Politechnika
Wrocławska

Fatigue lifetime prediction in metallic components - experimental and numerical analysis of SIF solutions

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Acknowledgments

First, I would like to thank Wroclaw University for giving me the opportunity to study in this university, I also would like to thank to my home university, Universitat Politècnica de València, without them this would not be possible.

I would also like to thank Dr. Gzegorz for guiding me and helping me in this project whenever I need, I can say that I find a great person and an incredible professional.

Finally, I would like to thank my family, for giving me to study abroad and for being with me at the distance in this difficult situation which we are living currently, without them it would not be possible too.

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Abstract

This project was carried out during the Erasmus in Wroclaw University of Science and Technology with the main objective of obtaining more information about the fatigue lifetime of metallic components.

The present Erasmus+ Project was supervised by Dr. Gzegorz Lesiuk.
In this project the student had a series of tasks related with the study of the fatigue lifetime prediction in metallic components. The main activity was the analysis of SIF (Stress Intensity Factor) solutions in order to know the different solutions we have.

Keywords: SIF, Fatigue, Fatigue Crack Growth

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1. Mechanical Fatigue

· *1.1. Fatigue definition*

Fatigue is the most common cause of failure among metals and often occurs in other materials too. It is defined as “failure under a reputed or otherwise varying load, which never reaches a level sufficient to cause failure in a single application.” This issue has three stages: crack initiation, crack propagation and final fracture. The principal aim focus on the prediction of the total fatigue life of a component and on the prevention of cracks (first stage), so that the other two are focus on the study of this phenomenon.

According to the source of stress, fatigue can be classified into two sorts: mechanical fatigue and thermal fatigue. In this matter, they can be combined as thermo-mechanical fatigue. Reference to the cycles to failure, there are high cycle fatigue and low cycle fatigue:

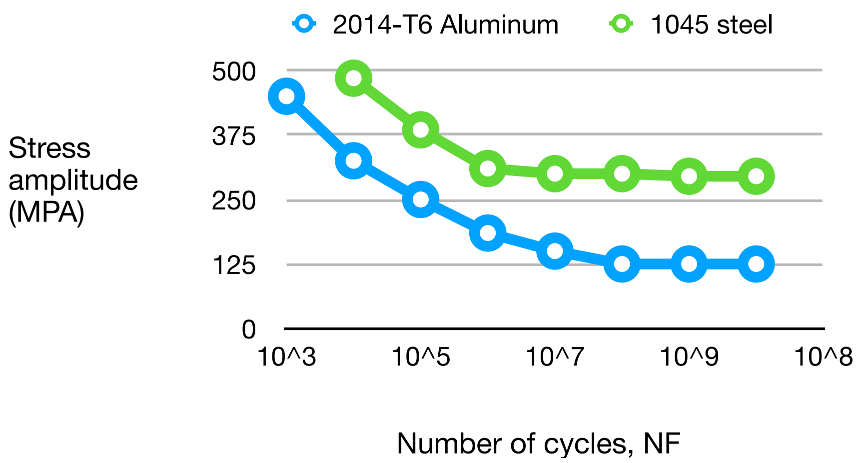
· ***HCF (high cycle fatigue)*** produces failures after cycles greater than 10^3 with low stresses and elastic deformation.
· ***LCF (low cycle fatigue)*** produces failures after cycles smaller than 10^3 with high stresses and plastic deformation.

The timescale of one cycle can vary greatly from one engine cycle to several hours. Although the damage pero cycle in LCF is grater than that of HCF, if the occurrence frequency of LCF is much lower than that of HCF, the component may reach a HCF failure earlier than a LCF failure. Different failure modes may have different fatigue mechanisms.

For example, if we talk about structures, they could be subjected to repetitive load cycles and may collapse under the effect of mechanical fatigue, although the stress level is considerably lower than the yield stress. The fatigue mechanism starts with the nucleation of small cracks in correspondence to microscopic defects on the material surface; the alternate loading causes the crack propagation inside the component, orthogonally to the surface, and the actual cross-section of the component is progressively reduced until its catastrophic.

· ***1.2. S-N curves***

Studies conducted on fatigue have produced many experimental results, which are usually reported on S-N curves, demonstrating that the lifetime of components is variable depending on the material, geometry, load characteristics, and environmental parameters.



(Figure 1)

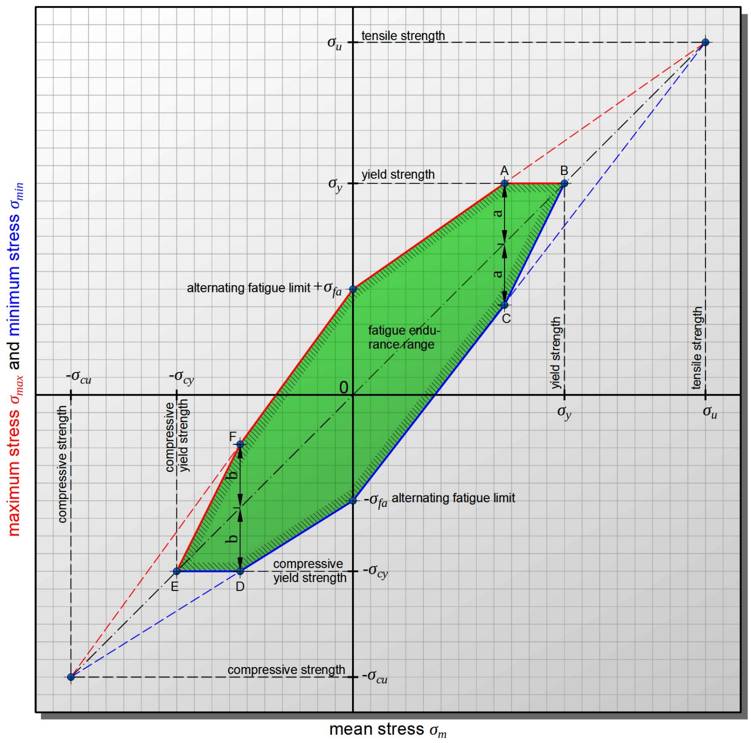
In the previous figure, we can see an example of S-N curve for steel, it is represented two examples of two components. I have depicted approximately the two curves, where we can see that they reach the fatigue limit in one point of the graph.

· ***1.3. Fatigue limit***

The fatigue limit 'σL, SL or Se' is the most important parameter to be considered at the fatigue design stage, since it identifies the stress level below which the component is not sensitive to fatigue. It is lower than the yield stress for ductile material, but unfortunately is not possible to identify the fatigue limit for all the materials. Another important matter to keep in mind on fatigue, is the shortening of lifetime when non-zero mean stress is added to the cyclic stress applied to the material.

