
Development of a design methodology for fatigue of adhesive joints

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Abstract

Adhesive bonding is a technology in rapid growth for engineering applications and has been replacing conventional fastening methods given the multiple merits offered. Most structural components experience fatigue and mixed mode loading conditions during their service life, and adhesive joints are no exception. Although some studies have been devoted to the fatigue behaviour of adhesive joints, their failure mechanisms are not completely defined. For this reason, the fatigue life prediction of structural adhesive joints is still a concern when applying this technique to real-life applications, where they usually experience a multiaxial stress state. Thus, the development of a life prediction methodology is primordial to avoid catastrophic failure.

One of the aims of the present work is to understand the fatigue behaviour of adhesive joints subjected to different mode mixities. Firstly, an experimental study was conducted. Arcan specimens, bonded by an epoxy adhesive, were tested at different mode mixities. For pure mode I conditions, two epoxy based adhesives and an acrylic adhesive system were considered. In order to obtain the rate of damage evolution for the tested conditions and adhesives, the stiffness degradation was also monitored during the fatigue tests. Based on the experimental fatigue results, Probability-Load-Life (P-L-N) curves were obtained. Using the curves fitted to the experimental results, fatigue envelopes were constructed for different fatigue life regimes. Secondly, this work targets the development of a fatigue model able to predict the life of adhesive joints experiencing different mode mixities. To this end, the joints loaded in pure mode conditions were used as the reference samples, and based on them a master S-N curve for the adhesive was obtained based on a proposed effective stress. By using this curve, and by conducting numerical simulations for the assessment of the proposed effective stress, the fatigue life of the joints subjected to mixed mode was accurately estimated. Different parameters that influence the construction of the master curve were also investigated.

As the last step, the developed master curve was considered to predict the fatigue life of single lap adhesive joints (SLJs). SLJs exhibit higher stress concentration at bonding ends compared with the Arcan specimens. This factor significantly influence the fatigue response of the joints. Accordingly, a critical distance based approach was applied on the previously developed method to take into account the effects of stress concentrations. The method was validated and showed good agreement with

experimental results of SLJs with different overlap lengths, substrate thicknesses and joint width.

Keywords: Adhesive joint; Fatigue; S-N approach; Stiffness degradation; Life prediction; Arcan specimen, Mixed mode, Critical distance.

Resumo

A utilização de ligações adesivas em aplicações de engenharia tem crescido rapidamente e estas têm vindo a substituir métodos clássicos de ligação mecânica devido às múltiplas vantagens que oferecem. A maioria dos componentes estruturais experencia fadiga e solicitações em modo misto em serviço e as juntas adesivas não são um excepção. Apesar de alguns estudos já se terem versado sobre o comportamento à fadiga de juntas adesivas, os seus mecanismos de falha ainda não são completamente conhecidos. Assim sendo, a estimativa da vida à fadiga de juntas adesivas ainda é um entrave à sua aplicação em condições reais, especialmente se estas estiverem sujeitas a um estado de tensão multiaxial. Portanto, o desenvolvimento de ferramentas de previsão da vida à fadiga de juntas estruturais é de primordial importância para evitar falhas catastróficas.

Um dos objetivos do presente trabalho é estudar o comportamento à fadiga de juntas adesivas sujeitas a diferentes modos de solicitação, nomeadamente modos mistos. Primeiramente, um estudo experimental foi conduzido. Juntas Arcan, coladas por um epóxico, foram produzidas e testadas segundo diferentes modos. Um adesivo acrílico foi também considerado para solicitações em modo I. Para obter a evolução do dano, para todas as condições testadas, a degradação da rigidez das juntas foi monitorizada ao longo dos testes à fadiga. Tendo por base os resultados experimentais, curvas de Probabilidade-Força-Vida foram obtidas. Finalmente, usando as curvas ajustadas aos resultados experimentais, foram construídos envelopes de fadiga para diferentes vidas. Secundariamente, este trabalho almeja o desenvolvimento de um modelo capaz de prever a vida à fadiga de juntas adesivas sujeitas a solicitações em diferentes modos. Para tal, as juntas solicitadas em modo I e II, foram usadas como referência para a construção de uma curva mestra do adesivo em estudo, tendo por base a tensão efetiva proposta. Considerando estas curvas e efetuando simulações numéricas para obter a tensão efetiva proposta, a vida das juntas solicitadas em modo misto foi estimada com precisão. Diferentes parâmetros que influenciam a curva mestra foram também analisados.

Finalmente, a curva mestra gerada foi utilizada para prever a vida à fadiga de juntas de sobreposição simples. Este tipo de juntas exibem uma concentração de tensões junto das extremidades bastante superior às das juntas Arcan. Este fator influencia significativamente a vida à fadiga destas juntas. Assim sendo, um método baseado na teoria das distâncias críticas foi aplicado ao modelo previamente

desenvolvido, de modo a ter em conta o efeito da concentração de tensões. Este método foi validado e mostrou uma boa correlação com os resultados experimentais de juntas de sobreposição simples com diferentes comprimentos de sobreposição, espessuras do substrato e larguras.

Keywords: Juntas adesivas, Fadiga, Abordagem S-N, Degradação da rigidez, Estimativa da vida à fadiga, Juntas Arcan, Modo misto, Distância crítica.

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Contents

Abstract	i
Resumo	iii
Acknowledgements	v
1 Introduction	1
1.1 Background and motivation	1
1.2 Problem definition	3
1.3 Objectives	3
1.4 Research methodology	3
1.5 Thesis outline	4
2 Literature review	7
2.1 Fatigue of structural adhesive joints	7
2.1.1 Factors influencing the fatigue behaviour of adhesive joints . .	9
2.1.2 Fatigue life prediction approaches	12
3 Experimental procedure	15
3.1 Materials	15
3.1.1 Adhesive A	15
3.1.2 Adhesive B	15
3.1.3 Adhesive C	16
3.2 Testing methods	16
3.2.1 Bulk specimen tests	16
3.2.2 Arcan specimen tests	17
3.2.3 Single lap joints tests	18
4 Numerical modelling	21
5 Conclusions and future work	23
5.1 Conclusions	23
5.2 Future work	24

CONTENTS

References	25
A Paper 1	29
B Paper 2	55
C Paper 3	85

List of Figures

1.1	Research methodology overview.	4
2.1	LCF vs HCF.	7
2.2	Crack initiation vs propagation phases.	8
2.3	Amplitude vs Mean stress/load diagrams.	10
2.4	Effect of frequency on the fatigue behaviour of adhesive joints.	11
2.5	Schematic fatigue crack growth propagation curve.	12
3.1	Bulk specimen's geometry (dimensions in mm)	17
3.2	Arcan apparatus.	17
3.3	Arcan specimen (only half is represented) (dimensions in mm).	18
3.4	Studied SLJ configurations (dimensions in mm).	19

List of Tables

3.1	General properties of the tested adhesives, given by the supplier.	16
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Introduction

1.1 Background and motivation

Adhesive bonding is a joining technique through which two materials are permanently connected by using an adhesive. An adhesive is a substance capable of joining two parts and make them resist separation, allowing the transferring of mechanical forces from one member to another [1; 2]. Many are the examples of the application of adhesive bonding in remote times. These range from before 4000BC where broken pottery was found to be glued by resins from trees to the Egyptians that used different bonding for many applications such as fastening wood or gluing gold leaf to plaster and to early hunters that bonded feathers to their arrows with beeswax to improve their aim [3; 4]. However, it was only in the last century that this joining method saw its breakthrough with the invention of synthetic polymers. Before this, adhesives would come from natural sources such as plants, animals skin and bones or minerals [4].

Nowadays this type of joining technique is a key technology in many sectors that range from shoe manufacturing, civil engineering and medical applications up to very demanding industries such as the automotive and aerospace. The level of importance that adhesives reached in the last years is directly linked to their advantages. They present an interesting design flexibility as they allow the introduction of new materials and design concepts mainly due to their ability of bonding dissimilar materials. They also provide a more uniform stress distribution which results in a higher stiffness and load transmission, representing a big improvement when compared to conventional mechanical fasteners as bolts and rivets. This leads to a higher fatigue resistance and allows an enhanced strength-to-weight ratio. It is also a cost effective bonding technique with the possibility of being automated. Despite the advantages, there are some adversities that still need improvement. These are its difficult quality control, the need for moulds during the curing period as the bonding process is not instantaneous, the need of surface preparation to guarantee good adhesion and its sensitivity to extreme environmental conditions [1; 5].

Another thing that raises barriers to a wider application of structural adhesive joints is its fatigue resistance. Despite presenting higher fatigue strength when compared to other fastening methods, the inherent complexity of the fatigue phenomenon makes it difficult to predict the life of adhesive joints. This usually leads to a propensity of adopting over-conservative design approaches which culminates in less optimised structures. Moreover, due to the lack of trust when using adhesive joints for real-life applications, this technology is often combined with conventional mechanical fasteners (hybrid joints), which decreases the efficiency of the structure in terms of weight and costs. Given that fatigue is the root cause of most failures of engineering materials, and that these failures may occur at a small percentage of the static strength, it is of prime importance to investigate the failure mechanisms of adhesive joints and accordingly develop simple and accurate fatigue lifetime prediction models [6; 7].

In industrial applications, mainly on the conceptual design phase, accurate, reliable, fast and easy approaches are a priority. For this reason, one of the available approaches to deal with fatigue that best suits this pre-requisites is the total-life method also known as stress-life approach. In this approach a load-related variable is plotted against the number of cycles to failure, to obtain the so called S-N curves. This approach has been widely used for its accuracy and simplicity. However, there are some limitations, being the most recognisable the difficulty to apply the experimental results to different testing conditions. Obtaining a S-N curve for every testing condition, for example for different mode mixities or geometries, is not effective as it is time consuming and very costly. Accordingly, the development of fatigue models that help overcome this issue maintaining the simplicity and providing accuracy is mandatory [1].

