CRANFIELD UNIVERSITY

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FATIGUE CRACK INITIATION IN METALLIC COMPOSITES FOR AEROSPACE APPLICATIONS

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
Aerospace Materials

MSc
Academic Year: 2017–2018

Supervisor: Dr Gustavo M. Castelluccio
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Abstract

Metallic composites are widely used in the aerospace industry due to the combination of low density and high resistance that they offer. Potential applications for them are found in the compressor of jet engines, airframes or spacecraft structures. One of the most important issues in these structures is the fatigue resistance of their components, since most of them are subjected to cyclic loads during their lives. Therefore, determining their durability plays a crucial role in terms of safety, cost and time in their maintenance. The time consumed in the crack initiation stage is usually considered to be a considerable amount of the total fatigue life. Hence, the aim of this project is to understand and analyse the main causes of fatigue crack initiation in metallic composites and estimate the number of cycles required to grow a crack until intolerable values. Several cases that represent the most common causes of fatigue crack initiation in these materials are studied to determine the most critical situation. Three different propagation laws are used to predict the small crack growth rate. Moreover, influence of the environment in each case is also considered to determine the most adverse circumstances. Therefore, a crack initiated in the matrix surface is found to be the most detrimental situation.

Keywords

Fatigue crack initiation; metallic composites; plastic strain; small crack propagation; propagation rate; strain-life correlation; fibre debonding; fibre breaking

Contents

List of Figures

List of Tables

List of Abbreviations

MMCs	Metal Matrix Composites
2D	Two Dimensions
LEFM	Linear Elastic Fracture Mechanics
PE	Plastic Strain

Acknowledgements

I am very grateful to my supervisor Dr. Gustavo Castelluccio for his guidance and advice during this project. He has always been very supportive and encouraging to keep learning and improving. I learnt a lot thanks to him.

I would also like to thank Samuel for his help with Abaqus and the time spent trying to solve the issues.

Chapter 1

Introduction

1.1 Scope

During the last years, metallic composites or metal matrix composites (MMCs) have been widely used in the aerospace industry due to the combination of low density, high resistance and improved elevated temperature properties that they offer. The reduction of weight without loosing stiffness and strength is one of the most demanded characteristics in materials used for aircraft structures, since a small weight decrease can lead to a considerably saving of fuel - and therefore money. Potential applications for metallic composites have been found in the compressor of jet engines, airframes and spacecraft strucutures - due to the improved thermal properties of these materials [2].

One of the most important issues in aerospace structures is the fatigue of their components, since most of them are subjected to cyclic loads during their lifetime. Therefore, determining the durability of these components plays a crucial role in terms of safety and saving money and time in their maintenance.

The process of replacing and introducing new materials in the aerospace industry is very challenging and slow. Moreover, the evaluation of these potential materials through experimental tests involve a great investment of money. It is because of this that other alternatives to analyse the materials behaviour, like the finite elements method, are being considered to reduce as much as possible the experimental tests necessary to characterise the material and optimise the time and cost of this process.

1.2 Aim and objectives

The main aim of this project is to study and understand the fatigue crack initiation stage in metallic composites. To do so, three objectives can be established:

- Analyse the main causes of fatigue crack initiation in these materials.
- Determine which one of these causes is more detrimental for the fatigue life of the component.
- Estimate the life of the material based on the results obtained and strain-life correlations found in the literature.

1.3 Structure of the thesis

This thesis is mainly divided into three parts. The first part consists of the review and explanation of the most important concepts (metal matrix composites and fatigue of materials) that must be understood to fully comprehend this project. The second chapter describes the problem of study and its modelling in Abaqus and the correlation used to predict the fatigue life based on the results obtained. Finally, there is the presentation of the results and their discussion, as well as the final conclusions of the project.

Chapter 2

Literature review

2.1 Introduction

This literature review provides the explanation of the most relevant concepts that must be known to understand this project and the results. It consists of the description of metallic composites and the relevant aspects about fatigue life that are addressed in this project.

2.2 Metal matrix composites

Metallic composites are composite materials that consist of a metallic matrix - aluminium, titanium or magnesium - and a reinforcement. This can be either discontinuous - short fibres or particulates - or continuous - long fibres embedded into the matrix. Materials commonly used for discontinuous reinforcement are alumina or silicon carbide (SiC), whereas carbon or ceramic fibres, such as graphite, silica or silicon carbide are usually used for continuous reinforcements [3]. The combination of the metallic matrix and the reinforcement results in a material with high specific strength and stiffness, better wear resistance, low specific coefficient of thermal expansion and good thermal conductivity [3]. In general, continuous fibre reinforced MMCs offer the maximum improvement in mechanical properties, but they are more expensive and difficult to produce, and their properties are generally more anisotropic [4]. The final choice of the materials for the matrix and the fibres and the type of reinforcement depends on the requirements and the desired properties of each component.

2.3 Fatigue of materials

Fatigue is the weakening or failure of a material due to cyclic loads, which means that they oscillate between a maximum and a minimum that are usually constant. Different parameters based on these maximum and minimum values, such as the mean stress (σ_m), the stress range ($\Delta\sigma$) or the loading ratio (R) are used to define each sequence of cyclic loads, and are described as follows:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{2.1}$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \tag{2.2}$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{2.3}$$

These parameters characterise each loading cycle and affect the fatigue life of the material.

2.3.1 Cyclic plasticity

One property that characterises metallic materials used in these composites is their ductility. When a material is subjected to greater loads than its yield strength, a non-reversible deformation appears, called plastic deformation. The relation between the stress (σ) and strain (ε) once plastic deformation has occurred does not follow Hooke's law - valid when the behaviour is purely elastic - and more general stress-strain correlations must be established.

There exist different models that characterise the relation $\varepsilon = f(\sigma)$ under monotonic loads (no cycles), such as the linear, multi-linear or exponential models. However, stress-strain behaviour is more complicated to model when cyclic loads are applied, thus there can be what is known as cyclic hardening, which means that the behaviour is different in every cycle. This effect can be observed in Figure 2.1.

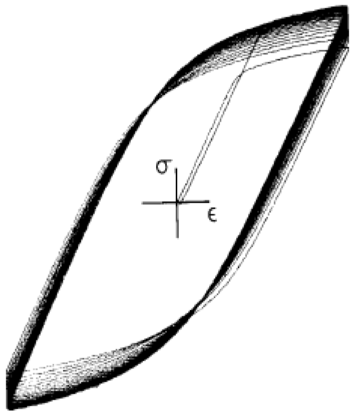

Figure 2.1: Hysteresis loop with cyclic hardening behaviour.

There are two main types of cyclic hardening: kinematic and isotropic (Figure 2.2). Isotropic hardening happens when the yield surface in 2D expands uniformly in all directions when stress increases. In kinematic hardening, the size of the yield surface remains constant but translates in stress space in the direction of yielding [1]. These hardening rules can appear alone or combined in more complex models.

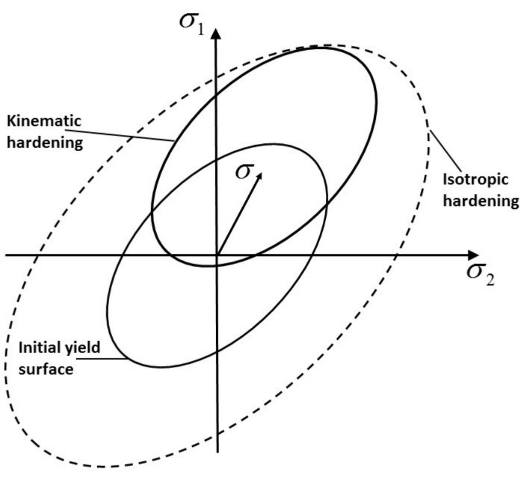

Figure 2.2: Isotropic and kinematic hardening [1].

The accumulation of plastic strain in one component can cause bigger deformations that can lead into failure. Moreover, it can also introduce residual stresses after the unloading that can affect the fatigue resistance of the material during the following loading cycles. Therefore, a good understanding and modelling of the cyclic plastic behaviour of the material is essential to determine its fatigue life and the number of cycles that it can withstand until failure.

2.3.2 Crack initiation in MMCs

Fatigue life can be divided into three stages: crack initiation, crack propagation and final fracture. This project focuses on the crack initiation stage, that can be divided into three more stages: crack incubation, crack nucleation and small crack propagation [5]. Some studies proved that the time consumed in the formation of a crack can be up to 70% of the total fatigue life [5], thus understanding the mechanisms that dominate this stage is essential to make a good estimation of the fatigue life of the component.