The influence of the mean stress on the lifetime is represented by Goodman-Smith diagrams. Here we can analyse one example of this diagram.

(Figure 2)



As we can see, the minimum stress σ_{min} and the maximum stress σ_{max} are plotted against the mean stress σ_m. With a mean Stress of $\sigma_m=0$ the alternating fatigue limit σ_{fa} of the material is obtained, so that the value of the maximum stress is $+\sigma_{fa}$ and the minimum stress is $-\sigma_{fa}$. Another fixed point results when the mean stress just reaches the ultimate tensile strength ($\sigma_m=\sigma_u$). In this case, the material can no longer withstand stress amplitude, as otherwise the tensile strength would be exceeded. The maximum and minimum stress curves are approximated again as Goodman lines, and these only run up to the maximum value of the yield strength. This applies to both the maximum stress (point A) and the mean stress (point B) since of course the mean stress must not exceed the yield point too.

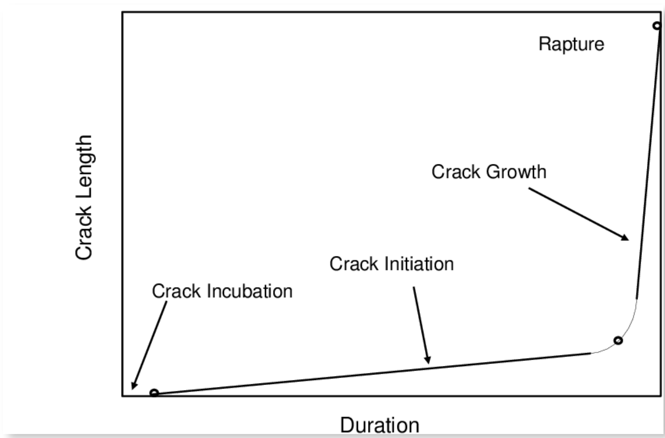
As soon as the yield strength at point A is reached, the line of the maximum stress continues as a horizontal line. Nevertheless, it is necessary an adjustment of the minimum stress, since the maximum and minimum stress must be symmetrical to the mean stress. To make it, the distance from point A and the mean stress line is symmetrically shifted downwards and the Goodman line of the minimum stress is reached (point C). Now, A, B and C limit the technically relevant fatigue endurance range. An extension of the negative mean stress values (compression) is also possible. The compressive yield strength σ_{cy} is used to limit the minimum stress (point D). It would be the same process but with the minimum stress.

2. Fatigue crack growth

· ***2.1. Phases in fatigue crack growth***

Normally, a fatigue crack begins at a point, usually on the surface of the component, and then grows into the metal as the component is subjected to the cyclic stress. The growth of crack often leads to failure of a component. Before crack initiate there is an incubation period, once the crack initiates It propagates at different rates a slow growth followed by rapid growth leading to failure. Initiation time for the crack can be very short, if a surface defect due to use and abuse or it can be longer; a crack can take millions of cycles of stress, even years, in some situations. The crack will grow or extend if the component is subject to a tensile or pulling stress.
Now, we can observe a figure where we can appreciate the different stages of the crack before failure occurs. As, it is seen, there are 4 phases: *crack incubation, crack initiation, crack growth and rapture.* In this 4 phases, there are 3 periods:

· ***Crack incubation-Crack initiation:*** beginning of the crack in the area where stress concentration causes cyclic plastic deformations. This period does not always occur, as the material could already contain crack imperfections.
· ***Crack initation-Crack growth:*** growth of the crack in the plastic zone where it was originated.
· ***Crack growth-Rapture:*** propagation of the crack in the piece, outside the concentration field of efforts where it was originated, until producing the final failure.



(Figure 3)

It is known, to evaluate the importance of fatigue cracking, the industry must have a good and empirically founded knowledge base about the scope and size of such cracks as well as their continuous growth rate. Better crack growth are needed which are supplemented by experimental data.

The analysis of the abrupt failures of loaded bodies is generally given by Paris law, a relation between crack growth and the stress intensity factor. The aim of developing such a model is to predict the safe operating life of a structure subject to cycling loading. Paris himself admits that while working to develop this relation, he would not fly on commercial aircraft because small cracks often developed on airframes and there was no wat to predict how fast the cracks would grow.

· 2.2. Precedents on Paris law

Paris and Erdogan determined that for the variation of cyclic loads, the variation of the stress intensity factor (ΔK) is the parameter that characterises the growth of fatigue cracks.

$$\Delta K = K_{max} - K_{min} \qquad [1]$$

Where Kmax and Kmin are the maximum and minimum values of the stress intensity factor (if Kmin is negative it is taken equal to zero in the equation above). Thus:

$$K_{max} = Y \cdot \sigma_{max} \cdot \sqrt{\pi \cdot a} \quad ; \quad K_{min} = Y \cdot \sigma_{min} \cdot \sqrt{\pi \cdot a}$$
$$\Delta K = Y \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a} \quad ; \quad \Delta\sigma = \sigma_{max} - \sigma_{min} \qquad [2]$$

The σmax and σmin values are the maximum and minimum stresses of each cycle (if, $\sigma_{min}<0$, σmin is taken equal to zero).

· 2.3. Paris law

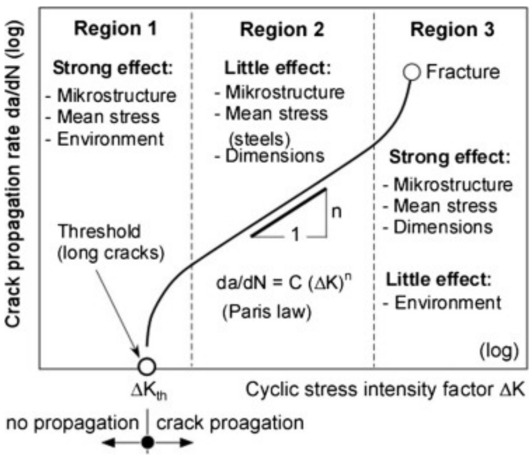
Paris proposed an empirical law based on the concepts of LEFM (Linear Elastic Fracture Mechanic), which unified all the experimental data of fatigue crack growth, only partially described by previous models. This law expresses:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \quad [3]$$

Where the term (da/dN) is the increase in length of the crack for each cycle of fatigue and ΔK is the variation of the stress intensity factor. C and m are constants that depend on the material and they are obtained experimentally. The constant C also could depend to some extent on the load ratio (R):

$$R = \frac{\sigma_{min}}{\sigma_{max}} = \frac{K_{min}}{K_{max}} \quad [4]$$

The Paris equation can be written in coordinates logarithmic, which result in a straight line of slope m:



(Figure 4)

Here, there are the 3 regions of fatigue crack growth. Using the equation in region 1 results in a lower prediction of life real of the piece, while in region 3 the growth of crack accelerates strongly. Region 2 yields results highly approximate; is the phase that present the best conditions and greater importance for designer.

$$\log \frac{da}{dN} = \log C + m \log \Delta K \quad [5]$$

Talking about the appearance of striations in the propagation of region 2, these appear clearly in metal components, ductile alloys and some polymers. The final failure of a component, in which a crack grows from fatigue, it happens when the Kmax value is equal to the critical value Kc. When Kmax approaches Kc in the region 3, the crack grows faster than in region 2 (Fracture —> Kmax=Kc).