Fatigue depends on many factors, and one of them is the loading conditions, where the mode mixity can be highlighted as a key aspect on the fatigue strength of adhesive joints. Most joints often experience complex mode mixities. A clear example of that, is the case of the most common adhesive joints: the single lap joints. Despite its very simple geometry, reason why it is so appealing both for industrial applications and research activities, during service this type of joint experiences a very complex mode mixity. That is one of the reasons why a study on the effect of mode mixity on the fatigue behaviour of adhesive joints is so relevant. Another aspect that jeopardises bonded structures subjected to fatigue loading conditions is the existence of stress concentrations. Thus, this should also be considered when developing fatigue life prediction models.

Although many researchers have dealt with the fatigue failure of adhesive joints, the fatigue failure mechanisms of adhesive materials are not fully understood yet. Accordingly, a design methodology for fatigue life estimation of adhesive joints, considering the influence of different mode mixities and stress concentrations, is still of a prime importance to avoid catastrophic failures.

1.2 Problem definition

With an increasing need for optimised structures in high performance applications, there is the urgency of better understanding the mechanisms of long-term cyclic behaviour of adhesive joints and accordingly develop life prediction methodologies. This would increase the level of trust on adhesive joints in applications subjected to fatigue. After a literature review it is understood that a study on the effect of mode mixity, ranging from pure mode I to pure mode II, on the fatigue behaviour of adhesive joints is not found. Also, despite all the efforts done through the years, a universally accepted fatigue design methodology is not available for adhesive joints. For this reason, predicting the fatigue life of bonded joints still remains a very challenging issue.

1.3 Objectives

In this context, this work has three main objectives. The first one is to experimentally investigate the fatigue behaviour of adhesive joints subjected to different mode mixities using Arcan joints. The second objective is to develop a simple and efficient fatigue lifetime prediction method based on the stress-life approach able to deal with the effect of mode mixity on adhesive joints. Finally, the third objective is to extend the previous model predict the fatigue life of SLJs with different geometries and by taking into account the effect of stress concentrations at bonding ends.

1.4 Research methodology

The previously mentioned aims of this thesis were accomplished by the performance of several steps. Initially, a careful literature review was performed, focusing on the characteristics of the fatigue life of adhesive joints, on the many factors that influence it and on several approaches to deal with this phenomenon. Then, experimental tests were conducted. At the first step,, the adhesives mechanical properties were characterised through static testing. Afterwards, fatigue testes were performed to generate the S-N curves for two types of joints: Arcan joints and single lap joints. For the former, different adhesive systems and different mode mixities were considered. The damage evolution, based on the stiffness degradation was also monitored for Arcan joints. A numerical simulation using a Finite Element Analysis (FEA) was executed to asses the stress parameters that govern the failure of adhesively bonded joints.

Finally, by taking in account the results obtained experimentally, and the stress parameters obtained through a FEA, a fatigue life prediction model was proposed. It was then further developed to be able to deal with the effect of stress concentration using a critical distance approach. An overview of the research methodology adopted

throughout the elaboration of this dissertation is presented in Figure 1.1.

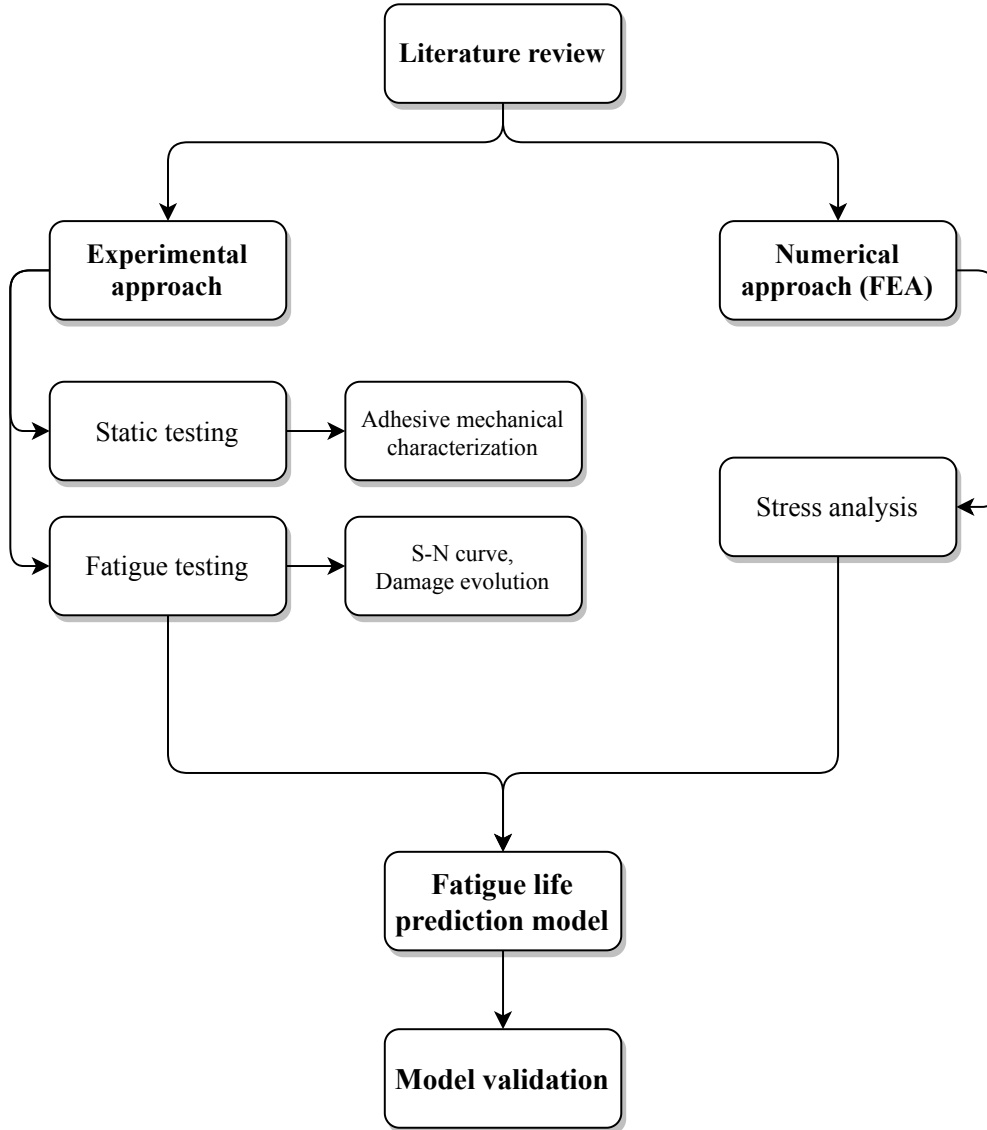


Figure 1.1: Research methodology overview.

1.5 Thesis outline

This thesis consist of a literature review, a summary and of three appended papers.

Paper 1- F. Castro Sousa, A. Akhavan-Safar, R. Goyal, L.F.M da Silva. **The influence of mode mixity and adhesive system on the fatigue life of adhesive joints** - Accepted for publication in *Fatigue & Fracture of Engineering Materials & Structures*.

Abstract of paper 1: In real applications, adhesive joints are commonly subjected to fatigue and mixed mode loading conditions. The aim of the current work is to experimentally analyse the influence of mode mixity on the fatigue strength of joints with an epoxy based adhesive. Different adhesive systems (acrylic and epoxies) were considered for pure mode I fatigue loading conditions. To achieve this, Arcan joints with an epoxy adhesive were manufactured and tested at different mode mixities. Based on stiffness degradation, monitored during the tests, damage evolution was calculated for different loading conditions and for all the tested adhesives. Finally, fatigue envelopes were constructed for different fatigue life regimes. Results show that a shear loading component reduces both the static strength and fatigue life of the joints. A small reduction rate of the stiffness was found throughout the most part of the life until a sudden drop was observed. indicating a smooth damage evolution.

Paper 2- F. Castro Sousa, A. Akhavan-Safar, R. Goyal, L.F.M da Silva. **Fatigue life estimation of adhesive joints at different mode mixities** - submitted to *The Journal of Adhesion*.

Abstract of paper 2: Fatigue life prediction of adhesive joints is a concern when using this bonding technique in structural components where the joints are subjected to multiaxial stress states. Thus, the development of a fatigue failure criterion that accounts for the effect of mode mixity is crucial. The main aim of the present study is to develop a fatigue model to be able to predict the fatigue life of an epoxy-based adhesive loaded at different mode mixities. For this purpose, Arcan joints were manufactured and tested in pure modes (I and II), and mixed mode loading conditions. Using the obtained experimental data for pure mode loading conditions, a master S-N curve was constructed based on a proposed effective stress. According to this curve and by considering the numerical simulations, the fatigue lives of the joints under mixed mode conditions were estimated. Two different relations (Basquin and Stromeier) were considered in this study. The influence of the number of load levels considered for the master curve was also analysed. It was found that more experimental results for the reference samples do not necessarily lead to a better estimation. Results show a good agreement between the experimental data and the predicted fatigue lives based on the proposed model.

Paper 3- F. Castro Sousa, A. Akhavan-Safar, R. Goyal, L.F.M da Silva. **Fatigue life estimation of single lap adhesive joints using a critical distance approach** - submitted to *Mechanics of Materials*.

Abstract of paper 3: The fatigue life prediction of adhesive joints still remains as one of the most challenging issues. Given the increasing need for safer and more efficient industrial bonded structures, the development of simple fatigue design methodologies is of primordial relevance. In this work, a model based on the S-N approach for the estimation of the fatigue life of single lap adhesive joints with

different geometries is proposed. Steel substrates and an epoxy adhesive were considered to manufacture joints with different overlap lengths, adherend thicknesses and widths. The joints were tested under static and fatigue loading conditions. A critical distance approach based on a recently developed effective stress is proposed to deal with the effect of stress concentrations exhibited by this type of joints. The results showed a good correlation between the experimental and the estimated fatigue lives.