Over the last years, experimental studies have been carried out to characterise the fatigue crack initiation behaviour in metallic composites. These have demonstrated that fibre breaking, fibre debonding and matrix cracking are the main causes of crack initiation in these materials [6] [7]. Moreover, they have also determined that crack nucleation is strongly influenced by the local microstructure - localisation of slip systems, specially if the material is markedly anisotropic - and accumulation of plastic strain [5], since the critical stress necessary to nucleate a crack decreases as more plastic strain is accumulated [8]. Based on these states it is possible to determine where is more likely to initiate a crack. However, it is still necessary to establish the small crack growth rate to fully characterise the first stage of the fatigue life. For engineering applications, several studies have considered that crack propagation starts with an initial crack length of 3 μm [9]. They stated that shorter cracks can be considered inclusions, which have a very low growth rate (less than 10^{-9} m/cycle) and therefore they cannot be treated as propagating cracks.

Crack propagation

Fracture mechanics is the field of mechanics that studies the propagation of cracks. According to it, there are three different ways of applying loads that enable a crack to propagate (Figure 2.3):

- Mode I. Opening mode: a tensile stress is applied normal to the plane of the crack. It is known to be the most critical crack propagation mode.
- Mode II. In-plane shear mode: a shear stress parallel to the plane of the crack and normal to the crack front.
- Mode III. Out-of plane shear mode: a shear stress normal along the crack plane and the crack front.

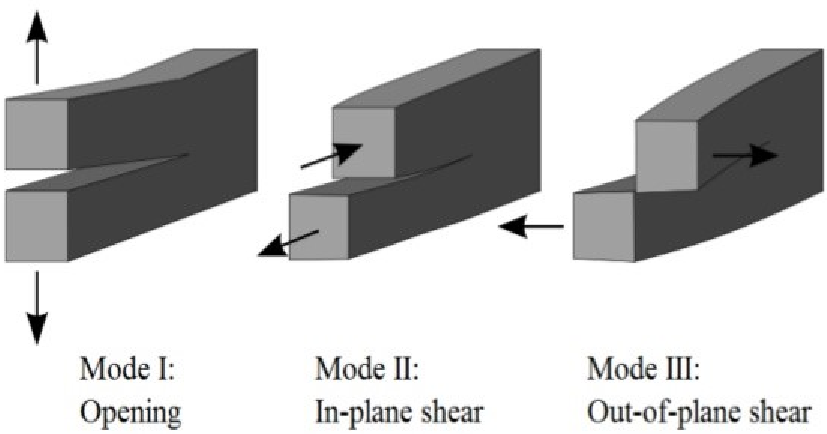

Figure 2.3: Modes of fracture.

Through the years, a lot of work has been done to characterise the fatigue crack propagation and give a solution for this problem. Figure 2.4 represents the crack growth rate per stress cycle as a function of the stress intensity factor (K), which describes the stress intensity at a crack tip and it depends on the applied loads, the geometry of the component and the location and size of the crack.

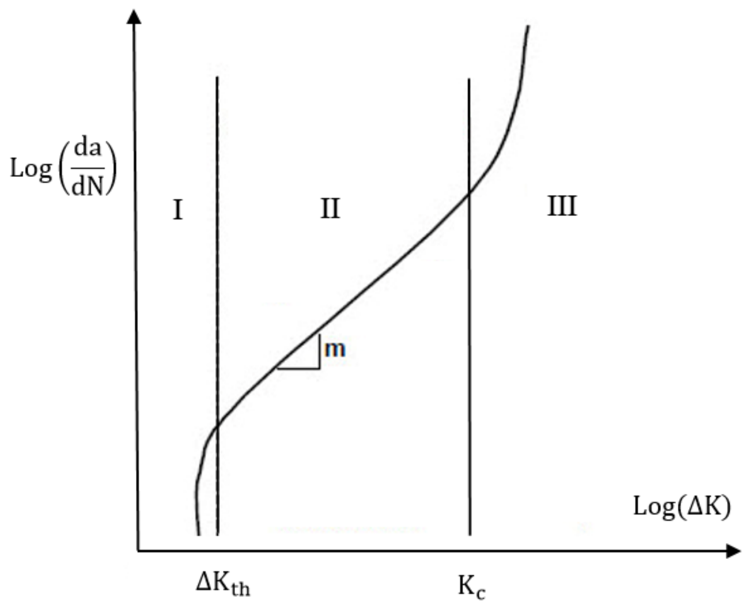

Figure 2.4: Fatigue crack growth rate stages.

It can be seen that the crack growth rate can be separated into three stages depending on its behaviour. The first stage is known as the small crack propagation stage and it is sensitive to microstructural effects, such as grain orientations, that can arrest the crack growth. When the crack length increases - and thus, K - microstructural effects can be neglected and crack growth rate is governed by a power law (stage II). In this stage some considerations must be taken into account. If the material of study is ductile - like common materials used for the matrix of metallic composites - a plastic zone develops ahead the tip of the crack and can affect the propagation rate. In this case, if the plastic zone around the crack tip is considerably small $\left(< \frac{1}{15}\right)$ compared to the crack length it is possible to ignore this plastic behaviour and establish a relation between the crack growth rate per cycle $\left(\frac{da}{dN}\right)$ and the stress intensity factor [10]. This principle determines the basics of the linear elastic fracture mechanics (LEFM) models. These are capable to formulate correlations dependent on the cyclic loading (history, range and ratio), material properties and geometric factors that predict the number of cycles that the crack growth will take. When the stress intensity factor is increased even further and it is near the fracture toughness of the material (K_C), final fracture occurs (stage III). Crack growth rate at this stage is very sensitive to microstructure and load ratio.

The small crack propagation stage of crack initiation phase responds to the first stage mentioned above. In this stage cracks are too small (less than 500-1000 μm [11]) that plasticity and microstructural effects cannot be neglected and LEFM cannot be applied to predict the crack growth rate. Therefore, it is essential to look for other correlation models adequate to characterise the crack propagation in the first stage of fatigue life.

2.3.3 Influence of the environment in fatigue cracks

It is well known that the operating environment can considerably affect some material properties and change the expected behaviour. This is the case of fatigue crack growth, which predictions can change noticeably depending on the operating conditions. This fact refers not only to the atmospheric conditions - sea level, cruise height or outer space in aerospace applications - but also the location of the crack. Under standard atmospheric conditions, external cracks are exposed to corrosive environments and the interaction of the material with the oxygen produces chemical reactions that can affect the material properties [12]. On the other hand, internal cracks are surrounded by the material. This can be considered as a vacuum environment where there is no oxygen to react with the material atoms. Therefore, there are two environments clearly distinguished depending on the location of the crack and their effects on its propagation must be taken into account when predicting fatigue life.

Several studies proved that the effects of the environment are different on each stage of fatigue life. For example, fatigue crack initiation period can be one order of magnitude higher in vacuum than in air [13]. Regarding crack growth rates, it was found out that environmental effects were stronger in the propagation of short cracks rather than in long cracks [9] and that these rates in air can be from 10 to 1000 times greater than in vacuum [14]. This factor depends on the stress intensity range and the material microstructure. Therefore, a reduction in grain size increases the differences between air and vacuum environments [14]. The same effect is observed for small stress intensity ranges [13]. Moreover, these results were obtained from experimental tests, thus the conditions of such tests must also be considered. It was shown that the lower the pressure, the greater the differences between both environments.

Based on everything explained above, it seems undeniable that the quantification of the effects of the environment on the material fatigue life is not an easy task. Several parameters must be considered, so despite that air environment has been proven to be less favourable for fatigue lives, numerical evaluation of this damage cannot be generalised. Therefore, a good knowledge of the microstructure and the operating conditions are basic to determine the influence of the environment on the behaviour of the component.

Chapter 3

Methodology

3.1 Introduction

The methodology describes the work carried out to accomplish the objectives of the project. The study consists in the modelling and analysis of several cases that simulate the different situations that can lead to crack initiation in metallic composites. These are fibre debonding, fibre cracking and matrix cracking due to surface irregularities (Section 2.3.2). The aim is to analyse the behaviour of the component on each case and determine which of these issues is more detrimental for fatigue life.

This chapter explains the modelling of the problem in Abaqus and the strain-life correlations used to predict the crack growth rate in small cracks based on the results obtained.

3.2 Model in Abaqus

This section reports the different cases of study and the steps followed to model each of them. The set up used in every step is described and justified, as well as the simplifications made.

3.2.1 Geometry

The case of study consists in a metallic matrix reinforced with continuous fibres, which are supposed to be periodically arranged. This allows to simplify the problem and work with a reduced model of the real case. This will consist of three continuous fibres embedded into the matrix, as shown in Figure 3.1.