In 1967, it was proposed a crack growth model for region 2 (by Laird), resembling the CTOD size (Crack Tip Opening Displacement) achieved at increasing loads. If the field of stresses at the front of the crack is in compression and the partially closes, then a spread of crack in every cycle. We could resume Laird model like this (6 states):

A) Minimum load

B) Increasing tensile load

C) Maximum tensile load

D) Beginning of the load descent

E) Minimum load of the new cycle

F) Increasing tensile load in the new cycle

The variation of the crack front opening is represented by:

$$\Delta\delta_t = \frac{\Delta K_I^2}{2 \cdot E' \cdot \sigma_y} \quad [6]$$

Applying the CTOD model, we can approximate (da/dN to ($\Delta\delta t$), being σy: creep resistance, E'=E (for flat stress), E'=(E/1+v^2) (for flat deformation), being v: Poisson coefficient.

In most cases, replacing terms is obtained that the value of m is approximately equal to 2; but in some materials, the relationship (da/dN) is inversely proportional to σy. This equation is only valid for region 2 of the Paris law. Because of this, many researchers focused on determining the crack behaviour for region 1 and 3, which yielded lots of theories about growth microcracks and others depending on the type of material.

· 2.4. Determination of the exponent "m" of Paris

As we have said, for a larger number of cases, the value of m is approximately equal to 2. But, actually, the value of this exponent yields results in a range from 1.5 to 4, varying according to the type of material, the environmental conditions and the type of load applied.

Before Paris law, there have been more laws. The first law is attributed to the *Australian Defence Science and Technology Organisation*- DSTO) which expressed the next law:

$$\ln(a) = \psi \cdot N_L = \ln(a_0) \quad [7]$$

$$\psi = \Omega \cdot (\Delta\sigma)^{\alpha} \quad [8]$$

The second one was developed by Frost and Dugdale, who define parameter ψ. Recently Polak and Zezulka proposed that the equation found by DSTO can be applied to microcracks. Their experiments were corroborated on stainless steels.

· 2.5. Different remarkable models

I would like to stand out two models. First, I am going to talk about *Elber model,* this model is based on the concept of crack closure. The ΔK factor is replaced by the intensity range of effective efforts:

$$\Delta K_{eff} = K_{max} - K_{op} \quad [9]$$

Where Kop is the stress intensity factor when the crack opens due to σop. To try to incorporate the stress ratio R, various models of Partial of crack closures have suggested expressing the equation evenly like so:

$$\Delta K_{eff} = f(R) \cdot \Delta K \quad [10]$$

Where f(R) is a function of the amplitude ratio load R. However, for both models it is difficult determining Kop because it is related to the relationship of loads R.

Now is time to speak on *Kujawski model.* This model does not use the concepts of enclosure crack but it implements a geometric mean of the positive part of the applied stress intensity factor ΔK+ and the maximum value Kmax:

$$\frac{da}{dN} = C \cdot (\Delta K^*)^m$$

$$\Delta K^* = (K_{max} \cdot \Delta K^+)^{0.5} = (K_{max})^{\alpha} \cdot (\Delta K^+)^{1-\alpha} = M\Delta K$$

[11]

The parameter α (correlation parameter) is obtained by graphing the logarithmic curve Kmax vs K+ give constant growth. By knowing the value of α, it is possible to know the value of ΔK+. This model is valid according to the experimental data if R>=0. ΔK+=ΔK when R>=0 and ΔK+=ΔKmax when R<0.

There are more models such as *Huang model.* This model would be a success if they knew each other more values of β and β1 (two parameters of this model), only are known for some steels and aluminums, and the model does not expose the methodology used to calculate said parameters.

3. Crack growth rate description

· *3.1. Crack growth rate definition*

A fluctuating stress intensity drives the crack to grow at some rate. When a stress intensity range ΔK is applied to a material for some number of cycles ΔN, this drives the crack to grow in length by a specific amount Δa. The crack rate growth at a specific intensity range is the given by the ratio Δa/ΔN. In continuous form, the crack growth rate is give by the derivative (da/dN).

The crack growth rate under fatigue loading, (dA/dN) is a function of the loading conditions, geometry and material, and can be related to the Paris law using the crack front width:

$$\frac{dA}{dN} = b * \frac{da}{dN} \quad [12]$$

The growth rate defined by the Paris law represents crack propagation in region 2 (seen in the previous point) of the typical pattern of the crack growth rate.

· 3.2. How increase or decrease the crack growth rate

If an experimental follow-up of crack growth in relation to the number of cycles is performed, for constant fatigue stress, it is usually observers that the crack growth rate increases with increasing crack length. Also, under certain test conditions, generally increasing fatigue stress increases crack growth rate.

Generally, the growth rate of a fatigue crack in relation to the number of stress cycles, (dA/dN), has been found experimentally to be of the form:

$$\frac{dA}{dN} = f(\Delta K, Kmax) \quad [13]$$

That is, if the same combination of ΔK and Kmax occurs in two different cracks, the same growth rate will be obtained.
For a cycle stress R>=0, the above equation can also be written as:

$$\frac{dA}{dN} = f(\Delta K, R) \quad [14]$$

As the stress ratio R is increased, the crack growth rate in material is also increased.

· 3.3. Stress ratio "R"

As we know, this is ratio of the minimum stress experienced during a cycle to the maximum stress expected during a cycle. It is important to note that the stress values can be positive (tensile stress) or negative (compressive stress).

In the easiest case to visualise, the test specimen starts out unloaded (zero stress), is loaded to required maximum positive stress level, and then unloaded to start the next cycle. In this case, the ratio R would be exactly zero. This is called **unidirectional (R=0) testing.** A spring contact in a modular jack would be an example of this loading condition.