Literature review

2.1 Fatigue of structural adhesive joints

As discussed previously, fatigue is a very complex phenomenon that can have a nefarious impact on adhesive joints and jeopardise bonded structures. For this reason, its characterisation is very important. Fatigue life can be divided into two parts: low cycle fatigue (LCF) and high cycle fatigue (HCF). In the first, the joints are subjected to loads close to their static strength and because of that commonly experience plastic deformations. Regarding the HCF, the load levels applied are lower and the deformations are primarily elastic. A rigid boundary is not defined between the two regions. However, it is generally assumed that the separation point occurs at 10^4 cycles [8]. A schematic representation of this classification is given in Figure 2.1.

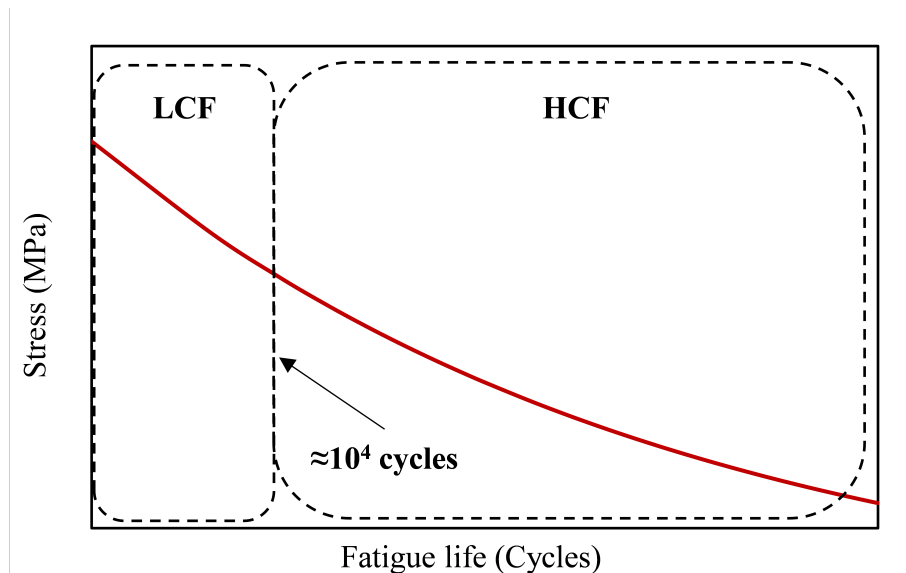


Figure 2.1: LCF vs HCF.

The total number of cycles until failure consists of two different phases: the num-

ber of cycles spent in the crack initiation/nucleation and the number of cycles spent in the crack propagation until final failure. The definition of which phase, crack nucleation or crack propagation, is dominant on the fatigue life of adhesive joints has been studied by several authors. Zhang et al. [9] proposed a backface-strain technique based on the principle that when a crack develops, a deformation relaxation happens locally in the substrate. By measuring this decrease in the deformation using strain gauges in the substrate it is possible to identify the nucleation of a crack. They have applied this concept to steel single lap joints bonded by an epoxy adhesive and concluded that the initiation phase is dominant in the HCF regime while the crack propagation phase is more pronounced in the LCF region as shown schematically in Figure 2.2. Similar conclusions were found by different authors, using aluminium-glass fiber reinforced polymer single lap joints under four-point bending bonded by an epoxy adhesive [10] and using aluminium single lap joints bonded by an epoxy film [11]. The existence of these two phases is directly linked to an inherent characteristic of fatigue which is variability. The fact that the crack initiation phase is dominant for higher cycle fatigue is one of the reasons why a big dispersion of the experimental results is found in this region. It is widely recognised that the crack initiation phase is very sensitive to defects, such as voids. For the region where the crack propagation prevails, less scatter is found since this mostly depends on the crack growth resistance of the material, being less susceptible to defects [12].

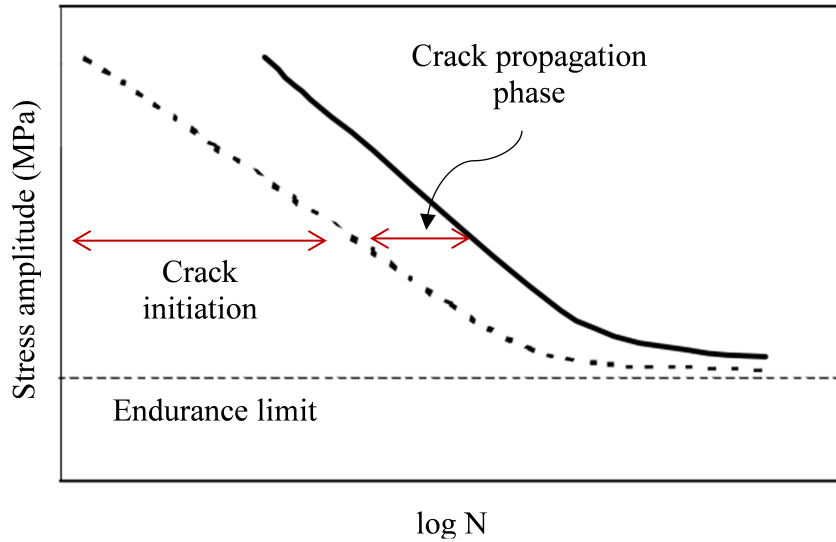


Figure 2.2: Crack initiation vs propagation phases (adopted from [13]).

Another common characteristic in fatigue for some materials such as steel, is the existence of an endurance limit, also known as fatigue limit. This represents a value of stress below which the component has an infinite life. However, adhesively bonded joints do not exhibit this characteristic. It is often theoretically defined for research purposes at a certain number of cycles. Different values have been defined

by different authors, ranging from one million cycles [7] to ten million cycles [14].

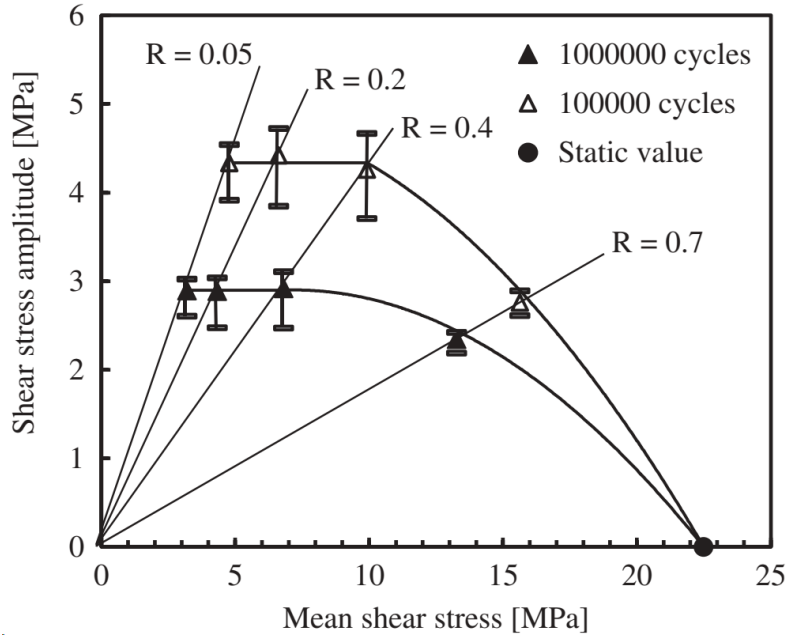
2.1.1 Factors influencing the fatigue behaviour of adhesive joints

Many are the factors that influence the fatigue life of adhesive joints. Some of them are transversal to the fatigue of all materials such as the effect of the amplitude, the mean and the minimum stresses. However, others are that are due to the fact that adhesive joints are a multimaterial component, and therefore the interaction between the different materials is also very important. These are the effect of substrate material, surface preparation and joint geometry. Environmental factors, such as the temperature and moisture also affect the fatigue behaviour of adhesive joints due to its polymeric nature. Since adhesives present a viscoelastic behaviour, the loading frequency affects greatly the fatigue behaviour of adhesive joints. Obviously, the adhesive's properties and its curing conditions are also factors that should be taken in account when selecting adhesives for fatigue applications.

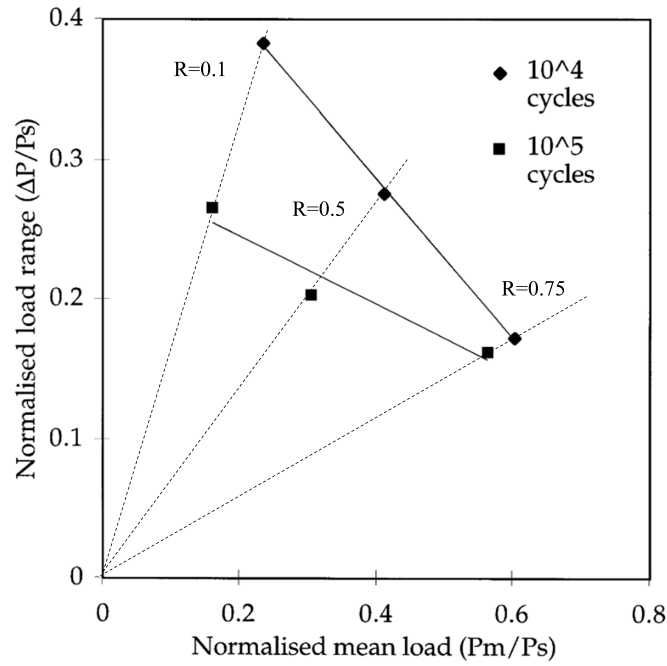
Some studies have been conducted to evaluate the effect of some of these parameters on the fatigue behaviour of adhesive joints. Pereira et al. [15] studied the effect of the mean stress of a steel single lap joint bonded by an epoxy adhesive. They considered four different stress ratios (R), 0.05, 0.2, 0.4 and 0.7 at a constant stress amplitude. Results showed that for a fixed maximum stress, fatigue life increases as R also increases. It was also found that the fatigue life had a small dependence on the stress amplitude, indicating that the only the maximum stress is important. This was only not valid for R values higher than 0.7, where for the same life, the shear stress amplitude was much lower, has shown in Figure 2.3a. However, slightly different results were found by different authors. Crocombe and Richardson [16] also studied a single lap joint bonded with an epoxy adhesive and found that the mean load has a significant effect on the fatigue life. They also found that a Goodman type curve represented accurately the experimentally obtained results, has demonstrated on Figure 2.3b. This difference may be justified by the fact that the selected R values are different for each case. In Figure 2.3a, it is possible to see that for R values higher than 0.4 a significant decrease in the fatigue strength is found. Since two of the three R values in Figure 2.3b are out of the almost constant region found in Figure 2.3a, it is not possible to conclude if between $R = 0.1$ and $R = 0.5$ the results are well represented by the Goodman line or not.