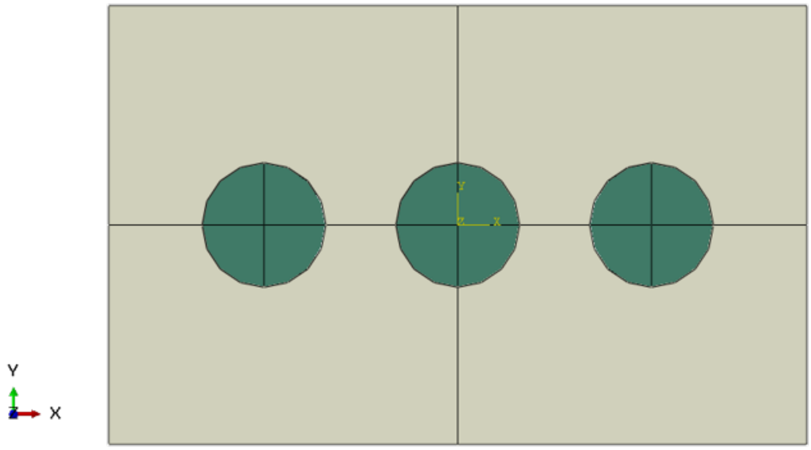

Figure 3.1: Cross section of the model in Abaqus.

Dimensions for the model were found in the literature [6]. Separation between fibres is 80μm and the rest of dimensions are summarised in Table 3.1.

Part	**Cross section [mm]**	**Length [mm]**
Matrix	0.8 x 0.5	2.5
Fibre	d = 0.142	2.5

Table 3.1: Dimensions of the model geometry.

It can be seen that the length of the composite is considerably smaller than that obtained from the literature. The reason for this shortening of the model is to reduce the computational cost, and this decision can be justified by Saint Venant's principle. As it will be explained later, the region of interest of study is located in the middle of the composite and the forces or displacements are applied in the ends of the model. Saint Venant's principle establishes that stresses in a region far enough of the point where the forces or displacements are being applied is the same if both systems are statically equivalent. Based on this the length of the composite can be reduced until the values shown in Table 3.1, since it has been proven that this shortening of the model does not affect the results.

As explained in Section 2.3.2, one of the main origins of crack initiation in metallic composites is matrix cracking, which in some cases can be due to surface irregularities. Therefore, the presence of irregularities in the matrix surface is studied in this project as one of the possible reasons for crack nucleation. To do so, a circular notch is used to simulate a surface irregularity. This notch is introduced along the X direction in the middle plane of the composite, as shown in Figure 3.2. One of the objectives of study in this thesis is to evaluate the importance of these surface irregularities and their influence on the component behaviour. Therefore, dimensions of the notch are different on each case.

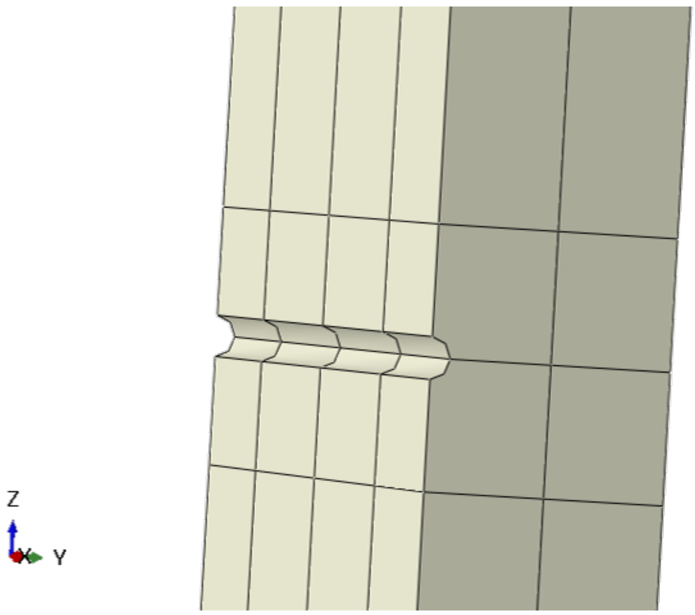

Figure 3.2: Scheme of the notch in the surface.

3.2.2 Materials

The choice of the materials used for this problem is based on the literature (Section 2.2). Material selected for the fibre is silicon carbide (SiC), commonly used for these composites. The behaviour of the fibre is assumed to be purely elastic, which means that there will not be accumulation of plastic strain in it. On the other hand, aluminium alloy AA6061 was chosen for the matrix. As it is explained in Section 2.3, plasticity plays a very important role in the behaviour of metallic materials and especially in the crack initiation period of MMCs. It is because of this that a elastic-plastic behaviour is required for the aluminium matrix. Table 3.2 summarises the material and behaviour chosen for each part, as well as their elastic properties [15] [16].

Part	**Material**	**Behaviour**	**E [GPa]**	**ν [-]**
Matrix	AA6061	Elastic-plastic	69.6	0.33
Fibre	SiC	Elastic	380	0.17

Table 3.2: Material behaviour and properties of each part of the model.

For the cyclic plastic behaviour of the matrix, two different constitutive models are considered. The first one is a combined isotropic and non linear kinematic hardening, which parameters can be found in the literature [16] and are summarised in Table 3.3.

σ_{y0} [MPa]	**Q [MPa]**	**b [-]**	**C [MPa]**	**γ [-]**
209.2	38.9	21.1	3529.3	65.16

Table 3.3: Combined hardening parameters.

The second consitutive model [17] bases the relation between the cyclic stresses and the cyclic strains on a power function, as shown in the following equation:

$$\frac{\Delta\sigma}{2} = K' \left(\frac{\Delta\varepsilon}{2}\right)^{n'} \tag{3.1}$$

where K' is the cyclic strain hardening coefficient and n' is the cyclic strain hardening exponent, and their values are summarised in Table 3.4.

Yield stress [MPa]	K' [MPa]	n' [-]
368	685	0.1

Table 3.4: Cyclic strain hardening parameters.

3.2.3 Loads and boundary conditions

After assigning materials to the fibres and the matrix, the interface between them must be defined and the boundary conditions of the model have to be applied.

Boundary conditions

Regarding the boundary conditions, the composite is supposed to be subjected to cyclic tensile loads in the fibre direction with a loading ratio of $R = -1$. This means an alternation of tension and compression loads of the same magnitude. Moreover, displacements are chosen as the type of loads applied. Magnitude of these displacements is 1% of the total length of the composite, which means a displacement of 0.025 mm. To do so, a 0.5% of the load is applied on each end so that the total displacement applied on the composite is the desired 1%. Figures 3.3 and 3.4 show an example of the cyclic loading history and the direction of the displacements applied on the composite, respectively.

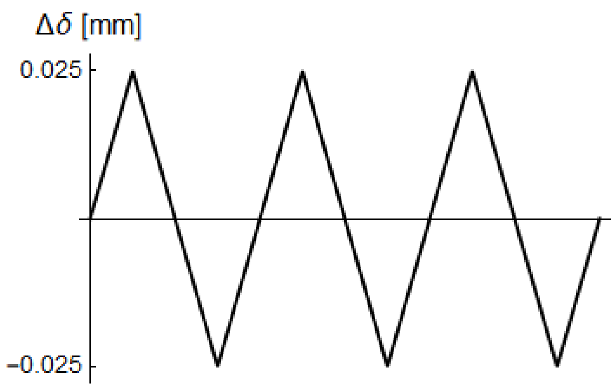

Figure 3.3: Loading cycles applied.

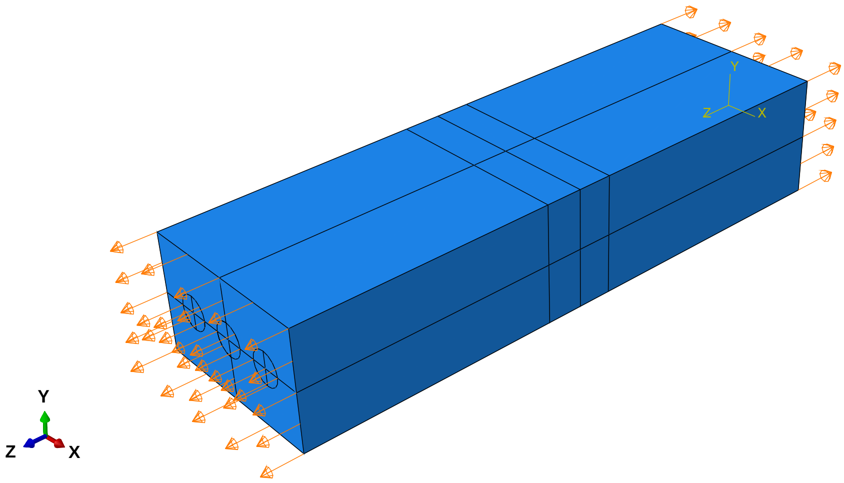

Figure 3.4: Tension displacement applied.