The most extreme case would be if each cycle consiste4d of loading the test specimen to a five stress level (in bending or torskon), and then loading to sun equal and opposite stress level in the other direction. In this case, the minimum stress would be the negative of the maximum stress, and the ratio R would be exactly equal to -1. This is known as **fully reversed (R=-1) testing.** A rotating axle or shaft subjected to a constant bending stress would be an example of this condition, as each point on the circumference of the shaft would alternately experience tension and compression as it rotates around the center.

The next case could be, when the minimum stress is some small positive value associated with the preload, and the maximum stress is a larger positive value. In this case, the R ratio is greater than 0 and less than 1. Another possibility is to have a minimum compressive stress of lower magnitude than the maximum stress. This would result in an R ratio between -1 and 0. This could be the case in some switch and relay contacts. We can call this as **fluctuating stress (R=0.5 or R=-0.5) testing.**

One important point to note in this issue is that the all sources of stress will factor into the fatigue performance of a component. This includes the design stress from mechanical sources (applied forces, pressures, or deflections), thermal stresses (elevated environmental temperatures or internally generated by joule heating), vibration, impact and even residual stresses from forming or machining operations.

Many of these sources are highly variable and unpredictable. This is why it is important to include safety factors in fatigue analysis.

· *3.4. Visual inspection of the crack length*

Crack growth rate curves are obtained by measuring crack length during the fatigue test. Crack tip positions are commonly determined by means of visual methods such as traveling cameras or microscopes. Such methods introduce two main uncertainties.
On the one hand, visually monitoring the crack length does not constitute a robust method, as it is considered `operator dependent´.
On the other hand, the fact that the rack length is measured at the edge of the coupons adds imprecision to the measurement because the crack front is not straight.

When using optical devices. The crack length is measured every certain number of cycles, which introduces scattering into the results. This scattering increases with the differentiation of the crack length against the number of cycles. In addition, as the crack growth rate decreases during the test, the crack front needs to be determined with even greater precision as the test evolves in order to produce reliable data near the threshold.

An alternative approach relies on the estimation of the crack length by means of compliance. The relationship between the compliance and the crack length should be calibrated before or after the test. This method is widely used in region II 3-point end-notched. The compliance calibration consists of the opening the specimen arms at different crack lengths (without damaging the specimen) to measure the compliance.

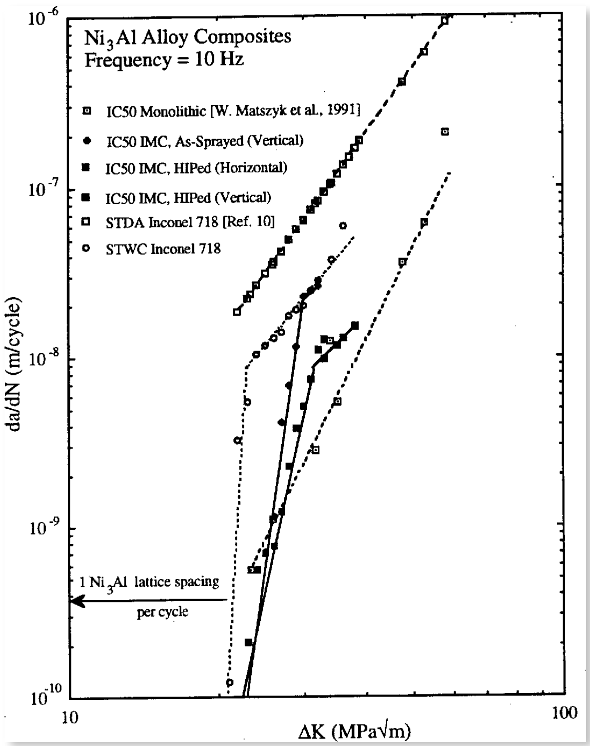
· *3.5. Environmental Effects*

Crack growth rates in Ni_3Al alloys are lower than for many superalloys, and rates of growth increase with increasing temperature. Detailed studies of an alloy designated IC-221 showed that environmental effects are very important, in that oxygen accelerates crack growth at elevated temperatures above 700ºC.

Crack growth rates increase with decreasing frequency in both vacuum and aire for this alloy at 800ºC, but the rates are always higher in air. Intergranular fracture occurs in air all test frequencies, while transgranular fracture is noted vacuum. Secondary cracking is enhanced at lower
frequencies, suggesting that diffusion of oxygen contributes to the initiation of secondary cracks.

According to the steel, the fatigue crack growth rate in steel is independent of the steel microstructure, but other factors such as the presence of a corrosive environment or operation at temperatures above 100ºC influence the crack growth rate. Fatigue cracks in welds exposed to seawater and marine environments propagate faster than ion welds simply exposed to air.

(Figure 5)



· 3.6. Example of Methodology for crack growth calculations

The crack growth rate can be calculated using a spreadsheet that is augmented by a plug in that performs the stress intensity factor calculations. The steps in the analysis process are as follows.

- 3.6.1. Determine through thickness stress distributions:

The distribution of stress through the thickness of the component to be analysed, starting at a highly stresses location on the surface, is determined from elastic-plastic finite element analysis results (FEA). The FEA model is subjected to the design autofrettage *(auto-encogimiento)* pressure and the pressures was reduced to ambient to determine the residual stress. For a cylindrical shell, taken as an example, the highest stress is at the bore surface. The residual stress after autofrettage is compressive through the entire thickness because the carbon fibre wrap has a significant residual tensile stress after autofrettage. The resulting reduction in mean stress reduces the crack growth rate. The stress at the inner surface of the cylinder, which is assumed to be the location of the initial crack, is shown at the 0 mm through thickness dimension.

- 3.6.2. Determine membrane and bending stresses:

Linearised membrane and bending stresses were used in the calculation of the reference stress. Stress linearisation is used to determine the membrane and bending stresses.

- 3.6.3. Calculation of crack tip stress intensity factor:

The stress intensity factor, K, is determined for the initial flaw size at both the surface and at the deepest point of the crack. The weight function method is used. For values of mean stress, as characterised by the ratio of minimum to maximum stress, Rk, that are between 0.2 and 0.5, the values of C and m were determined by interpolation of the different values given in a specific table. For values of Rk above or below those values, the mean stress correction is used.

- 3.6.4. Calculation of crack growth rates:

The crack tip stress intensity factors is used to calculate crack growth rates both along the surface and in the through thickness direction.

The calculated da/dN is presumed to be essentially constant over an increment of cycles (ΔN) so that the crack extension in the depth or through thickness direction (Δa) in this increment was evaluated from the product (da/dN)*(ΔN).