Azari et al. [17] studied the effect of substrate modulus on the fatigue fracture behaviour of adhesive joints under mode I loading conditions using a double cantilever beam (DCB) specimen. It was found that for a specific value of energy release rate, by changing from an aluminium substrate to a steel substrate, the threshold energy release rate decreased by 8% and the crack growth rate increased. However, using a steel substrate did not make the joint weaker, since a higher load needs to be applied to reach the same energy release rate when compared to the aluminium

substrate.



(a) Shear stress amplitude vs Mean shear stress [15].



(b) Goodman type curve (adopted from [16]).

Figure 2.3: Amplitude vs Mean stress/load diagrams.

Barros et al. [18] studied the effect of mechanical surface treatment on the fatigue behaviour of adhesive joints. Three types of surface treatments were considered: bristle blasting, grit blasting and sand blasting. The static tests were done using thick adherend shear test (TAST) specimens while the fatigue test were conducted in

end-notched flexure (ENF) specimens, both made of steel and bonded by an epoxy adhesive. The grit blasting was the surface treatment with the highest roughness. The sand blasting provided a roughness similar to the one found with bristle blasting. However, the latter had a more uneven surface (bigger difference between peaks and valleys). Although the surface treatment did not impact significantly the static results, the fatigue results varied significantly being the fatigue life around 10 times higher for sand blasted surfaces when compared to bristle blasting for similar load levels.

In recent years, Costa et al. [19] published a review paper on the effect of environmental conditions on the fatigue behaviour of adhesive joints. This work focused primarily on temperature, moisture and hygrothermal (a combination of temperature and moisture) effects. The effect of temperature was the one that presented more clear results, showing that both the fatigue strength and the threshold energy release rate decreased with an increase in temperature. Regarding the other effects no clear trend was observed, which is in part related to the fact that few studies are available. Therefore, more studies on these fields are required to fully understand the effect of environmental conditions of the long-term cyclic behaviour of adhesive joints.

Reis et al. [9] studied the influence of frequency on the fatigue life of a steel single lap joint bonded by an epoxy adhesive. Three frequencies were taken into account: 2 Hz, 10 Hz and 40 Hz. For lower lives, the influence of frequency was almost negligible while for higher cycle fatigue a significant difference was found. By moving from 2 Hz to 10 Hz the fatigue strength increased and at 40 Hz the fatigue life decreased being in between the previous two, as shown in Figure 2.4a. The lower strength for 2Hz was attributed to creep effects while for 40 Hz this decrease is due to the fact that the temperature rises significantly, as observed in Figure 2.4b, causing a reduction of the mechanical properties.

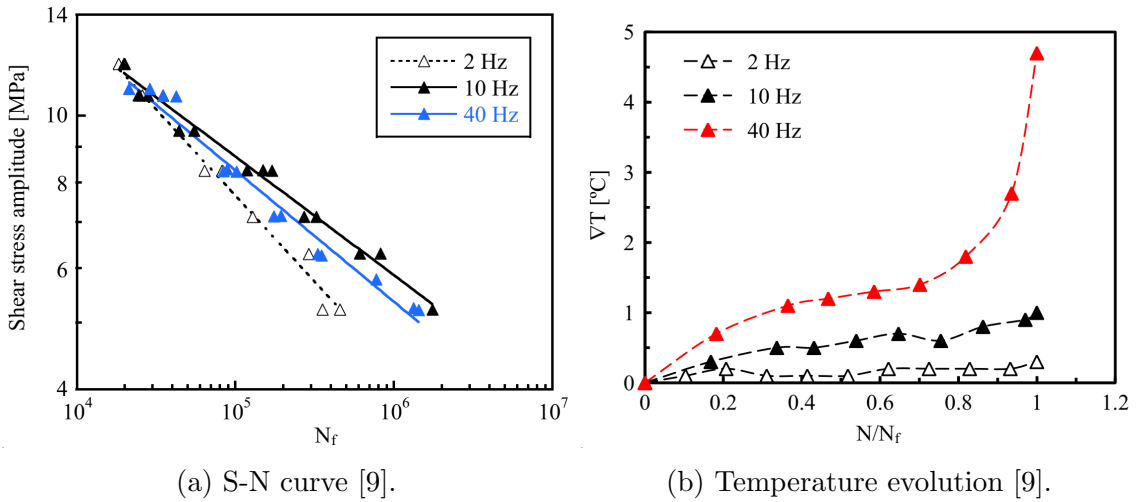


Figure 2.4: Effect of frequency on the fatigue behaviour of adhesive joints.

2.1.2 Fatigue life prediction approaches

Predicting the fatigue behaviour of adhesive joints is a complex task. Yet, it is important to develop simple and accurate fatigue life prediction models to prevent a catastrophic failure from happening during service, and help the design of safer, cheaper and more effective structures. The approaches available to predict the fatigue life of adhesive joints can be categorised into three main categories: total-life methods, fracture mechanics based and damage mechanics based approaches. The fracture mechanics based methods focus on the fatigue crack propagation phase, neglecting the crack initiation phase. It assumes that the joint under analysis contains flaws and determines how it will propagate for the imposed loading conditions. It relates the fatigue crack propagation rate ($\frac{da}{dN}$) to fracture mechanics parameters such as the stress intensity factor (K) or the energy release rate (G) [20]. Since in adhesive joints the effect of substrates makes the characterisation of the stress field around the crack very complex, G is usually preferred towards K . Fatigue crack propagation curves commonly exhibit three distinct regions, as shown in Figure 2.5. The first one is the threshold region that is characterised by the threshold energy release rate, G_{th} , below which measurable crack growth does not occur. In the second region the crack propagation is almost linear in a log-log plot and is described by Paris law, Eq.(2.1) where C and m are empirical constants. The third region concerns the unstable crack propagation.

$$\frac{da}{dN} = C \cdot (G_{max})^m \quad (2.1)$$

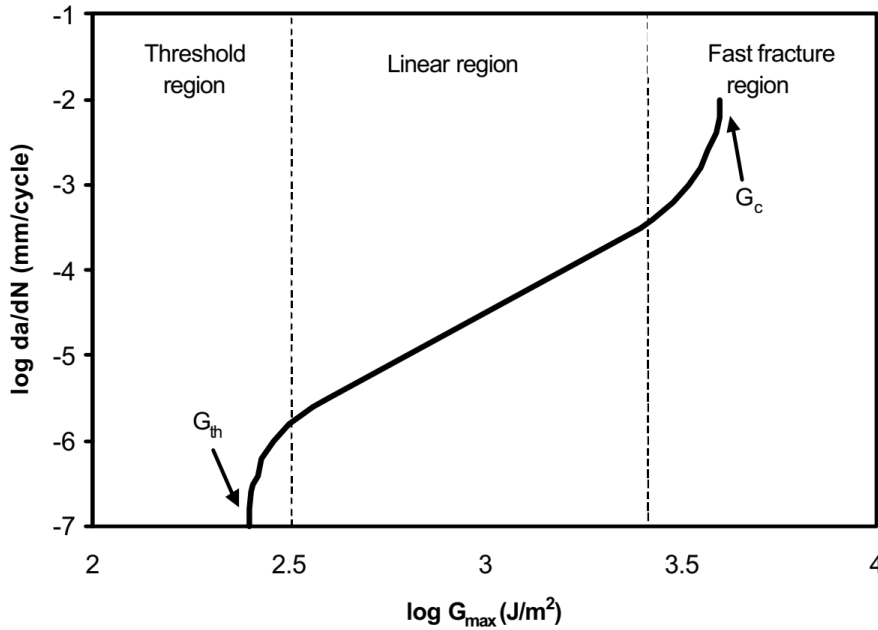


Figure 2.5: Schematic fatigue crack growth propagation curve [13].

The damage mechanics based models are significantly less studied and this is

due to the difficulty of modelling the crack initiation phase. This type of technique uses continuum mechanics to study the damage initiation and then applies fracture mechanics to describe the damage propagation phase [21].