In order to implement the cyclic loads, several steps are defined. These will characterise every loading cycle that is applied on the composite. Each cycle comprises a tension and a compression load, as shown in Figure 3.5. Hence, it can be divided into 4 segments, each one of which is assigned a loading step. The value of the displacement applied on each step is the final value that must be reached at the end of it, and the transition between steps is linear. This means that each step takes one increment of time, and it is defined just by two points: the value of the displacement at the beginning of the step and that value at the end of it.

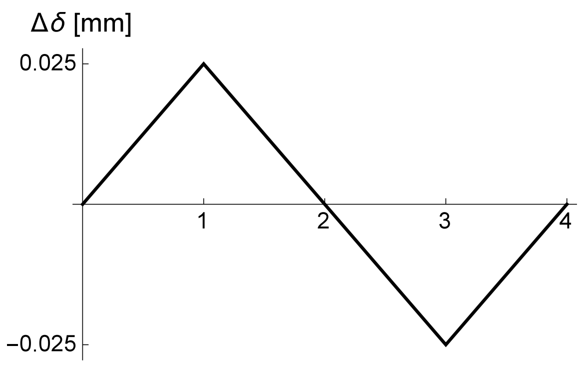

Figure 3.5: History of one loading cycle.

The total number of cycles implemented in each case depends on the results. To determine how many cycles are required, the plastic strain range on each cycle is computed. When variations of this parameter are considerably small, it is said that it has saturated and simulations can be stopped, as shown in Figure 3.6.

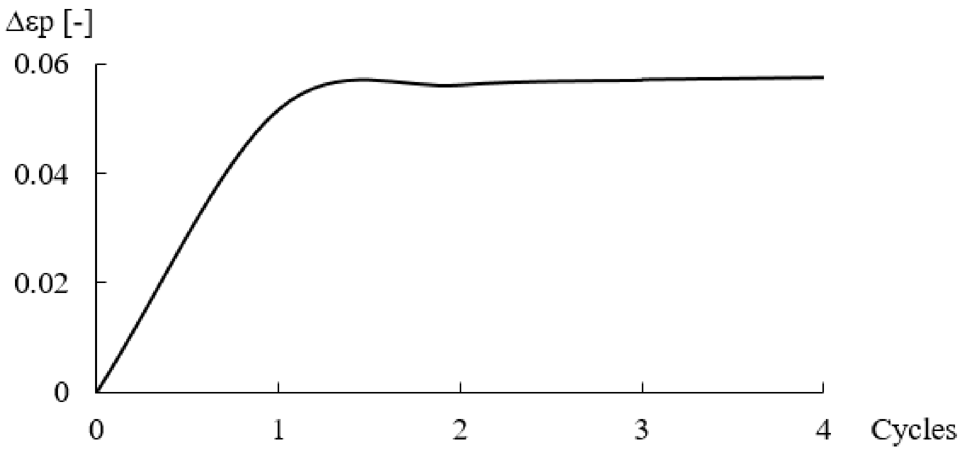

Figure 3.6: Evolution of the plastic strain range on each cycle.

Matrix/fibre interface

As explained before, several cases are modelled and analysed to determine which case is more detrimental for the fatigue life of the component. The difference between each case studied is based on the interaction between the fibres and the matrix (fibre debonding or fibre cracking) and the presence of a notch in the matrix surface. For those cases in which there is no fibre debonding, a tie constraint is applied between the matrix and the fibre. To do so, one surface is defined as the master surface (the contact surface of the matrix in this case) and the other one is the slave (the fibre contact surface). This means that the degrees of freedom of the slave surface are eliminated and coupled to the movement of the master surface. In those cases in which there is supposed to be fibre debonding, no contact is applied between the debonded surfaces.

Up to this point, it is necessary to define the characteristics of the fibre debonding. It has been assumed that the most critical region when a fibre is debonded is located in the transition area between the bonded and debonded surfaces. Hence, half fibre is considered to be fully debonded along the axis (as shown in Figure 3.7) to study the behaviour of the composite in this region. Due to symmetry reasons, the debonded fibre is assumed to be the middle one.

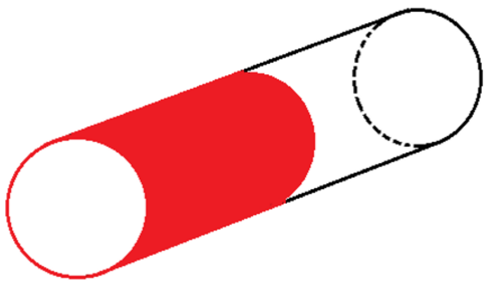

Figure 3.7: Scheme of the fibre debonded surface.

In order to study the behaviour of the composite when a fibre is broken, the middle fibre is supposed to be the broken one. To do so, this fibre is divided in two equal parts and no contact is applied between them. However, this does not affect the matrix/fibre interface, and the contact between these surfaces is the one that corresponds on each case. The combination of the several issues explained (fibre cracking, fibre debonding or surface irregularities) constitutes the different cases of study summarised below.

- **Case 1**. This case considered to be the ideal case, with no debonded or cracked fibres and no surface irregularities.
- **Case 2**. Central fibre debonded.
- **Case 3**. Surface irregularity. Notch radius $r = 0.02$ mm.
- **Case 4**. Central fibre debonded and surface irregularity (notch radius $r = 0.02$ mm).
- **Case 5**. Surface irregularity. Notch radius $r = 0.0071$ mm (10 % of the fibre radius).
- **Case 6**. Central fibre debonded and surface irregularity (notch radius $r = 0.0071$ mm).
- **Case 7**. Central fibre cracked.

3.2.4 Mesh

In order to ease the meshing of the geometry the model was divided in several parts. Hence, it is possible to assign different element types and sizes to each region, according to the expected gradients and the accuracy needed. Like in every finite element study, it is necessary to guarantee that the final results do not depend on the quality of the mesh. Therefore, a mesh independence study must be done.

Mesh independence study

A mesh independence study consists in analysing the results obtained with different meshes. Based on what is explained in Section 2.3.2, the plastic strain has been chosen as the variable of interest in this problem. Therefore, the model is meshed with different element types (hexahedral, wedge and tetrahedral) and number of elements and the value of the plastic strain is analysed. If the results vary considerably between the different meshes, size of elements must be reduced, specially in the regions where gradients are maximum (near the notch of the notched cases and in the transition region between the debonded and bonded fibre surfaces). This process has to be repeated until the results are the same when refining the mesh. Hence, it can be ensured that results are independent of the mesh and can be considered reliable. When the results are the same with two different meshes, the one with the lower computational cost and time is chosen in order to optimise the resources. Figure 3.8 shows an example of the mesh independence study carried out in Case 5.

After this study, the final model is meshed with linear wedge elements of 6 nodes (type C3D6) and quadratic tetrahedral elements of 10 nodes. The regions of interest of study - such as the notch and the fibre/matrix interfaces - are meshed with smaller elements than the rest of the regions. Figure 3.9 shows the mesh near the notch.

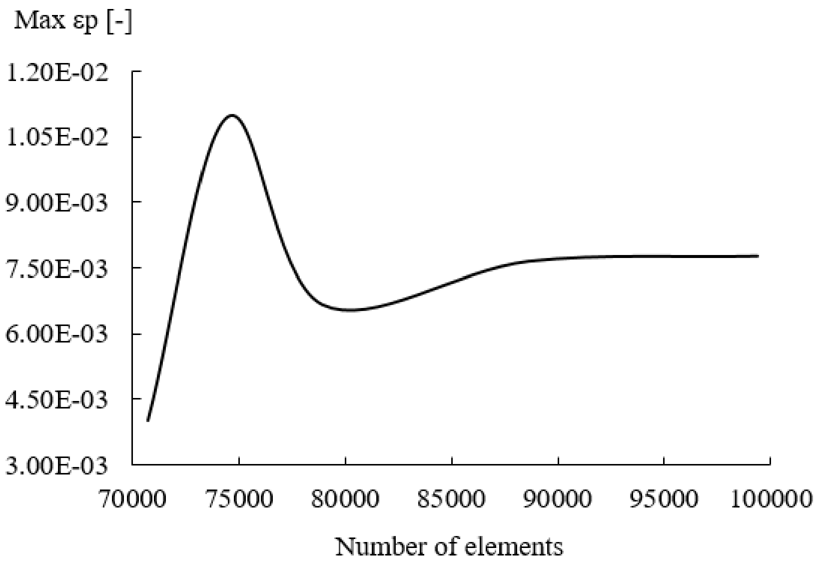

Figure 3.8: Mesh independence study in Case 5.