The crack extension along the surface is calculated using a similar procedure. The number of cycles in each increment is adjusted to limit the total crack growth to a value that results in an increase in the crack tip stress intensity factor of less than about 2%. (The stress intensity factor, K, is a function of the crack depth and length).

Since the stress intensity factor is, of necessity, calculated based on the initial crack size for the current increment of crack growth, this stress intensity factor must be updated by a small percentage to account for the increase in crack size during the previous increment.

- 3.6.5. Determination of cyclic stress and number of cycles:

There are typically several types of stress cycles that a pressure vessel is exposed to. It has been studied an example (cylindrical shell), and for that example, three types of cycles are assumed as shown in the next table. For each type of cycle, the number of cycles per year is shown. For simplicity, one set of FEA results is used. The pressure cases can be scaled to the range of pressure for each type of cycle, since the stress range from the FEA results is linear after the completion of autofrettage. However, in most assessments, different FEA results would be used for thermal stresses.

Load case	Cycles/year	Stress range (% of maximum from FEA)	Maximum stress (% of maximum from FEA)	Minimum crack opening pressure (MPa)	Maximum crack opening pressure (MPa)
Pressurization	1825	50	90	41,4	93,1
Blow down	2	90	90	0	93,1
Temperate cycle	365	16,2	90	76	93,1

4. Stress intensity Factor

· *4.1. Brief description*

The stress intensity factor is a function of geometry, size and shape of the crack, and the type of the load. Which is give by the following equation:

$$K = \sigma\sqrt{\pi a}$$ [15]

This factor, as we have commented in the second point (Fatigue crack growth), is one of the parameters responsible for fatigue failure.

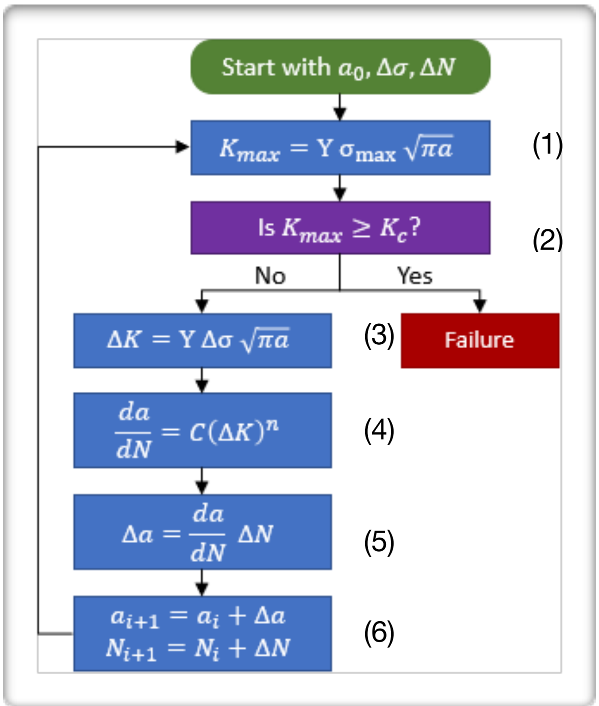
As a crack grows, the stress intensity factor at the crack tip increases. Failure occurs once the stress intensity factor exceeds the critical stress intensity Kc of the material. For thick sections the value of Kc could be plane-strain fracture toughness, but it could also be the critical stress intensity for the specific section thickness.

In the case of a cyclic applied stress, the stress intensity facto should be calculated using the maximum stress value in the stress range. This maximum stress intensity factor, Kmax, should be compared to the Kc to determine failure.

· *4.2. Life Prediction*

The lifetime of a cracked part is typically expressed as the number of cycles that it takes to grow the crack from some initial condition to a critical condition. Closed form expressions to determine the lifetime of a cracked part do exist for simple cases. However, in general it is necessary to use numerical methods to determine the expected lifetime of a part. We ca simulate the crack growth using the general procedure, in this procedure, the initial crack size is known or assumed. The applied stress range $\Delta\sigma$ is also known, and a step size for number of cycles, ΔN, is selected.

(Figure 6)



The first step is to calculate the stress intensity facto for the current crack size at the maximum applied stress in the stress range (1). If Kmax exceeds the material's critical stress intensity Kc (2), then the failure condition is met and the simulation is stopped. Otherwise, the simulation is continued to determine the crack growth for the current iteration.

The next step is to calculate the stress intensity range (3). Using the calculated stress intensity range, one of the rack growth relationships (4) can be used to calculate the crack growth rate (da/dN). We use this crack growth rate together with the cycle step size to determine the incremental growth of the crack for this iteration (5). The new crack size is then the last formula expressed in the procedure (6).

This new crack size is then used for the next iteration of the simulation. The crack is grown iteratively until the failure condition is met. Once failure occurs, the total number of cycles that it took to grow the crack to the critical size becomes the predicted life of the part.

· 4.3. Factor of Safety

There is uncertainty in the initial size of the crack (what size crack can be detected), the stress levels experienced during operation, and the crack growth rate properties of the material.
The factor of safety can be calculated with respect to stress (considering maximum applied stress as compared to the residual strength remaining in the part), or with respect to the number of cycles to failure. The factor of safety with respect to cycles to failure is:

$$FS = \frac{Nf}{Ns}$$ [16]

Where Nf is the expected number of cycles to failure and Ns is the number of cycles that the part will experience in service.

In the case that the number of cycles experienced during service is too large as compared to the expected number of cycles to failure, periodic inspections may be required to ensure that cracks do not grow to the point that they become critical. The inspection period should be chosen at some fraction of the expected time to failure. Cracks detected during inspection may be repaired. if repair is impractical, then crack growth analysis should be performed to determine the expected cycles to grow the detected crack to failure. The results of the analysis may indicate that part replacement is necessary.

Some systems may be designed to allow for some crack growth before repair and replacement. In this case, fatigue crack growth analysis is key to safe operation of the system. This approach to allowing and accounting for a safe level of crack growth during the operation of the system is referred to as damage-tolerant design.

· *4.4. Influence of Material Microstructure*

The influence of various characteristics of the microstructure on the fatigue properties, at the initiation stage or the propagation stage, is important.

The first thing to consider when trying to understand the effects of the microstructure of materials on their fatigue resistance is the size of the plastic zone with respect to that of the microstructural units: the grain size, the distance between inclusions. If it is much greater one would not expect effects very different from the ones observed in a specimen deformed homogeneously: grain size Hall-Petch effect on the flow stress, ductility reduced by inclusions. On the other hand if the plastic zone size becomes of the same order of magnitude or smaller than the microstructural units new effects are expected and indeed observed in fatigue.