The total life method is the one adopted for the present work and for that reason deserves to be described in detail. This approach takes into account the total fatigue life of an adhesive joint by counting the numbers of cycles that a joint can withstand at a given load level until final failure occurs. These results are presented in stress- life (S-N) curves. These curves can be log-linear or log-log plots. However, in the case of adhesive joints the fatigue results are usually present as Load-Life curves (L-N). The reason for this is that for example for single lap joints, the stress component that should be used is not clear. The first stress that comes to mind is the average shear stress. However, this stress component is not uniform. Moreover, it is widely acknowledged that the failure of these type of joint highly depends on the peel stress, which is not very easy to obtain. Thus, the load value is used as the ordinate for a matter of simplicity [13]. Given this, it is clear that the L-N curves are not directly applicable to different testing conditions. For this reason it would be necessary to perform fatigue testes to every joint geometry and to every loading condition, for example for different mode mixities. This is a very time consuming and expensive process even for very simple joints. For very complex geometries, that are commonly used in real life application this is impracticable. Thus, this lack of transferability of the fatigue results to different testing conditions is the major disadvantage of this approach [22]. To overcome this difficulty it is necessary to define an effective stress. The idea behind this, is that for a specific value of the effective stress, the life will have a defined value no matter the joint geometries or loading conditions. With this, a master curve is defined for a specific adhesive. Different adhesives will have different master curves. This effective stress is a combination of two different aspects. The first one is the equivalent stress, which is a junction of different parameters that govern the failure of adhesive joints. The second aspect, is where that equivalent stress should be measured. It can be the maximum value or, since adhesive present inhomogeneous stress distributions, a value measured at a specific distance away from the maximum. The assessment of the effective stress has become much easier with the development of finite element analysis. Few analytical solutions are available and can only be applied to simple structures. Numerical methods are a great ally of the S-N approach for allowing the calculation o the effective stress even for very complex structures. Despite the constraints, this is still a powerful design tool that provides simple and accurate predictions [1].

Experimental procedure

3.1 Materials

The substrates used were made of a high strength steel, DIN 40CrMnMo7. The high strength steel was selected to avoid plastic deformation during the tests. The most relevant properties of the substrates for this work are the Young's Modulus (E), $E = 210$ GPa, and the Poisson's ratio (ν), $\nu=0.3$. These substrates were used to bond three different adhesives with two different adhesive systems. The adhesives will be denominated as A,B and C from now on and further details will be given next.

3.1.1 Adhesive A

The first adhesive is a high performance and impact resistant one component epoxy based structural adhesive. It is destined to bond steel components where improved impact resistance, stiffness and high durability is required. The general properties given by the supplier are given in Table 3.1. This is a hot curing adhesive. The adhesive was cured at 220°C for a period of 65 min. The curing temperature and the applied pressure to prevent out of plane misalignment of the specimens were controlled using a hot-plate press.

3.1.2 Adhesive B

The second adhesive considered is a two-part methacrylate structural adhesive. It is destined to bond metal, thermoplastic and composite substrates. Is it commonly used in the transportation sector and in marine industries as it requires reduced surface preparation. It also provides excellent fatigue endurance, high toughness, and good impact resistance. The properties provided by the manufacturer are presented in Table 3.1. The adhesive was cured at room conditions for twenty-four hours.

3.1.3 Adhesive C

A toughened and high impact resistant two component epoxy structural adhesive. Its main application is in the bonding of metallic surfaces namely steel and aluminium but can also be applied in composite substrates. General properties given by the supplier can be found in Table 3. The curing conditions for this adhesive were two weeks at room condition.

Table 3.1: General properties of the tested adhesives, given by the supplier.

	Adhesive A	Adhesive B	Adhesive C
Specific gravity	1.05-1.20	0.97	1.1
Viscosity (Pa.s)	30-50 (@50°C)	95-119 (@23°C)	320 (@20°C)
Pot life	$\approx \infty$ (@25°C)	17-24 min (@23°C)	60 min (@23°C)
Tensile strength (MPa)	>30	18.6 - 20.7	30
Elongation at break (%)	>8.5%	75-100%	4%
Young's Modulus (MPa)	>1400	379 - 586	2000

3.2 Testing methods

The experimental part of the present work consists of three main steps. Initially, strength tests using bulk specimens were performed to characterise the adhesives, obtaining its tensile properties. Then, static tests were conducted, using Arcan specimens to assess the influence of mode mixity on the static strength and to define the load levels at which the fatigue tests should be performed. Fatigue tests were conducted to obtain the L-N curves for the different adhesives. Finally, both static and fatigue tests were conducted on single lap joints bonded by adhesive A with different configurations.

3.2.1 Bulk specimen tests

The bulk specimens, shown in Figure 3.1 were machined from a cured sheet of the cured adhesive. The procedure used is in accordance to the BS2782 standard. These tests are used to obtain the tensile properties of the adhesive. The load and displacement are recorded and a stress-strain curve is obtained. Using this curve it is possible to obtain the tensile strength, the elongation and the Young's modulus. It should be noted that these tests were only performed for adhesive C, as for the other adhesives the results were found in literature [23].

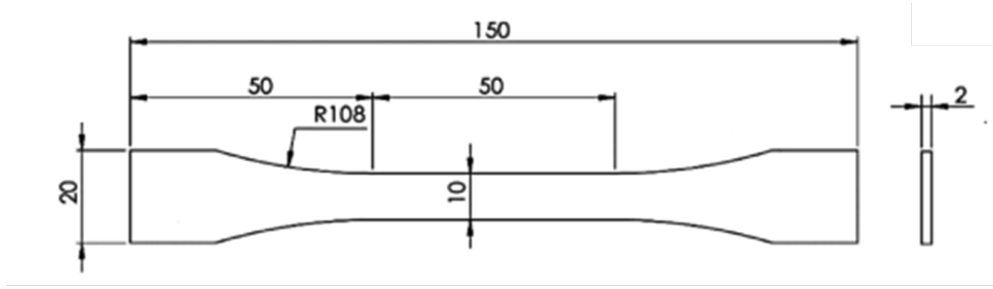


Figure 3.1: Bulk specimen's geometry (dimensions in mm)

3.2.2 Arcan specimen tests

This type of joint, is named after one of the authors that initially proposed it [24]. Many times it is also referred to as butterfly specimen due to its shape. It was initially intended to obtain the shear properties of a material, allowing an almost uniform stress distribution. However, the Arcan fixture suffered some changes over the years. The modified version of this testing apparatus allows to test joints with a wide range of mode mixities that range from pure mode I to pure mode II. The Arcan apparatus used to perform the tests is presented in Figure 3.2. The dimensions of the Arcan specimen can be found in Figure 3.3.

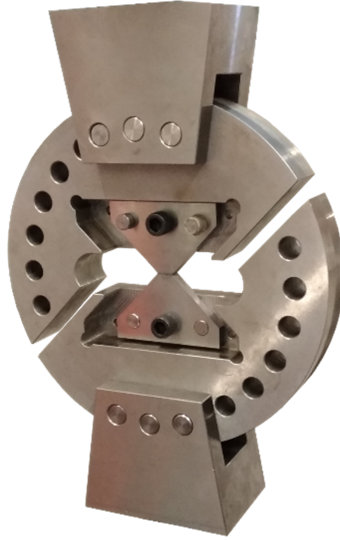


Figure 3.2: Arcan apparatus.

Both static and fatigue tests were performed using this apparatus. For adhesive A, three different mode mixities were considered while for the other adhesives only pure mode I was studied. Stiffness degradation can be a very important non-destructive damage metric [25]. Thus, the stiffness degradation was monitored during fatigue tests and based on this the damage evolution was obtained for different adhesive systems and for different mode mixities.

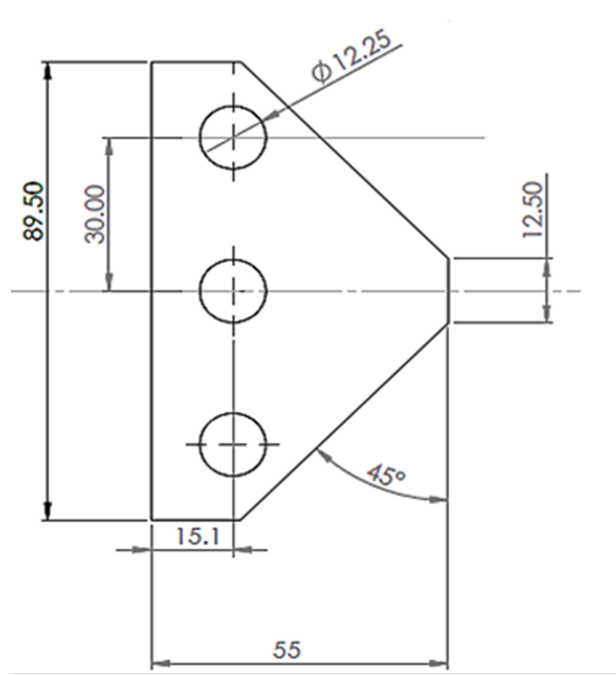


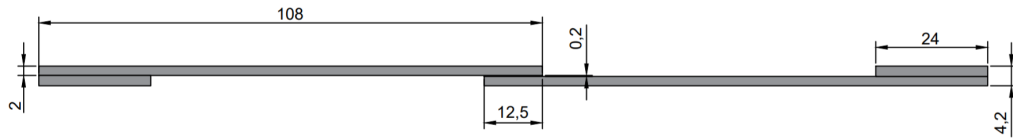
Figure 3.3: Arcan specimen (only half is represented) (dimensions in mm).

Detailed information regarding the testing conditions, the experimental results and its discussion can be found in Appendix A: Paper 1.

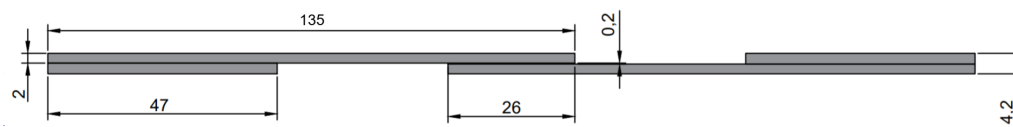
3.2.3 Single lap joints tests

Both static and fatigue tests were conducted on the single lap joints with three different configurations, where the overlap length, adherend thickness and joint width were varied. The dimensions of configurations I, II and III are present in Figure 3.4a, 3.4b and 3.4c respectively.

