that in most materials the stress decays linearly until reaching na inflection point that happens between approximately 10^6 and 10^7 cycles. This point marks he fatigue limit (S_e) of the material. Stress values below this line have their fatigue life measured as infinite [4].

Not all materials have this clear limit, as the curve continues to decay as the number of cycles progresses, however, in these cases, it is common to observe a smaller slope of the straight line from 10^7 cycles. Thus, even if the material does not have a fatigue limit as described above, a new magnitude S_f can be adopted that gives the value of the fatigue strength at this point where the slope of the curve decreases [4].

The data plotted on the S-N curves of various materials is usually obtained from tests on carefully prepared specimens under controlled conditions. It cannot be assumed that these values will be the same for the same materials under different circumstances. Some causes that influence this are the manufacturing method, the corrosive environment, the temperature, the part size, the stress concentration, among others. In order to correct these differences, there are correction factors that can be used [2].

Therefore, if the data for the fatigue strength ($S_{f'}$) or for the fatigue limit ($S_{e'}$) of the material are available, they must be used, otherwise they must be estimated and the correction factors must be applied to them [4].

The corrected estimated fatigue strength and fatigue limit values, S_f e S_e respectively, are then given by eq. (1) e (2):

$$S_e = K_{loading} K_{size} K_{surface} K_{temp} K_{reliab} S_{e'} \tag{1}$$

$$S_f = K_{loading} K_{size} K_{surface} K_{temp} K_{reliab} S_{f'} \tag{2}$$

The fatigue strength stress value S_m is plotted for a number of cycles $N = 10^3$ and the corrected fatigue limit value S_e for the number of cycles $N = 10^6$, since the area of interest in the graph for the high cycle fatigue regime is in this range. A line is drawn between the two points and after that a line is continued horizontally until $N = 10^9$ to indicate the beginning of the infinite life of the part. This procedure is performed for materials that have a fatigue limit such as steel, the material used here [4].

For the steel beam, the fatigue limit of the material can be approximated by $S_{e'} \cong 0{,}5\, S_{ut}$ and the fatigue strength by $S_m \cong 0{,}9\, S_{ut}$, as in eq. (3) and eq. (4), where S_{ut} is the ultimate tensile strength equal to 460 Mpa adopted in Tab. 1.

$$S_{e'} \cong 0{,}5(460) = 230\ Mpa \tag{3}$$

$$S_m \cong 0{,}9(460) = 414\ MPa \tag{4}$$

On the coefficients that make up the expressions (1) and (2), $K_{loading}$ is the factor due to the type of loading. Here, a unit value was assigned since it corresponds to a bending test.

The size factor, K_{size}, is obtained as a function of a portion of the cross-sectional area of the beam subject to stresses equal to or greater than 95% of the maximum acting stress represented in equation (5). This portion is converted into a value that represents an equivalent diameter in Equation (6).

$$A_{95} = 0{,}05bh = 1 \times 10^{-4}m \quad (5)$$

$$d_{eq} = \sqrt{\frac{A_{95}}{0{,}0766}} = 0{,}036m \quad (6)$$

Thus, the diameter obtained in eq. (6) is within a range of values established in the literature, which points to the coefficients used to define the K_{size} described in equation (7).

$$K_{size} = 1{,}189\ d_{eq}{}^{-0{,}097} = 0{,}84. \quad (7)$$

The surface factor, $K_{surface}$, dependes on the quality of the finish of the actual part surface. Whereas the beam has a machined or cold-drawn surface finish, the tabulated coefficients *A* = 4.51 and *b* = -0.265 applied in eq. (8).

$$K_{surface} = 4{,}51(S_{ut})^{-0{,}265} = 0{,}89 \quad (8)$$

The unit value is also assigned to the temperature factor, K_{temp}, since the beam is considered to work at temperatures below 450°C.

Since most of the data recorded in the literature are based on mean values of the results obtained, the fatigue limit must be adjusted according to the reliability required for the project. Assuming a reliability of 99.9999% for the project, the reliability factor, K_{reliab}, has a value of 0.62.