At the nucleation stage, the plastic deformation which counts usually is concentrated in the surface grains: microstructure will play an important role at this stage.

In crack propagation little effect is expected in the striation regime where the plastic zone at the tip is large. On the contrary the microstructure has a large influence on the fate threshold and at low crack propagation rates where the plastic zone size is smaller than the grain size.

In studying these effects we will examine first those which can be related to the interatomic bonding, then to the stacking fault energy, to the grain size, to precipitates, to different phases, to inclusions and finally to porosities.

- 4.4.1. Interatomic bonding:

The interatomic bonding interacts with the fatigue resistance through the elastic constants energy. A higher stiffness decreases the strain energy release rate and the crack opening displacement. It is thus expected that a low modulus of elasticity, associated with a low surface energy, promotes the ease of initiation and propagation of fatigue cracks.

- 4.4.2. Stacking fault energy:

Cross slip is directly connected with the stacking fault energy. The more or less planar nature of the slip lines influences the initiation and the propagation of fatigue cracks.

The extend of region 1 is related to the grain size. Concerning crack propagation the grain size is to be compared with the plastic zone size. When it is small, near the threshold, the grain size modifies the slip amplitude and it plays an important role on the threshold level. In a particular it determines the fracture surface roughness and this induces a smaller or larger crack closure. On the contrary, at large crack propagation rates, the grain size acts only through its influence on the yield strength and it has then much lower effects.

- 4.4.3. Precipitates:

The role of precipitates differs according to whether or not they are sheared. In the first instance the slips are very planar and this can result in cyclic softening. Precipitates dissolution and precipitation can occur, with a strong influence of temperature. When the precipitates are not sheared they contribute instead to cyclic hardening.

- 4.4.4. Inclusions:

Inclusions which are preferred cities for cavities nucleation, modify the large crack propagation rates when striation and ductile mechanisms occur simultaneously. Inclusion play a fundamental role in initiating fatigue cracks, particularly in rolling fatigue.

Particular phenomena appear when fatigue cycling induce phase changes, particularly austenite destabilisation.

- 4.4.5. Porosities:

In porous materials, the cavities can be considered as a damage and the increase of the crack propagation rate can be explained using an effective stress.

· *4.5. Effect of loading frequency on fatigue life*

This is going to explain by an experiment, which was done it with wood-based panels. These panels are subjected to cyclic panel shear load caused by wind and seismic forces in such an application as the sheathing of bearing walls.

The fatigue behaviour of structural plywood under panel shear load with two different loading frequencies was examined. Pulsating panel shear load with triangular waveform and loading frequency of 0.5 or 5 Hz was applied to the plywood specimens. Stress-strain hysteresis loops were measured throughtout the fatigue tests. Fatigue life was highly dependent on loading frequency at more than 0.5 stress level.

The deterioration of mechanical property and damage accumulation in plywood specimen was observed to be slower at higher loading frequency at more than 0.5 stress level.

Analyses based on energy loss suggest that panel shear load with higher loading frequency causes less damage to the plywood specimen during one loading cycle at

higher stress level, and that the fatigue damage accumulation causing failure might be dependent on stress level although it seems to be unaffected why loading frequency.

Based on these results, a new fatigue failure model for plywood specimen was qualitatively developed by combining Weibull's weakest link model and Daniel's fibre bundle model.

· *4.6. Multiaxial Fatigue*

Multiaxial fatigue is a general term that may be used to describe loading and/or loading plus geometry conditions resulting in complex states of stresses and strains, either locally or globally. More specifically multiaxial loading will result in state of stress and/or strain, which manifests as two or more components in the stores or strain tensor.

Global multiaxial loading may result from multiple external forces being applied along different lines of action and it can also result from separate external loads (forces and torques). Local multiaxial loading, on the other hand, will occur at any geometric discontinuity, even when the global state of stress is uniaxial. A particular note for designers is that all notices, holes, bends in structures, and so on, will experience multiaxial loading, and therefore multiaxial fatigue.

The state of stress within a component experiencing multiaxial loading is best determined by the use of finite element methods and therefore somewhat trivial. Failure criterion for multiaxial fatigue, on the other hand, is the subject of ongoing research and remains a difficult task for engineers and scientists. One failure criterion that has been successfully applied to multiple metals, loading conditions, and boundary conditions is the Fatemi-Socie (F-S) fatigue indicator parameter (FIP). The F-S FIP estimates that there will be failure when a critical combination of shear strain and normal stress occur on a critical plane. The F-S FIP equation is provided below.

A similar approach to predicting multiaxial fatigue is the use of the Modified Wöhler Curve Method (MWCM). This method, based on the concept of a critical plane, uses the assumption that damage from fatigue is at a maximum on planes of corresponding maximum shear stress amplitudes.

We can conclude this discussion of multiaxial fatigue by acknowledging that determining the effects of multiaxial fatigue is further complicated by the existence of a graded microstructure in FSW (a sort of material, aluminium tubes). Localised portions of these regions are likely to exhibit a multiaxial state of stress even when the long-range state of stress is uniaxial. As such, the alignment of the critical planes is not random, and likelihood of favourable alignment within regions of stress triviality may manifest int multiaxial fatigue-like damage accumulation. Thus, future work is needed to develop multiaxial approaches that consider the microstructure in FSW.

5. Methods for fatigue lifetime calculation

· 5.1. Introduction

The fatigue life prediction methods can be divided into two main groups, according to the particular approach used.
The first group is made up of models based on the prediction of crack nucleation, using a combination of damage evolution rule and criteria based on stress/strain of components. The key point of this approach is the lack of dependence from loading and specimen geometry, being the fatigue life determined only by a stress/strain criterion.
The approach of the second group is based instead on continuum damage mechanics (CDM), in which fatigue life is predicted commuting a damage parameter cycle by cycle.

· 5.2. Palmgren-Miner rule

Generally, the life prediction of elements subjected to fatigue is based on the "safe-life" approach, coupled with the rules of linear cumulative damage. Indeed, the so-called Palmgren-Miner linear damage rule (LDR) is widely applied owing to its intrinsic simplicity, but it also has some major drawbacks that need to be considered. Moreover, some metallic materials exhibit highly non-linear figure damage evolution, which is load dependent and is totally neglected by the linear damage rule.
The major assumption of the P-M rule is to consider the fatigue limit as a material constant, while a n umber of studies showed its load amplitude-sequence dependence. This rule can be represented as follows:

$$\frac{n1}{N1} + \frac{n2}{N2} + \frac{n3}{N3} + \ldots + \frac{ni}{Ni} = 1$$ [17]

We can see the term "n" which is the number of cycles for a specific provided point referring to a given stress , and "N" which represents the number of cycles for a given stress at the point of intersection with the S-N curve.