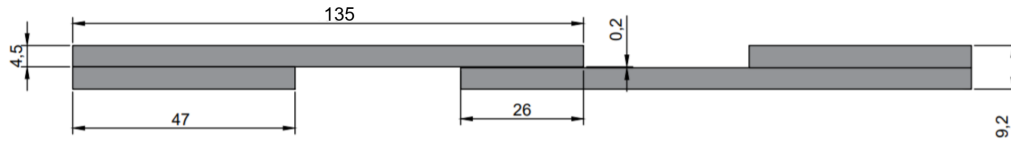
The author wishes to acknowledge Deere & Company, Asia Technology and Innovation Center, for kindly providing the experimental results for configuration II and III.



(a) Configuration I (Width=25mm).



(b) Configuration II (Width=38mm).



(c) Configuration III (Width=38mm).

Figure 3.4: Studied SLJ configurations (dimensions in mm).

Further details regarding the testing conditions, the experimental results and its discussion can be found in Appendix C: Paper 3.

Numerical modelling

One of the goals of this work is to develop a simple fatigue lifetime prediction model able to deal with the effect of mode mixity. To achieve this, numerical modelling was carried out for stress assessment. Different approaches, such as damage based models, rely on complex numerical simulations that have on its down-side very long computation times and a need for expertise from the user. When this is applied in real-life applications, structures reach a considerable level of complexity, making these disadvantages almost unbearable. The work developed throughout this thesis is intended to be used in industrial applications mainly on a conceptual phase of design. Here, what is needed is a fast methodology to understand if a design option is viable or impracticable.

For these reasons, the goal was to keep the numerical simulations as simple as possible. A static linear elastic analysis was performed to obtain multiple stress parameters at the adhesive's mid-plane. This location was selected based on the assumption that the cohesive failure occurs at the middle of the adhesive thickness. Also, this avoids the interference of the interface properties and the numerical singularities at the corners of the adhesive layer. A 2D model, with a plane strain assumption was also used as it allows a significantly shorter simulation time when compared to 3D models.

For Arcan joints, information regarding the proposed fatigue model and the numerical modelling details, such as loading conditions, mesh and elements used and a validation of the 2D plane strain assumption as well as the effect of mesh size on the proposed model can be found in Appendix B: Paper 2.

The information regarding the numerical simulation of single lap adhesive joints as well as the developments performed on the previously mentioned fatigue model to account for the effect of stress concentration is presented in Appendix C: Paper 3.

Conclusions and future work

5.1 Conclusions

The influence of mode mixity on the fatigue behaviour of adhesive joints was studied in the present work. L-N curves were obtained for an epoxy adhesive under three different modes, pure mode I, mixed-mode (45°) and pure mode II loading conditions. For pure tensile loading conditions, two different adhesive systems, epoxy and acrylic, were analysed. The stiffness degradation was monitored during the fatigue tests for all the testing conditions.

From the experimental results it was possible to conclude that joints loaded under conditions with a shear component suffered a reduction of its static strength and stiffness. The same reduction was found on the fatigue life for similar load levels. For lower cycle fatigue the different mode mixities did not have a big influence on the fatigue life. However, this difference was very significant on the high-cycle fatigue region where the ratio between the fatigue life under pure mode II conditions and the one obtained for pure mode I was 10. The acrylic adhesive presents a lower strength when compared to the epoxy adhesive system. One possible justification for this observation may be its lower stiffness. From the stiffness degradation curves it was also found that the acrylic adhesive presented a higher degradation rate. These stiffness degradation curves also indicate that the crack initiation phase is the responsible for a significant part of the fatigue life and that it prevails over the crack propagation part. Fatigue envelopes were also constructed for different lives and they have proven to be an useful tool to estimate the fatigue life of a joint under different loading conditions.

A simple fatigue lifetime prediction model able to deal with the effect of different mode mixities was also proposed. A new effective stress, that takes in account stress parameters that govern the failure of adhesive joints was used to build a master S-N curve for the studied adhesive, having joints subjected to pure mode conditions as reference samples. The effect of several parameters on the construction of the master curve was studied. Two different relations were considered, Basquin and Stromeyer.

The relation that best describes the adhesive's behaviour and consequently presented the best prediction results is the Stomeyer's relation. The effect of mesh size and model type was also investigated. A 2D linear elastic analyses proved to be sufficient and the mesh size did not have a big influence on the proposed model. These can be considered as advantages of the proposed model, for allowing shorter simulation times. The number of load levels used to fit the master curve has also shown to be an important factor to take into account, mainly the consideration of reference points in the HCF was proven to be a factor that greatly benefited the accuracy of the predictions. Overall, the proposed fatigue model accurately estimated the fatigue life on an Arcan adhesive joint subjected to mixed mode fatigue loading conditions.

This fatigue model was further developed and by using a critical distance approach, it was able to deal with the effect of stress concentrations on the fatigue behaviour of single lap joints with different values of overlap length, adherend thickness and joint width. The fatigue life prediction results showed good agreement with the fatigue life experimentally obtained.

5.2 Future work

Given the multiple factors that influence the fatigue behaviour of adhesive joints, it would be interesting to assess the effectiveness of the proposed model when dealing with these factors. Of all these factors there are two that are very important and should be considered: the joint geometries and type of adhesive used. Regarding the geometry, two different major categories should be investigated. The first would be the implementation of the life prediction methodology to different adhesive joints. The second important aspect to take into account would be the different parameters that influence the fatigue life of one joint. For this, considering more joint's configurations as well as several substrate materials would increase the confidence level on the prediction model. The adhesive used highly impacts the fatigue life of adhesive joints, so different adhesives should be considered. Given that the studied adhesive is brittle, considering a very ductile adhesive would be a interesting to understand the influence of the adhesive behaviour on the proposed fatigue model. It would also be worthy to consider mode III loading conditions. By doing such even more complex mode mixities could be covered.

Using different methods contemplated on the theory of critical distances to understand its impact on the accuracy and robustness of the model would add value to this design methodology.

Since in industrial applications the frequency to which adhesive joints are subjected can vary significantly and due to the fact that adhesive materials show a viscoelastic behaviour the study of the influence of frequency on the fatigue life is also crucial.

Additionally, extending the model to different environmental conditions would also be something that would increase the utility of the proposed model.

References

- [1] L.F.M. da Silva, A Öchsner, and R. Adams. *Handbook of Adhesion Technology*. 05 2018.
- [2] Anthony Kinloch. *Adhesion And Adhesives: Science And Technology*. 1987.
- [3] R.D. Adams. *Adhesive bonding: Science, technology and applications*. 2005.
- [4] E.M. Petrie. *Handbook of Adhesives and Sealants, Second Edition*. McGraw-Hill Education, New York, 2nd ed. edition, 2007.
- [5] R.D. Adams, J. Comyn, and W.C. Wake. *Structural Adhesive Joints in Engineering*. Springer, 1997.
- [6] L.F.M. da Silva and A. Öchsner. *Modeling of Adhesively Bonded Joints*. 01 2008.
- [7] M.M. Abdel Wahab. Fatigue in Adhesively Bonded Joints: A Review. *ISRN Materials Science*, 2012, 2012.
- [8] N. E. Dowling. *Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue*. Pearson Prentice Hall, 2007.
- [9] P. N. B. Reis, J. F. R. Monteiro, A. M. Pereira, J. A. M. Ferreira, and J. D. M. Costa. Fatigue behaviour of epoxy-steel single lap joints under variable frequency. *International Journal of Adhesion and Adhesives*, 63:66–73, 2015.
- [10] P. Zamani, A. Jaamialahmadi, L. F.M. da Silva, and K. Farhangdoost. An investigation on fatigue life evaluation and crack initiation of Al-GFRP bonded lap joints under four-point bending. *Composite Structures*, 229:111433, 2019.
- [11] V. Shenoy, I.A. Ashcroft, G.W. Critchlow, AD. Crocombe, and M.M. Abdel Wahab. An investigation into the crack initiation and propagation behaviour of bonded single-lap joints using backface strain. *International Journal of Adhesion and Adhesives*, 29(4):361–371, 2009.
- [12] Jaap Schijve. *Fatigue of Structures and Materials*. 2009.

- [13] I. A. Ashcroft and S. J. Shaw. Mode I fracture of epoxy bonded composite joints 2. Fatigue loading. *International Journal of Adhesion and Adhesives*, 22(2):151–167, 2002.
- [14] M. Imanaka and T. Iwata. Fatigue Failure Criterion of Adhesively-Bonded Joints Under Combined Stress Conditions. *The Journal of Adhesion*, 59(1-4):111–126, 1996.
- [15] A. M. Pereira, P. N. B. Reis, and J. A. M. Ferreira. Effect of the mean stress on the fatigue behaviour of single lap joints. *The Journal of Adhesion*, 93(6):504–513, 2017.
- [16] A.D. Crocombe and G. Richardson. Assessing stress state and mean load effects on the fatigue response of adhesively bonded joints. *International Journal of Adhesion and Adhesives*, 19(1):19–27, 1999.
- [17] S. Azari, A. Ameli, N. Datla, M. Papini, and J. K. Spelt. Effect of substrate modulus on the fatigue behavior of adhesively bonded joints. *Materials Science and Engineering: A*, 534:594–602, 2012.
- [18] S. de Barros, P. P. Kenedi, S. M. Ferreira, S. Budhe, A. J. Bernardino, and L. F. G. Souza. Influence of mechanical surface treatment on fatigue life of bonded joints. *The Journal of Adhesion*, 93(8):599–612, jul 2017.
- [19] M. Costa, G. Viana, L. F. M. da Silva, and R. D. S. G. Campilho. Environmental effect on the fatigue degradation of adhesive joints: A review. *The Journal of Adhesion*, 93(1-2):127–146, jan 2017.
- [20] D.A. Dillard. Improving adhesive joint design using fracture mechanics. In *Advances in Structural Adhesive Bonding*, Woodhead Publishing Series in Welding and Other Joining Technologies, pages 350–388. Woodhead Publishing, 2010.
- [21] A. Akhavan-Safar, M. Salamat-talab, A. Ajdani, M. R. Ayatollahi, and Lucas F. M. da Silva. Mode II fracture energy characterization of brittle adhesives using compliance calibration method. *Fatigue & Fracture of Engineering Materials & Structures*.
- [22] V. C. Beber, B. Schneider, and M. Brede. Efficient critical distance approach to predict the fatigue lifetime of structural adhesive joints. *Engineering Fracture Mechanics*, 214:365–377, 2019.
- [23] A. Rocha, A. Akhavan-Safar, R. Carbas, E. Marques, R. Goyal, M. El-Zein, and L. F. M. da Silva. Fatigue crack growth analysis of different adhesive systems: Effects of mode mixity and load level. *Fatigue & Fracture of Engineering Materials & Structures*, 2019.