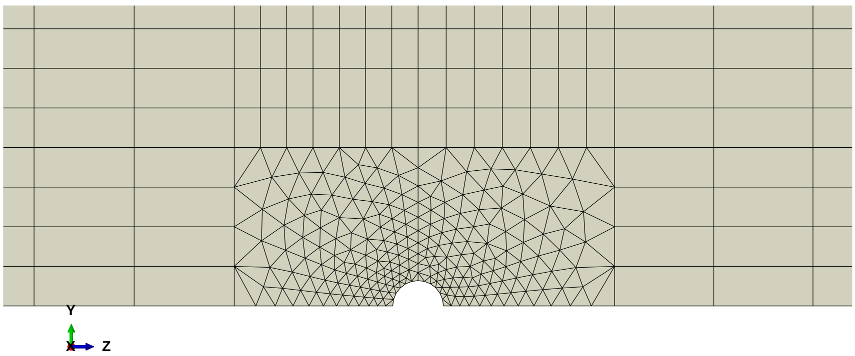

Figure 3.9: Mesh near the notch in Case 3.

3.3 Crack propagation rate

This study is focused on analysing the cases in which is more likely that fatigue cracks initiate and give the approximate number of cycles that the small crack propagation will take. To do so, several $\frac{da}{dN}$ correlations applicable to the material of study must be found.

The first model studied was developed for aluminium alloy 6061-T6 and it follows the following equation [17]:

$$\frac{da}{dN} = \frac{\lambda \pi^2 Y^2}{4} \left(\frac{n'+1}{n'}\right) \left(\frac{K'}{R_p}\right)^3 \left(\frac{\Delta\varepsilon_{pl}}{2}\right)^{3n'+1} a \tag{3.2}$$

where Y is a geometry factor (1.12 for notched specimens, 1 for unnotched ones), K' and n' are the hardening parameters, R_p is the yield stress (Table 3.4) and λ is a cyclic plastic zone correction factor (0.19 [17]).

The second model studied was developed for an aluminium alloy 6082-T6 [18]:

$$\frac{da}{dN} = k_{g0}\Delta\varepsilon_p^d a \tag{3.3}$$

where $k_{g0} = 0.472$ and $d = 0.65$ are constant parameters [18].

A third model was used to study the small crack propagation rate [19]:

$$\frac{da}{dN} = \Delta_{\gamma p}\rho_{max} \tag{3.4}$$

where $\Delta_{\gamma p}$ is the plastic shear strain range ($\Delta_{\gamma p} = 1.5\Delta_{\varepsilon p}$) and ρ_{max} is the maximum plastic zone length. This is related to the crack size (a) and the grain diameter (D):

$$\rho_{max} = \frac{iD}{2} - a \tag{3.5}$$

where $i = 1,3,5...$ represents the number of half grains that the crack has crossed over.

These equations give the small crack propagation rate and thus, the number of cycles that takes a crack to grow from one initial length (a_i) to a final one (a_f). Therefore, these initial and final values must be established. To do so, the initial crack length is the minimum propagating crack length described in the literature (3μm) and the final crack length is assumed to be 2 mm.

3.3.1 Influence of the environment

As explained in Section 2.3.3, the environment plays a very important role in the propagation of small cracks. To establish the difference between the crack growth rate in air and vacuum environments, studies shown in the literature can be used. Since it is not clear the exact difference between these operating conditions, the less favourable case can be considered. Thus, it is assumed that the small crack propagation rate in vacuum is 10 times lower than in air, since it is the situation - according to the literature - in which their differences are minimum.

Chapter 4

Results

4.1 Introduction

The present chapter consists in the summary of the results of the Abaqus models for all the cases studied and the prediction of the small crack propagation rate and fatigue life for the most detrimental ones. To do so, results obtained in the simulations and the correlations found in the literature are used.

4.2 Abaqus models results

As explained in the previous chapter, several cases were studied to analyse the fatigue crack initiation problem in metallic composites and determine which one is more detrimental. Moreover, two different plastic behaviours were implemented for the metallic matrix, so results obtained in both of them can be compared. Since the accumulation of plastic strain has been established as one of the most important parameters in the crack nucleation period, the value of this variable at the end of the loading cycle in each case is compared to determine the most damaging situations. The following graph (Figure 4.1) shows the plastic strain range in the cases described in Section 3.2.3 for both constitutive models implemented (Section 3.2.2) when a displacement of 1% is applied.

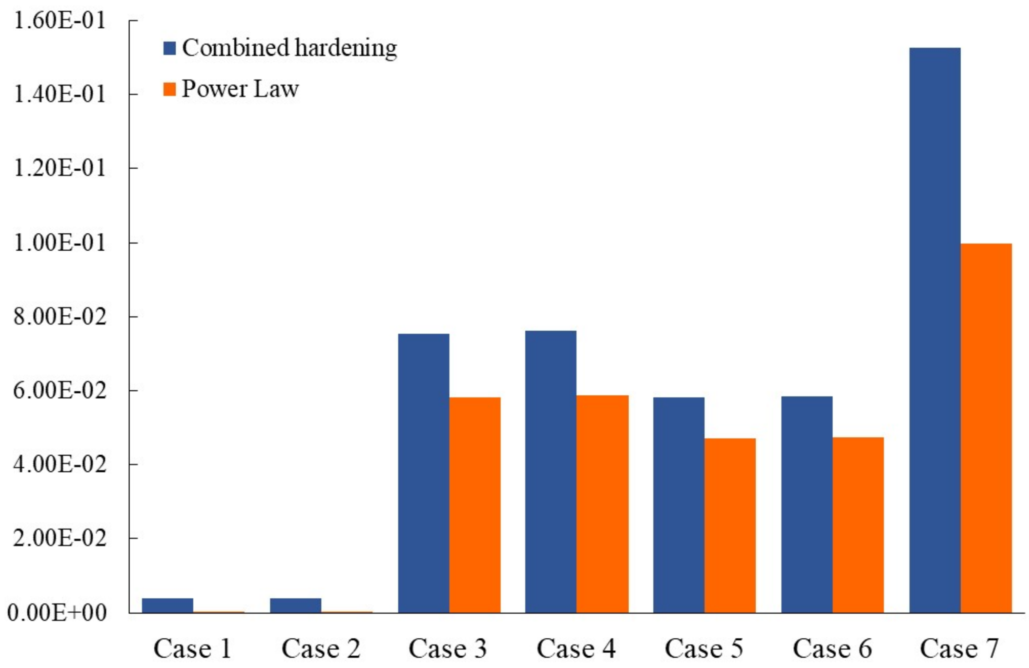

Figure 4.1: Values of plastic strain range for both hardening behaviours subjected to a displacement of 1%.

It can be observed that the cases in which the highest values of plastic strain are accumulated are Case 3, 4 and 7, which correspond to those with the big notch and the one with the broken fibre. Moreover, it can be noticed that a fibre debonding does not represent a considerable worsening (Cases 1 and 2), since the increase in plastic strain due to fibre debonding is insignificant. Based on this, it can be assumed that fibre breaking and the presence of surface irregularities are the worst circumstances for fatigue life, so the next studies are focused on these cases (Cases 3 and 7). It can also be appreciated that the second constitutive model used gives lower values of plastic strain accumulation than the first one, but it estimates higher values of plastic deformation during the loading cycles, as shown in Figure 4.2.

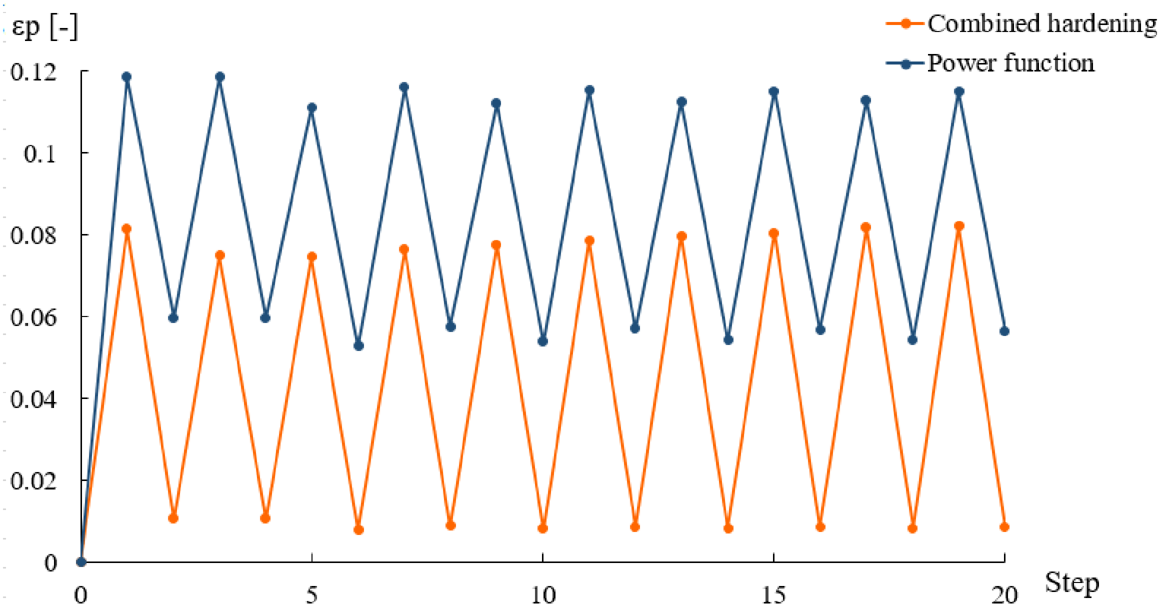

Figure 4.2: Evolution of plastic strain in Case 3 during the loading cycles for both constitutive models.