· 5.3. Linear damage summation rule

This rule assumes that damage, regardless of whether it comes from creep or fatigue, is cumulative in a linear fashion. That is, failure occurs when:

$$Df + Dc = 1$$ [18]

Where $Dc = \Sigma i \frac{ni}{Ni}$ is the damage caused by fatigue based on the linear damage hypothesis (Palmgren-Miner), $Dc = \Sigma i \frac{ti}{tRi}$ is the damage due to creep based on the life-fraction hypothesis (Robinson) or $Dc = \Sigma i \frac{\varepsilon ci}{\varepsilon Ri}$ based on the strain- fraction hypothesis (Goldhoff); where ni is the number cycles at a given strain range Δεp (as we explain in the 5.2 point); Ni is the fatigue lifetime at the same strain range at a temperature at which the mechanism of creep is inactive; ti and εci are time and creep strain, respectively, at a given stress and temperature; tR and εR are time-to-rupture and rupture strain, respectively, at the same stress and temperature.

· 5.4. Strain range partitioning method

This one apportions the damage within a cycle using the following rule:

$$\frac{1}{N} = \frac{\Delta\varepsilon_{\mathrm{pp}}}{\Delta\varepsilon_{\mathrm{in}} N_{\mathrm{pp}}} + \frac{\Delta\varepsilon_{\mathrm{cc}}}{\Delta\varepsilon_{\mathrm{in}} N_{\mathrm{cc}}} + \frac{\Delta\varepsilon_{\mathrm{cp}}}{\Delta\varepsilon_{\mathrm{in}} N_{\mathrm{cp}}} + \frac{\Delta\varepsilon_{\mathrm{pc}}}{\Delta\varepsilon_{\mathrm{in}} N_{\mathrm{pc}}}$$ [19]

Where Δεin=Δεp+Δεc (being Δεp the plastic strain range and Δεc the creep strain range), Δεpp is plastic strain reversed by plastic strain, Δεcc his tensile creep strain reversed by compressive deep, Δεcp is tensile creep reversed by compressive plasticity and Δεpc is tensile plasticity reverse by compressive creep. Individual strain components are assumed to obey their respective Coffin-Manson relation.

By partitioning the four mechanisms of creep-fatigue interaction, this model has been shown to be capable of modelling a wide range of creep-fatigue phenomena with reasonable accuracy (Penny & Marriott, 1995) and has been adopted by the power and aviation industries.

· *5.5. Hysteresis energy method*

It is based on experimental observations that there is little creep damage during compression, suggests that the inelastic damage accumulated in a cycle is given by the tensile portion of the stress-strain hysteresis energy (the limits contained in the tensile cycle):

$$w = \int_{\text{tension cycle}} \sigma \varepsilon_{\text{in}} \, \mathrm{d}\varepsilon \qquad [20]$$

A similar method that uses the entire stress-strain hysteresis energy is often adopted by the microelectronics assembly community for modelling the creep-fatigue of solder joints (Liang, 1997). Inherent in this method is the linear summation of plastic and creep damages, which, as discussed, is not supported by microstructural evidence.

· *5.6. Fracture mechanics-based method*

This method, resting on the observation that low-cycle fatigue is dominated by crack propagation, suggests that the rate of crack growth is driven collectively by cyclic fatigue and creep; that is,

$$\left.\frac{da}{dN}\right|_{\text{cycle}} = \left.\frac{da}{dN}\right|_{\text{fatigue}} + \left.\frac{da}{dt}\right|_{\text{cycle}} \qquad [21]$$

$$\left.\frac{da}{dN}\right|_{\text{fatigue}} = C_1 \Delta J_{\text{eff}}^{n/2} \qquad [22]$$

$$\left.\frac{da}{dt}\right|_{\text{cycle}} = \int_{\text{tension cycle}} C_2 {C^*}^{n'} dt$$

[23]

ΔJeff is the effective range of J-integral; and C* is the time-dependent fracture parameter. The Darveaux's model (Darveaux, 2002) that is used extensively for modelling solder joints assumes crake initiation and propagation are power-law functions of the total stress-strain hysteresis energy:

$$N = N_o + \frac{a_{allow}}{da/dN} \quad [24]$$

$$N_o = C_1 \Delta w^{C_2}, \quad \frac{da}{dN} = C_3 \Delta w^{C_4} \quad [25]$$

a_{allow} is the allowable crack length and is commonly taken as the smallest diameter of a solder joint.

$$\begin{aligned} \frac{1}{a}\frac{da}{dt} &= \begin{Bmatrix} T \\ C \end{Bmatrix} \left(1 + \alpha \ln \frac{c}{c_o}\right) \left|\varepsilon_{in}^{m}\right| \left|\dot{\varepsilon}_{in}^{k}\right| \\ \frac{1}{c}\frac{dc}{dt} &= \begin{Bmatrix} G_T \\ -G_C \end{Bmatrix} \left|\varepsilon_{in}^{m}\right| \left|\dot{\varepsilon}_{in}^{k}\right| \end{aligned} \quad [26]$$

Where T and GT are for tension, C and -Gc for compression and co is a threshold cavity size below which cavities will be sintered away. While academically interesting, this method is too complicated to be adopted for industry practices.

· 5.7. Frequency modified method

It accounts for the effects of creep through the introduction of a frequency term into the Coffin-Manson equation:

$$\Delta\varepsilon_p = C_c \left(N f^{k-1}\right)^{-\beta_o} \quad [27]$$

· 5.8. Frequency-temperature modified method

It accounts for the effects of creep by introducing a frequency and a temperature term into the Coffin-Manson equation, which is a natural extension of the frequency-modified method, and the inclusion of temeperature completes the description of creep. In analysing the creep-fatigue of eutectic SnPb solder joint in leaded IC packaging, Engelmaier (1983) came to the following frequency-temperature modified strain-life equation:

$$\Delta\varepsilon_{\mathrm{p}} = C_{\mathrm{o}} N^{-\beta(T,f)}$$ [28]

$$\beta = 0.442 + 6 \times 10^{-4}\overline{T} - 1.74\times10^{-2}\ln(1 + 43200f)$$

[29]

Here, $\overline{T}$ is the mean cyclic solder joint temperature in ºC. Unlike Coffin (1976), Engelmaier (1983) has assumed that the effects of frequency-temperature is an altering the magnitude of the fatigue ductility.