- [24] M. Arcan, Z. Hashin, and A. Voloshin. A method to produce uniform plane-stress states with applications to fiber-reinforced materials. *Experimental Mechanics*, 18(4):141–146, 1978.
- [25] Y. Zhang, A. P. Vassilopoulos, and T. Keller. Stiffness degradation and fatigue life prediction of adhesively-bonded joints for fiber-reinforced polymer composites. *International Journal of Fatigue*, 30(10-11):1813–1820, 2008.

Appendix A

Paper 1

The influence of mode mixity and adhesive system on the fatigue life of adhesive joints

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Abstract

In real applications, adhesive joints are commonly subjected to fatigue and mixed mode loading conditions. The aim of the current work is to experimentally analyse the influence of mode mixity on the fatigue strength of joints with an epoxy based adhesive. Different adhesive systems (acrylic and epoxies) were considered for pure mode I fatigue loading conditions. To achieve this, Arcan joints with an epoxy adhesive were manufactured and tested at different mode mixities. Based on stiffness degradation, monitored during the tests, damage evolution was calculated for different loading conditions and for all the tested adhesives. Finally, fatigue envelopes were constructed for different fatigue life regimes. Results show that a shear loading component reduces both the static strength and fatigue life of the joints. A small reduction rate of the stiffness was found throughout the most part of the life until a sudden drop was observed, indicating a smooth damage evolution.

A.1 Introduction

Adhesive joints are nowadays figuring as a good alternative to conventional fastening methods in many industries such as automotive and aeronautical. This is due to the many advantages they present such as their ability to bond different materials, presenting a more uniform stress distribution when compared to other fastening techniques, higher fatigue strength, and their lower weight which allows a cost reduction and lower energy consumption [1]. During their service life, most adhesive joints are often subjected to cyclic loadings. For these types of joints, fatigue failure mechanisms usually govern the life of the bonded structures. The effect of some parameters such as environmental conditions [2], mean stress [3], substrate material [4] and surface preparation [5,6] have been vastly studied for their high impact on the fatigue behaviour of adhesive joints. However, the fatigue failure mechanisms of adhesion are not yet completely defined and a design methodology for fatigue estimation of adhesive joints is still of a prime importance to avoid catastrophic failures.

Fatigue life can be divided into two parts: crack initiation and crack propagation. The initiation life is significant for joints subjected to low load levels where the deformations are mainly elastic and consequently the joints experience high cycle fatigue lives. On the other hand, for joints in which the propagation life dominates, the load levels are higher where the adhesive may usually experience plastic deformation during the service loads [7,8]. Accordingly, three different approaches are available for fatigue life prediction of adhesive joints. The first approach is the total life method which is usually referred to as stress-life (S-N) approach. Fracture mechanics based methods are the second method which deal with the fatigue crack propagation life. The third approach is damage mechanics that mainly focuses on crack initiation but can take in account both fatigue life phases [9]. Fracture mechanics based methods have been experimentally and numerically considered by several authors [10–18]. In these works, the influence of different geometrical and loading parameters have been analysed on fatigue crack growth of adhesive materials. Ajdani et al. [15] presented a new test method to measure the fracture energy of brittle and semi-brittle adhesive joints subjected to mixed mode loading conditions. The specimen used is a semi-circular bend specimen. The measurements performed using this new specimen show good agreement with the ones performed using classical specimens such as double cantilever beam (DCB), single leg bending (SLB) and end notched flexure (ENF). Akhavan-Safar et al. [17] applied an existing data reduction scheme, commonly used in composite materials, in order to obtain the fracture toughness of brittle adhesives with unstable crack propagation in pure mode II loading conditions. This approach provided better estimation, up to 20%, when compared to common data reduction methods. Ayatollahi et al. [18] investigated the effect of notch length and pre-crack size on the fracture energy of brittle adhesives under mode II loading conditions. It was shown that ENF tests with inappropriate notch size and pre-crack lengths

lead to a mixed mode condition, which significantly affects the measurement of the fracture energy. Tserpes and Floros [16] developed a numerical model to simulate the fatigue crack growth in adhesively bonded joints subjected to different mode mixities, from pure mode I to pure mode II. The numerical results have shown good agreement with the experimentally obtained crack growth data.

The stress-life approach has been also considered in some studies. The stress life approach is based on S-N curves where the number of cycles until failure versus a load-related variable are plotted. This life prediction method has some limitations. For example, the applicability of the S-N results is usually limited to the tested conditions in terms of mode mixity and joint geometry. However, despite such limitations, the utility of this approach is undoubtable, and it figures as a powerful design tool, specially for the conceptual design stages of bonded structures in industries.

Given this, many researchers have investigated the fatigue life of adhesive joints using this approach. Jen [19] studied experimentally the fatigue life of scarf joints using an epoxy-based adhesive and concluded that the life increases significantly as the scarf angle increases. A change of failure mechanism from adhesive to cohesive was also observed with the increase of the scarf angle. He improved a fatigue life prediction method and found a satisfactory correlation between the experimental results and the predicted data. Imanaka and Iwata [20] used an epoxy based adhesive to manufacture scarf joints with six angles (30° , 33.75° , 45° , 60° , 75° and 90°) and butterfly butt joints with two inclination angles (0° and 11.25°). They correlated the principal stress ratio to three types of effective stress at the endurance limit: the maximum principal stress, the Von Mises stress and the maximum shear stress. They found that the above-mentioned stresses decreased linearly with the increase of the principal stress ratio allowing the estimation of the endurance limit of the scarf and the butterfly-type butt joints. By using the regression equation based on the maximum principal stress, obtained from the S-N data of scarf and butterfly joints along with the point stress criteria, the endurance limit of single and double lap joints was estimated [21]. Beber et al. [22] studied the influence of material model (linear elastic, Von Mises plasticity and linear Drucker-Prager) and stress multiaxiality in the fatigue life of a toughened epoxy adhesive. They proposed a method for fatigue lifetime prediction based on the stress multiaxiality using the hydrostatic pressure-Von Mises diagrams. Results showed that the material model affects the stress multiaxiality of single lap adhesive joints mainly on singular regions. For scarf and thick adherend shear test (TAST) specimens, discarding the singularity regions, the stress multiaxiality was nearly constant and decreased with increasing the bond line angle. Elastoplastic models were proven satisfactory for single lap and scarf joints, while elastic models were only suitable for the last. Results also suggested a critical distance which is a function of material and joint configuration. Li et al. [23] studied adhesively bonded hollow cylindrical butt joints bonded by a silicone sealant under axial and torsional loading conditions and proposed a modified Chen-Xu-Huang life

prediction model. By considering the tensile failure behaviour and the shear failure, a good agreement between the predictions and the experimental data was obtained.

As stated before, the S-N approach is an extremely important tool for the design of components under fatigue loadings, providing a much needed simple and agile approach for industrial applications. Despite the advantages of numerical models, such as the celerity and low cost, the credibility of this type of analysis is still very low, therefore, an experimental analysis is mandatory to achieve good confidence levels. The aim of the current work is to experimentally analyse the influence of mode mixity on the fatigue strength of joints with an epoxy based adhesive. Different adhesive systems have been also considered for pure mode I fatigue loading conditions. To achieve this, Arcan joints were manufactured and tested at different load levels and different mode mixities using an Arcan device.

A.2 Experimental details

In the experimental procedure, three adhesives were tested under static and fatigue loading conditions using Arcan specimens in order to obtain the S-N data and to analyse the influence of mode mixity on the total fatigue life.

A.2.1 Materials

The adhesives used to bond high strength steel substrates are as follows:

Adhesive A- A high performance and impact resistant one component epoxy based structural adhesive. It is destined to bond steel components where improved impact resistance, stiffness and high durability is required.

Adhesive B- A two-part methacrylate structural adhesive. Meant to bond metal, thermoplastic and composite substrates. Provides excellent fatigue endurance, high toughness and good impact resistance.

Adhesive C- A toughened and high impact resistant two component epoxy structural adhesive. Its main application is in the bonding of metallic surfaces namely steel and aluminium but can also be applied in composite substrates.

Tensile bulk tests (according to the BS2782 standard) were used to determine the tensile properties of the three considered adhesives. The mechanical properties of the tested adhesives are given in Table A.1. Typical tensile stress-strain curves for the three adhesives are shown in Figure A.1. Some extra properties such as the pot life, the viscosity and the specific gravity, collected from the manufacturer's datasheets are also presented in Table A.1.