The following images show the distribution of plastic strain after the loading cycles in the above-mentioned cases. The maximum plastic strain in the notched sample is located in the tip of the notch (Figure 4.3), whereas in Case 7 the strain is accumulated in the matrix near the cracked region of the fibre (Figure 4.4). Therefore, these are the places where it is more likely that a crack initiates, and several considerations must be taken into account to make life predictions.

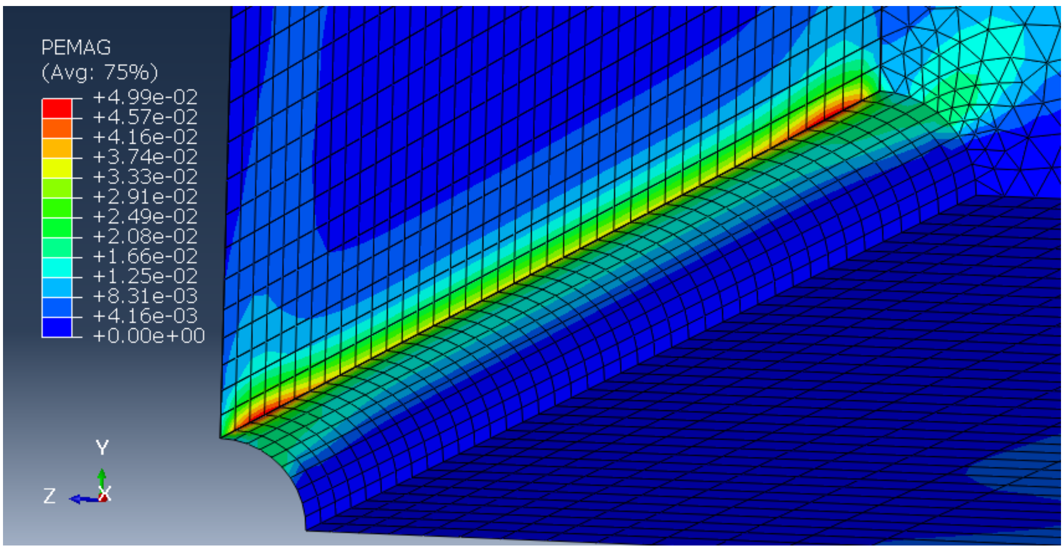

Figure 4.3: Plastic strain distribution in Case 3.

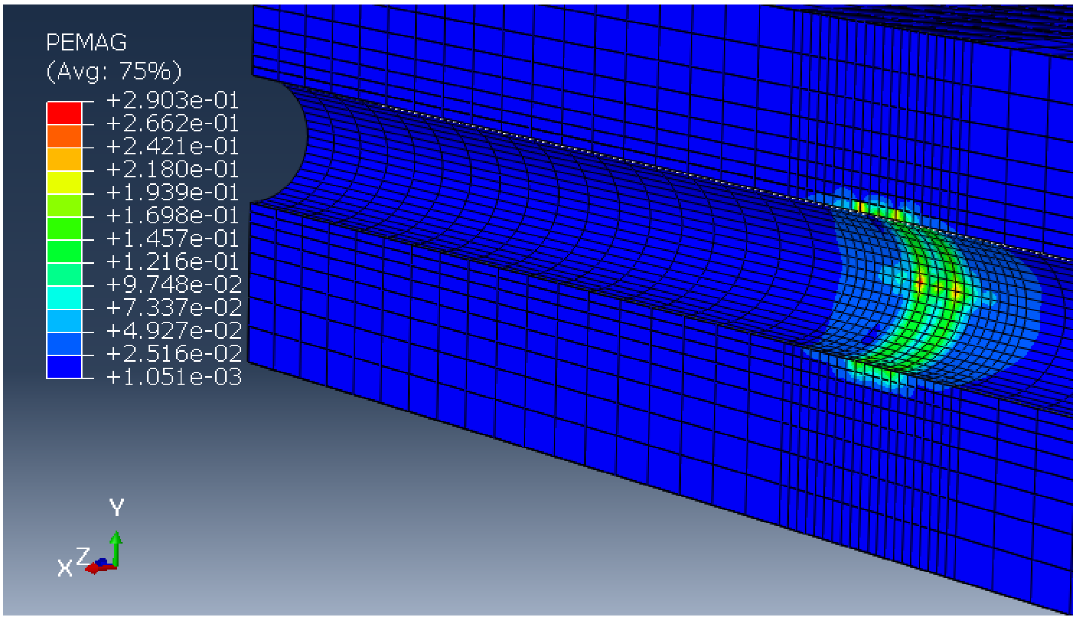

Figure 4.4: Plastic strain distribution in Case 7.

4.3 Small crack propagation life

Using the equations described in Section 3.3 and the plastic strain values summarised above it is possible to determine the number of cycles that a crack needs to grow from 3μm to 2 mm (Section 3.3) in the cases studied. Moreover, differences in predictions between the several $\frac{da}{dN}$ correlations can be analysed, and how can the disparity in the results obtained with each constitutive model (Figure 4.1) affect these predictions.

The following graph (Figure 4.5) shows the results obtained for the three correlations (Section 3.3) in Case 3 for both hardening behaviours studied. It is possible to observe that lower values of plastic strain (Power function) tend to give lower propagation rates. It can also be noticed that the growth rate predicted by the first law studied predicts is much higher than the other ones. Therefore, the number of cycles required to grow a crack from 3μm to 2 mm in the first propagation law is around 10 cycles, whereas the second and the third laws predict that this process would take around 75 cycles. This makes a difference of about one order of magnitude between both tendencies.

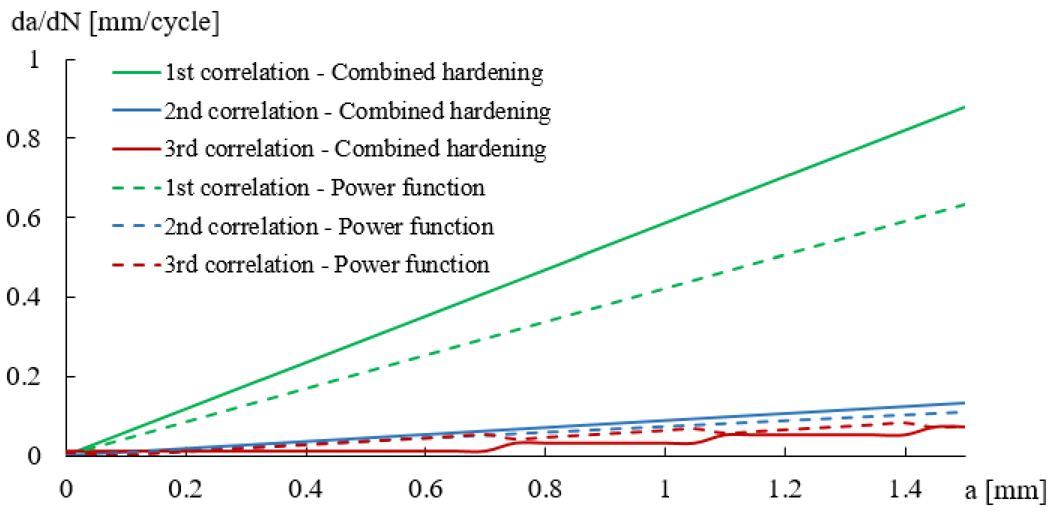

Figure 4.5: Crack propagation prediction in Case 3 for both hardening behaviours and the three correlations.

As explained before, the influence of the environment must be considered to make better predictions of the crack growth rate. According to the results shown in Figure 4.1, the breaking of a fibre (Case 7) involves larger accumulations of plastic strain. Therefore, this situation would be the most detrimental for small fatigue cracks propagation if considering the same environment, as shown in Figure 4.6.