Shi (2000) performed an elaborate characterisation of the eutectic SnPb solder under uniaxial tension-compression loading over the temperature range from -40 to 150ºC and frequency range from 10^-4 to 1 Hz. They proposed the following frequency-temperature modified strain-life equation:

$$\Delta\varepsilon_{\mathrm{p}} = C_{\mathrm{c}}(T)\, f^{\beta(T)[1-k(T)]}\, N^{-\beta(T)}$$

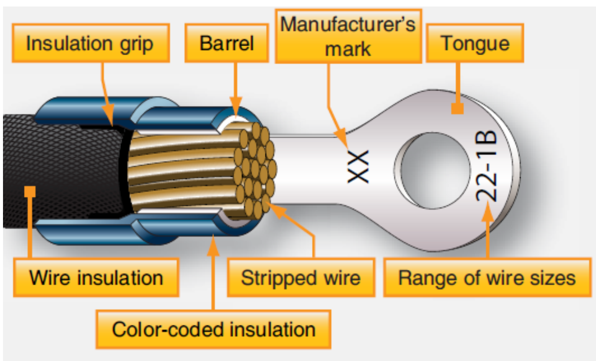
[30]

6. Selection of the metallic component

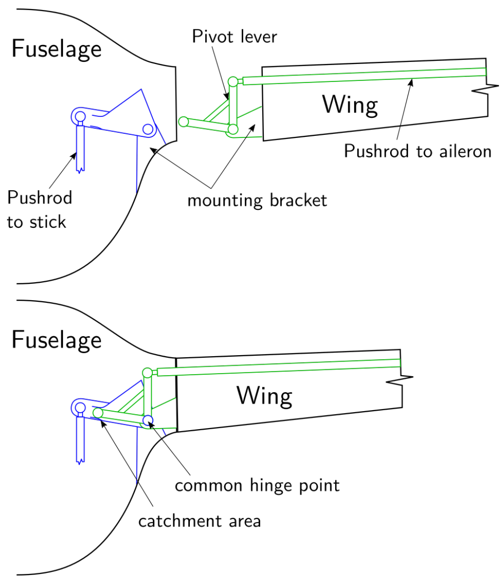
· *6.1. Wing-fuselage connector*

The wing-fuselage connector plays an important role in force transmitting of airplane structure. To meet the requirement of load carrying capacity, material plasticity is usually taken into consideration.

A fixed-wing aircraft usually uses a wing-fuselage connector to transmit forces from the wing to the fuselage. Fatigue damages often occur to the connector due to overstresses. The capacity of bearing flight loads for wing-fuselage connector plays an important roles in the service life of an airplane. Failure analysis of wing-fuselage connector was presented to estimate the first fatigue crack and total damage of connector lug. Experimental data on riveted lap joints for aircraft fuselage was obtained to describe fatigue crack location and life.



(Figure 7)



(Figure 8)

· 6.2. Design of connector

This design is limited because of the layout of the integral structure. There is only partial alteration left to be allowed. The changed connector should keep the original form of transmitting loads. To predict the location of crack around the fastener holes, 3D explicit simulations was used to get edge-of-contact stresses in fretting contact condition.

There are several criteria for the design of wing-fuselage connector. The strengthened structure should satisfy the design requirement of planes. To take into account moving loads, there should be some safe margin in the residual strength. The feasibility of structural processing is fully considered to satisfy the manufacturability requirements. The fatigue damage form go lugs depends on the location of the maximum concentrated stresses and the direction of loads. The stretch/shear damage of lugs and bend damage of bolt are the main damage forms of the wings-fuselage connector.

· 6.3. Experiment simulation

We have four models in this experiment: with sleeve, with gasket, gapped with sleeve and gapped with gasket. We are studying which of them is better in terms of load bearing.

The maximum von Mises stress of the four model is subjected to the same load case that is listed in the next table. The maximum of the model with sleeve is located in the sleeve, and it is 1275 MPa. The location of maximum of the model with fanjet is at the lower joint, and the value is 927.9 MPa. Comparing the two models, it can be found the maximum stresses of both bolts are close. The results of the error of the upper and the lower joints are 55.25% and 23.78%, respectively, whereas the hollow pin and the gasket/sleeve are raised to 5.25 and 4.18 times. In short, the model with gasket is better in load bearing.

By comparing the model with gap to the original model, it can be found that the von Mises stress possesses the upward trend with little increments. Among all these parts, the hollow pin in the model with gasket has the most remarkable change and the difference increases to 9.13 times, which turns into the section of maximum stress.

According to the mechanical property of the material, the lug and sleeve of upper joint in model with sleeve are in the local plasticity phase.

Model	Total	Upper Joint	Lower Joint	Hollow Pin	Screw	Sleeve Gasket
With sleeve	1275	1027	749.6	613.8	354.1	1275
With gasket	927.9	661.5	927.9	98.1	359.3	245.9
Gapped with sleeve	1327	1127	789.9	641.4	374.8	1327
Gapped with gasket	9093.6	706.2	953.1	993.6	369.3	211.9

7. Conclusions

After this report we can see that cracks are a result fatigue, which is simply applied cycling load. Since engineering is exponentially growing today and the fatigue cracks are present in engineering part, I can tell that is a very important issue.

It was possible to learn how to solve this problem by studying how to analyse the crack, predict the fatigue crack growth rate, the latter is the finally of the project. This is a very useful process in many areas such as aviation, bridges, cars and many other industries.

Now I can say that the best way to prevent cracks caused by fatigue is to use surface treatment because it will eliminate the flaws of the material and in this was it is more difficult to obtain the crack.

In order to have a control about our materials, we should predict the fatigue life using equations as Paris law and if the material is already cracked it is possible to strength the material through strengthening methods, but this is not our topic, now this is secondary.

In short, this report has developed skills in the area fracture mechanics, as well as the ability to work more autonomously, work with my supervisor and improve the technical English language.

In general, this report surpassed my expectations. It was possible to use some of theoretical-practical knowledge taught in some courses such as Strength of Materials or Materials.

In turn, the welcoming university provided the student with the opportunity to work in the field that the student was training offering skills that will be fundamental for the future journey, the routine and the continuous need for work brings challenges that allow a different vision.

I am very grateful to Dr. Grzegorz Lesiuk and the Wroclaw University of Science and Technology (as I said previously) because from the point of view of acquiring knowledge this repot was very positive and it allowed the contact with great professionals, as well as research and development, thus making my academic education more complete.

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