Therefore, replacing these modifying factors in eq. (1), the corrected fatigue limit S_e for the beam is shown in eq. (9):

$$S_e = (1)(0{,}84)(0{,}89)(1)(0{,}62)S_{e'} = 106{,}6\ Mpa \quad (9)$$

Equation (10) describes the S-N curve, where S_n is the stress corresponding to any number *N* of cycles, and *a* and *b* are constants defined by the boundary conditions:

$$S_n = aN^b \quad (10)$$

In order to find the values of the constants, the following boundary conditions are used: $S_n = S_m$ in $N = N_1 = 10^3$ and $S_n = S_e$ in $N = N_2 = 10^6$ for the case with fatigue limit [3].

Equations (11) and (12) show the calculation of constants *b* and *a*:

$$b = \frac{1}{z} log\left(\frac{S_m}{S_e}\right). \quad (11)$$

$$\log(a) = \log(S_m) - b\log(N_1) = \log(S_m) - 3b \quad (12)$$

where, $z = log\ N_1 - log\ N_2$.

Using the calculated fatigue strength stress value, S_m , and the fatigue limit stress value, S_e , in equations (4) and (9) to find *a* and *b*. Equation (10) makes it possible to know the number of cycles *N* that causes fatigue failure for each stress S_n in eq. (13):

$$S_n = 1607{,}7N^{-0{,}1964}. \quad (13)$$

Thus, the estimated S-N diagram for the beam is illustrated in Fig. 2 and the equation describing the line will be used as input parameter for numerical calculations of quantities in Ansys.

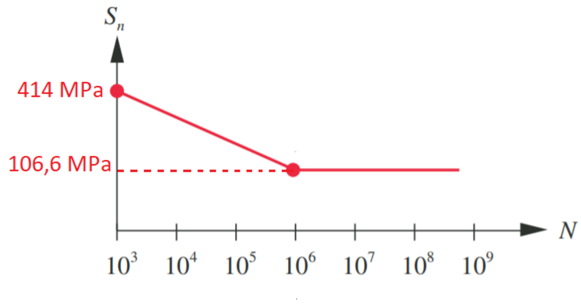

Figure 2. Estimated S-N diagram for the studied beam

4.2 Fatigue life

The value of the number of cycles for fatigue life (*N*) at different points were analytically and numerically calculated. The difference in values was not significant. A greater difference was observed close to the support because this is a stress concentration region, as shown in Tab. 2. Figure 3 illustrates the distribution of the number of cycles near to the beam support.

Table 2. Comparison of fatigue life

Fatigue Life (*N*)		
Point	Analytical	Numeric
A	1,00E+06	1,00E+06
B	8,10E+05	8,14E+05
C	5,47E+05	5,47E+05
D	3,78E+05	3,80E+05
E	2,68E+05	2,86E+05
F	1,04E+05	1,28E+05

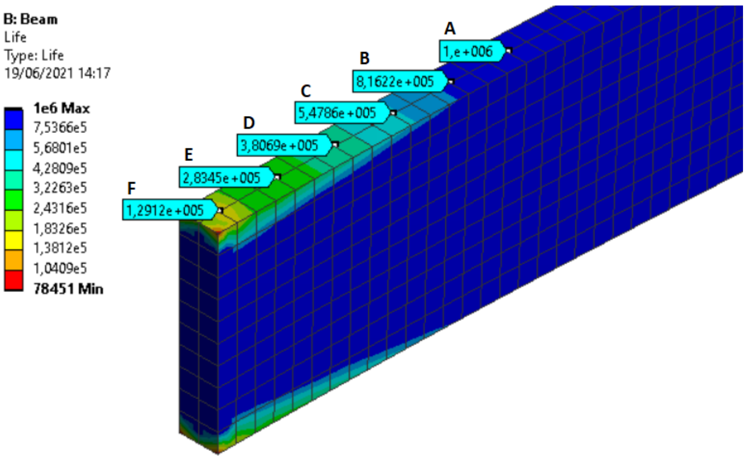

Figure 3. Fatigue life in *Ansys*

4.3 Safety Factor

The safety factor for the project is the ratio between the fatigue limit stress, S_e = 106.61 Mpa , and the von Mises stress σ' at each point, as shown in eq. (14):

$$SF = \frac{S_e}{\sigma'} \tag{14}$$

Table 3 shows that there is no difference between the analytical and numerical values of the safety factors at the analyzed points and Fig. 4 illustrates the simulation of this parameter in the software.