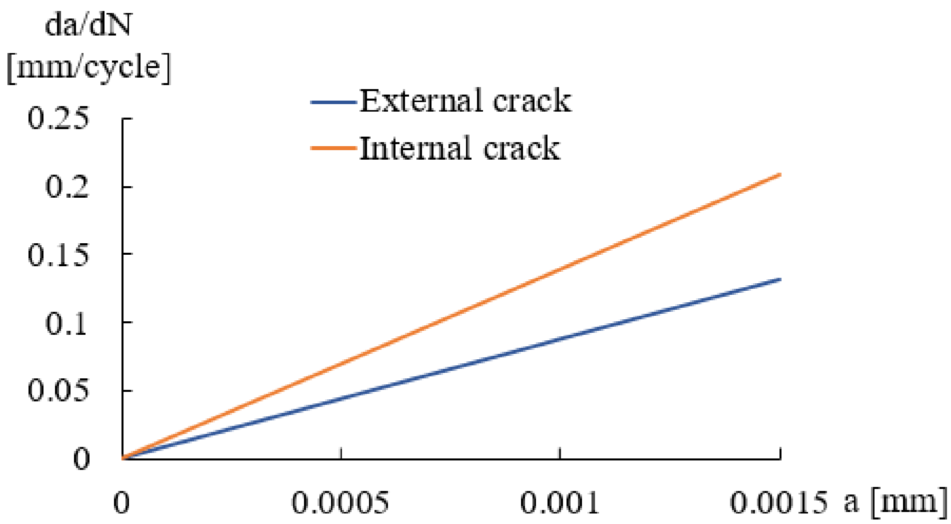

Figure 4.6: Crack propagation prediction for the second correlation in Cases 3 and 7 assuming the same environment.

However, the crack initiated in Case 7 is located inside the matrix, as seen in Figure 4.4. Therefore, it is possible to consider vacuum conditions in this case, which affects the crack propagation rate. Assuming that the crack growth rate in vacuum is 10 times lower than that for air (Section 3.3.1), a new comparison between both cases can be done taken into account the environment of each one, as depicted in Figure 4.7.

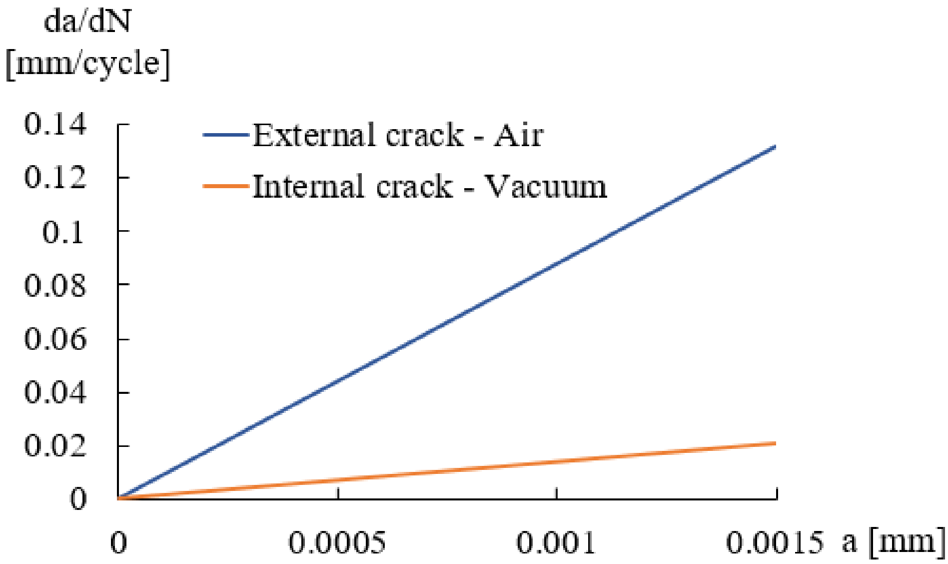

Figure 4.7: Crack propagation prediction for the second correlation in Cases 3 and 7 considering different environments.

It is possible to observe that the propagation rate is much lower in vacuum. Therefore, despite the accumulation of plastic strain in the matrix is higher when a fibre breaks, the propagation of a possible crack nucleated in this environment is much slower than that for a crack initiated in the surface. The number of cycles required to grow an external crack from 3μm to 2 mm using the second correlation is around 70, whereas this number increases until 430 when the crack is internal and vacuum environment is considered (Figure 4.8). For that reason, it seems reasonable to assume that the initiation of cracks in the matrix surface is the most critical situation for the fatigue life of the component, since their propagation is much faster. Table 4.1 summarises results obtained with the three correlations for both constitutive models when considering the environment.

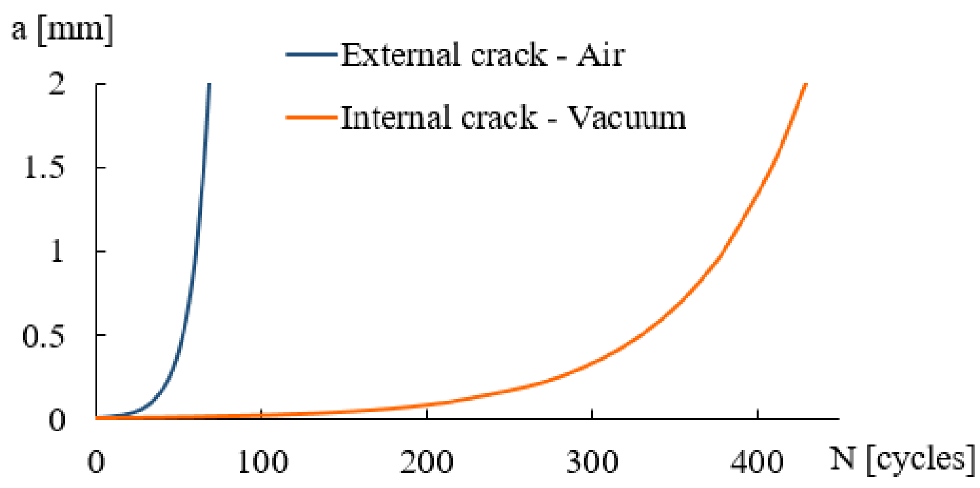

Figure 4.8: Life prediction based on the second correlation for external and internal cracks considering the environment.

Correlation	**First**		**Second**		**Third**	
Model	**First**	**Second**	**First**	**Second**	**First**	**Second**
Case 3	10	14	68	80	69	89
Case 7	50	88	430	567	342	523

Table 4.1: Number of cycles to grow a crack from 3μm to 2 mm in Cases 3 and 7 for the propagation laws with both constitutive models.

Finally, a study of the influence of the loading magnitude was carried out in the case with the notch sample. Following the steps described in the methodology (Section 3.2.3), displacements of 0.5% and 1.5% were applied and results obtained are shown in Figures 4.9 and 4.10. It can be observed that the plastic strain increases with the displacement (Figure 4.9). Introducing these values in the equations described in Section 3.3 it is possible to obtain the crack growth rate and the fatigue life in each case. Hence, the lower the displacement the lower the propagation rate, and thus, the higher the number of cycles until failure. According to the results shown in Figure 4.9 it is possible to notice that the difference decreases when the displacement applied increases, which could mean a saturation of the plastic strain with the loading amplitude.

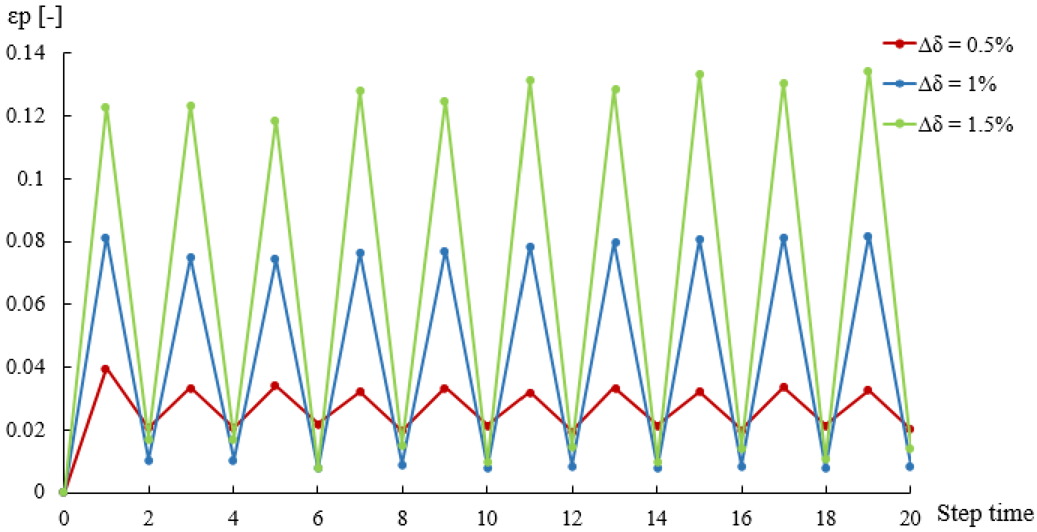

Figure 4.9: Evolution of plastic strain in Case 3 during the loading cycles for the displacements applied.

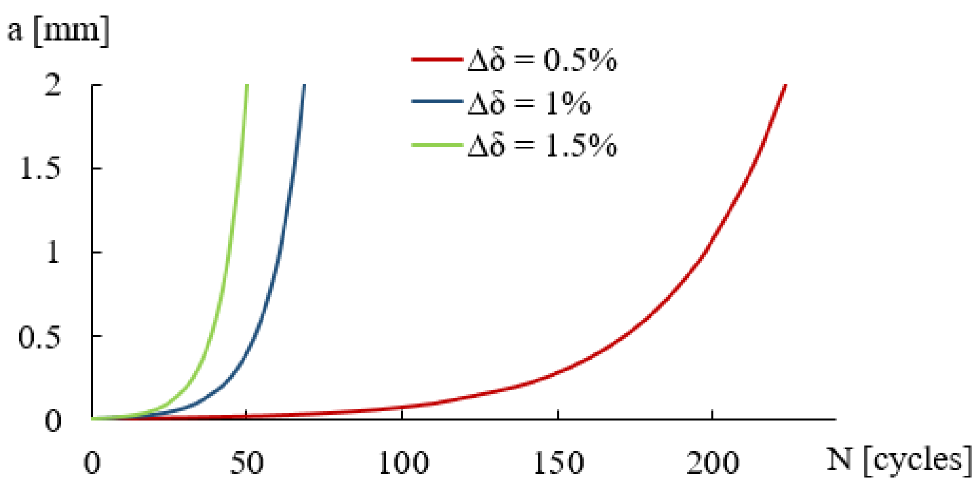

Figure 4.10: Life prediction for different loadings in Case 3 using the second correlation.

Chapter 5

Discussion

The results presented in the previous chapter follow a clear tendency. They show a maximum value in plastic strain for the fibre breaking case, which is located in the matrix around the cracked region. This result seems reasonable, thus when the fibre is broken it cannot withstand properly the efforts transferred by the matrix, and then stresses are concentrated in the matrix, leading to plastic deformations when their values are higher than the material yield strength. On the other hand, maximum plastic deformations in Case 3 are located in the tip of the notch. This result also coincides with what was expected, thus the notch acts as a stress concentrator and amplifies the values of the stresses in that region. Therefore, results obtained in the Abaqus simulations are reasonable and can be accepted.

Although the behaviour of the composite follows the expected trend, some assumptions and simplifications were made to obtain the final results, so this could lead to errors that must be considered and evaluated to determine if these can be accepted. The first thing to look at is the material microstrucutre and its influence in this type of problems. As explained before, microstructure plays a crucial role in the crack initiation period. Since the initial crack length is much smaller than the grain diameter ($a_i = 3\mu m < d = 180\mu m$), not only the size of the grain must be considered, but also the orientation of its crystals respect the applied loads. Dislocation movement is necessary for plastic deformation to occur, which is the variable of study in this project, and this depends on the existence of slip systems. The location and orientation of these slip systems was not taken into account and hence, further work should be carried out to model the material microstructure in Abaqus and get a more realistic behaviour of the component. Regarding crack propagation, it happens when a slip system is activated. Activation of the slip systems depends on their orientation with respect the applied loads, and this can determine the propagation or not of the crack. Therefore, crystals orientation should also be considered when talking about microstructurally small crack propagation. However, this was not taken into consideration in this analysis. Nevertheless, and based on the results obtained, the simplification made to address this problem can be acceptable at this level.

Secondly, it is important to analyse the results obtained with the different plasticity models. Regarding the accuracy of the constitutive models used, it must be mentioned that for lower loads than $\Delta\varepsilon = 0.3\%$ there was no plastic strain predicted in the material. According to the approaches studied, this would mean infinite life, which is questionable. The reason for this behaviour could be the range of study: these plasticity models were developed and studied for higher loads, so their validity out of this range is not guaranteed. Therefore, a constitutive model that covers a wide range of operating conditions should be used to get more accurate results and establish a more general tendency. On the other hand, results of the cases 3 and 7 observed in Figure 4.1 are summarised in Table 5.1.

Case	**$\Delta\varepsilon_p$ [-] Combined hardening**	**$\Delta\varepsilon_p$ [-] Power function**	**Differences**
Case 3	$7.53 \cdot 10^{-2}$	$5.83 \cdot 10^{-2}$	-22.6%
Case 7	$1.53 \cdot 10^{-1}$	$9.99 \cdot 10^{-2}$	-34.6%

Table 5.1: Numerical results for both constitutive models for Case 3 and 7.

The differences between both constitutive models in the most important cases of study are considerable. However, the final objective is to analyse the small crack propagation rate and so, a further study on how can this disparity in the plastic strain values affect the number of cycles to grow a crack must be done. These results are presented in Table 4.1. To properly evaluate the variability in the results, the concept of one cycle must be reviewed. In aerospace, one cycle is commonly translated into one flight for some structures and components. Therefore, a difference of more than 10 cycles - and then, flights - between two predictions can be meaningful depending on the importance of the component. On the other hand, if the system or structure of study is subjected to thousands of cycles during its life, a difference of 100 cycles between two predictions can be considered insignificant. Then, it is not possible to make a clear statement on which differences are acceptable, since a deep understanding on the component operating mode is necessary. However, it is possible to assume that the second constitutive model studied gives lower values of the plastic strain range and therefore, it estimates higher lifetimes.

The disparity in the crack growth rate predictions between the first correlation studied and the other two are considerable. This can be attributed to several reasons. Firstly, the first and the second correlations are based on experimental tests, so the conditions of the tests may vary from one to another and can affect the results. The similarity in the predictions made by the second model and the third one - which is the only one that considers the microstructure - and the fact that they were made independently one from another suggest that this trend is more reliable. Therefore, the differences between these two and the first model could lie in the quality of the experimental work (not enough tests were performed) or in some mistakes when extrapolating the results to establish a law. Further work could be carried out to analyse the reasons of these dissimilarities. Although the trend predicted by the second and the third correlations seems to be more reliable, the first one may be used if a very conservative model is desired. However, this could lead to non-optimum designs and heavier structures, which are far from being what aerospace industry needs.

Finally, it has been proven that when considering the environment the most damaging situation for fatigue life is the initiation of cracks in the matrix surface. The assumption made in the comparison of the crack growth rate in both environments (air and vacuum) is the most conservative found in the literature - crack propagation in vacuum is 10 times lower than in air. Therefore, results obtained could be accepted as a general statement. This seems reasonable, thus external cracks are exposed to a corrosive environment that can react chemically with the material and modify its mechanical properties, accelerating the damage. However, further work should be carried out to quantify the exact differences between both environments and how they affect the crack propagation rate in metallic composites.

Chapter 6

Conclusions

The present project studies the main causes of fatigue crack initiation in metallic composites and determines which one is the most detrimental: fibre debonding, fibre breaking or matrix cracking due to surface irregularities. According to the literature, fatigue crack initiation is driven by the presence of plastic strain. Thus, results show that fibre breaking leads to a higher values of plastic deformation range, and therefore, to a situation in which is more likely to initiate a crack. Nevertheless, the surrounding environment of the propagating crack has proven to be of significant importance in the growth rate of such crack. A vacuum environment such as that inside the matrix can slow down the crack propagation rate and therefore, increase the number of cycles until such crack reaches intolerable values. Despite the high accumulation of plastic deformation when a fibre is broken, this case usually generates internal cracks, whose growth rate is slower than that for an external crack, which is in contact with a corrosive environment. Hence, surface defects could be considered the most damaging situation for the fatigue crack initiation stage life. However, further work must be done to give more accurate predictions and ensure that the design of aerospace components made of metallic composites is optimum.

Appendix A

CURES approval

Dear Natalia

Reference: CURES/5496/2018

Title: Fatigue crack initiation in metallic composites for aerospace applications.

Thank you for your application to the Cranfield University Research Ethics System (CURES).

Your proposed research activity has been confirmed as Level 1 risk in terms of research ethics. You may now proceed with the research activities you have sought approval for.

Please remember that CURES occasionally conducts audits of projects. We may therefore contact you during or following execution of your fieldwork. Guidance on good practice is available on the research ethics intranet pages.

If you have any queries, please contact cures-support@cranfield.ac.uk

We wish you every success with your project.

Regards

CURES Team

Appendix B

Supervisor confirmation for longer report

Natalia,

I confirm that you can go over 8000 words. You work has justified the length.

Regards,

Gustavo M. Castelluccio, PhD

Research Senior Lecturer in Manufacturing

School of Aerospace, Transport and Manufacturing

Cranfield University

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