Table 3. Comparison of safety factor

Safety Factor		
Point	Analytical	Numeric
A	1,04	1,04
B	0,96	0,96
C	0,88	0,88
D	0,82	0,82
E	0,78	0,78
F	0,66	0,66

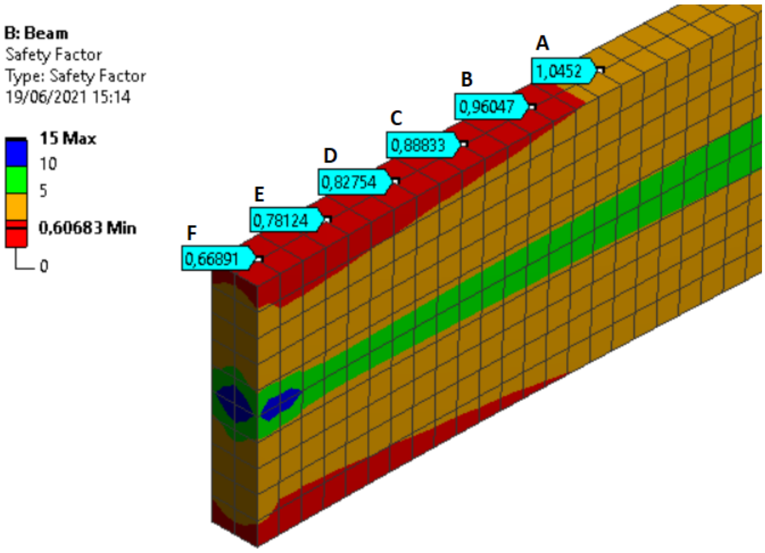

Figure 4. Safety factor in *Ansys*

4.4 Damage

Fatigue damage is the ratio between the fatigue life required for the project and the available life (N) at each point on the beam. Adopting 1×10^9 as the number of cycles determined for the project, the formula to be used is given in eq. (15):

$$Damage = \frac{1 \times 10^9}{N} \tag{15}$$

Table 4 shows the damage obtained by the numerical and analytical procedure.

Table 4. Comparison of damage

Damage (10^3)		
Point	Analytical	Numeric
A	1	1
B	1,23	1,23
C	1,83	1,83
D	2,65	2,63
E	3,73	3,53
F	9,61	7,83

As well as the fatigue life parameter, fatigue damage showed no significant difference between the values obtained, except at points close to the support due to stress concentration.

5 Conclusion

Considering the analysis demonstrated in this project, it is possible to estimate a number of cycles called fatigue life using the S-N method for structures subjected to high-cycle fatigue. Through this, it is also possible to determine the safety factor for a project or part, the damage caused by the application of cyclic loads and the chance of failure due to fatigue depending on the chosen material

Since fatigue failure occurs before the ultimate strength of the material and sometimes before the yield stress, tests and maximum stress calculations are not sufficient to guarantee the safety of projects subjected to cyclic loads. Thus fatigue analysis represents a very important step to ensure the validity of engineering projects in the current context, helping to avoid accidents and prolonging the lifespan of parts and structures.

The purpose of this work was to validate the analysis procedures using the *Ansys Student* fatigue module. In view of the above, the results of analytical calculations and numerical calculations showed good agreement with each other. Thus, the analyses presented fulfilled their proposed objective, and from this point onwards, we can safely advance into more complex studies.

The use of computational tools to solve engineering problems is extremely important as it helps to perform more elaborate calculations, speeding up the process and offering favorable results.

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