A.2.2 Joint geometry and preparation

As mentioned previously, the tests were performed using Arcan specimens. The dimensions of the specimens are shown in Figure A.2a. The thickness of the spec-

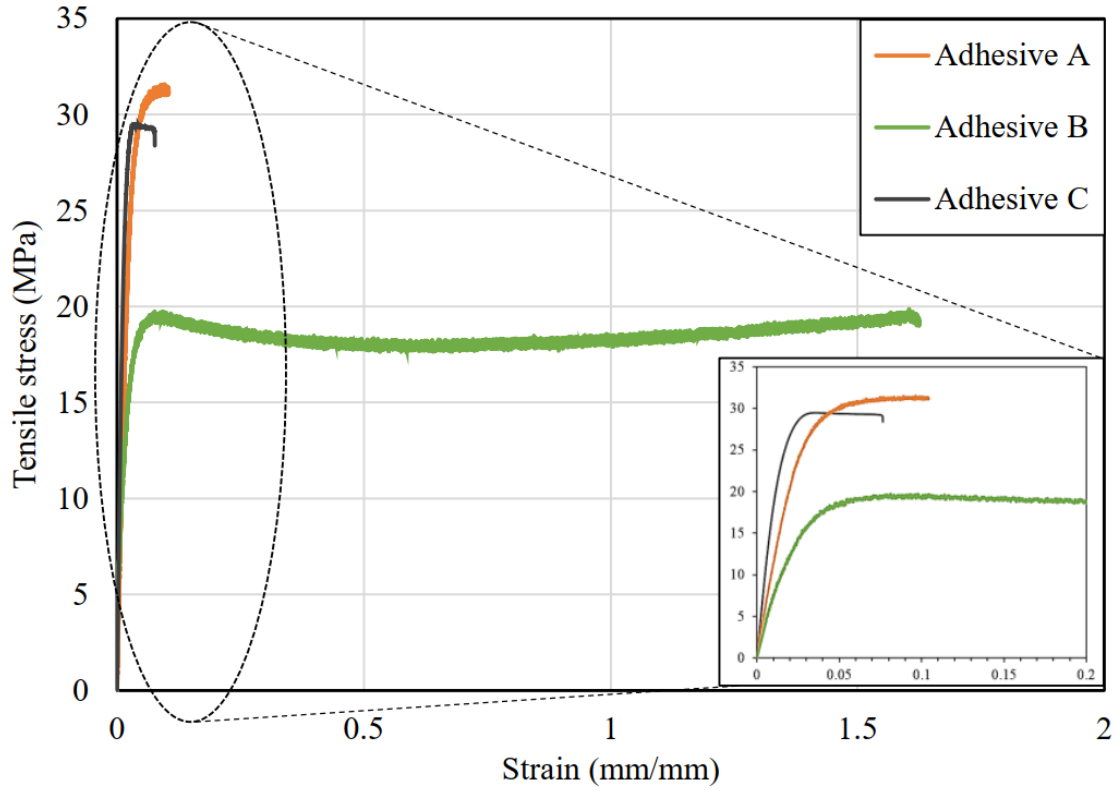


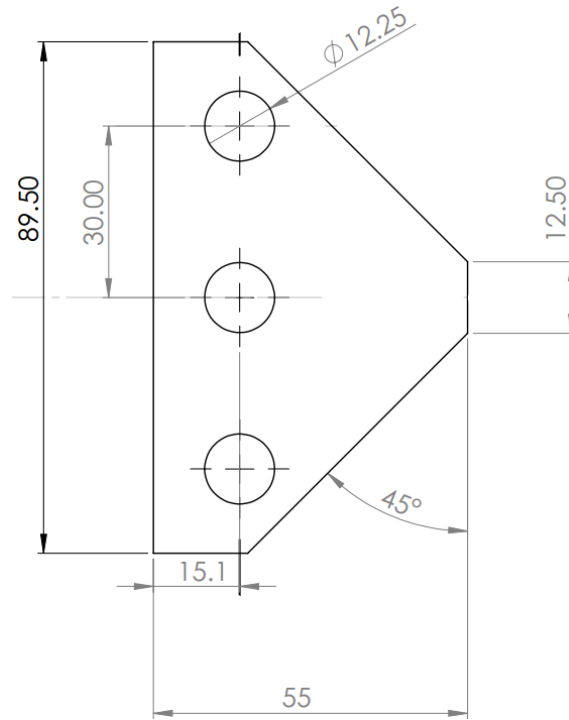
Figure A.1: Typical tensile stress-strain curves for adhesives A, B and C.

Table A.1: Properties of the tested adhesives.

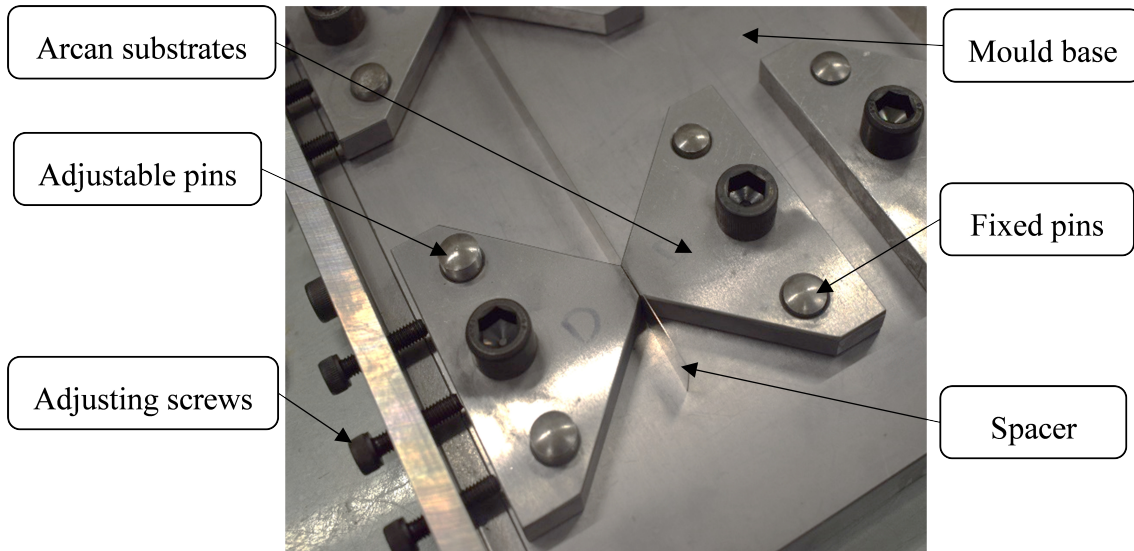
Properties	Adhesive A	Adhesive B	Adhesive C
Maximum tensile strength (MPa)	31.3 ± 0.6	19.5 ± 0.36	29.62 ± 0.28
Maximum tensile strain (%)	10.4 ± 0.5	142.4 ± 14.4	7.58 ± 0.52
Young's modulus (MPa)	1159 ± 29.3	994 ± 71.4	2085 ± 31
Number of tested specimens	3	3	3
Pot life	$\approx \infty$ (@25°C)	17-24 min (@23°C)	60 min (@23°C)
Viscosity (Pa.s)	30-50 (@50°C)	95-119 (@23°C)	320 (@20°C)
Specific gravity	1.05 - 1.20	0.97	1.1

imens was set to 10 mm. The surfaces were sandblasted for a better mechanical adhesion and then were cleaned with acetone. To assure quality and standardisation of the manufacturing process, the mould shown in Figure A.2b was used. The adhesive layer thickness was controlled using calibrated metal spacers and it was set to 0.2mm.

For the curing process, a hot-plate press was used to control both the pressure and temperature. The curing temperature for adhesive A was 220°C for a period of



(a) Dimensions (in mm) (only half is represented)



(b) Mould used during the manufacturing process.

Figure A.2: Arcan specimen.

65 min. Adhesive B was cured at room temperature for 24 hours. Regarding adhesive C, the curing time was two weeks at room temperature. The curing condition for all adhesives are in accordance with the manufacturer's datasheets. However, small adjustments were performed to account for the effect of heat transfer. After the curing process all the specimens, joined by adhesive A and B were kept at room

conditions for 5 days before testing. Before the tests, the adhesive surplus was removed using a metal file.

A.2.3 Testing conditions

The tests were performed at room conditions using an Instron 8801 servo-hydraulic testing machine. The specimens were mounted on the loading frame using two pins for load transmission and one bolt to prevent out of plane misalignment and specimen movement during the test. The apparatus used is shown in Figure 3a. Static tests and fatigue experiments at different load levels were performed to obtain the fatigue life behaviour of the adhesives. For the static tests the crosshead speed was set to 1mm/min. Accordingly, the strain rate defined by the ratio of the crosshead speed to a reference length is slightly different between the pure mode and the mixed mode condition. For mode I and mode II the reference length is the adhesive thickness, 0.2mm, and the strain rate takes the value of 5 min⁻¹. However, for mixed mode conditions the reference length is the adhesive thickness divided by cosine of the load angle. Therefore, the strain rate for mixed mode (45°) condition is 3.54 min⁻¹. Despite this disparity, a significant effect on the failure load for mixed mode conditions is not expected as the difference between the strain rate for different mode mixities is very small. Regarding the fatigue tests, the load ratio (R), defined as the ratio of minimum applied load (F_{min}) to the maximum applied load (F_{max}), was set to 0.1, and the loading frequency considered as 10 Hz. For adhesive A, three different load angles, as defined in Figure 3b, were taken into account including 0° (mode I), 45° and 90° (mode II) to analyse the influence of mode mixity in fatigue life. To understand the influence of the adhesive system on fatigue life behaviour of Arcan joints, mode I tests were carried out on all the considered adhesives.

A.3 Results and discussion

A.3.1 Static results

Average failure loads obtained during the static tests from Arcan joints for each tested mode mixity and average failure strength (defined as the average failure load divided by the bonded area A ($A = 125\text{mm}^2$)) are shown in Table A.2. The average failure strength for mixed mode conditions was divided into two components, tensile and shear. These were calculated multiplying the total failure strength, defined as described previously, by the cosine or sine of the load angle, for the shear and tensile component, respectively. All the tested specimens presented a cohesive failure. For adhesive A, these results showed that there is a decrease of the failure load with increasing the load angle. As expected, the failure load for mixed mode lies within the range of mode I and mode II. Figure A.4a shows typical load-displacement curves for adhesive A under different mode mixities. Based on Figure A.4a, the

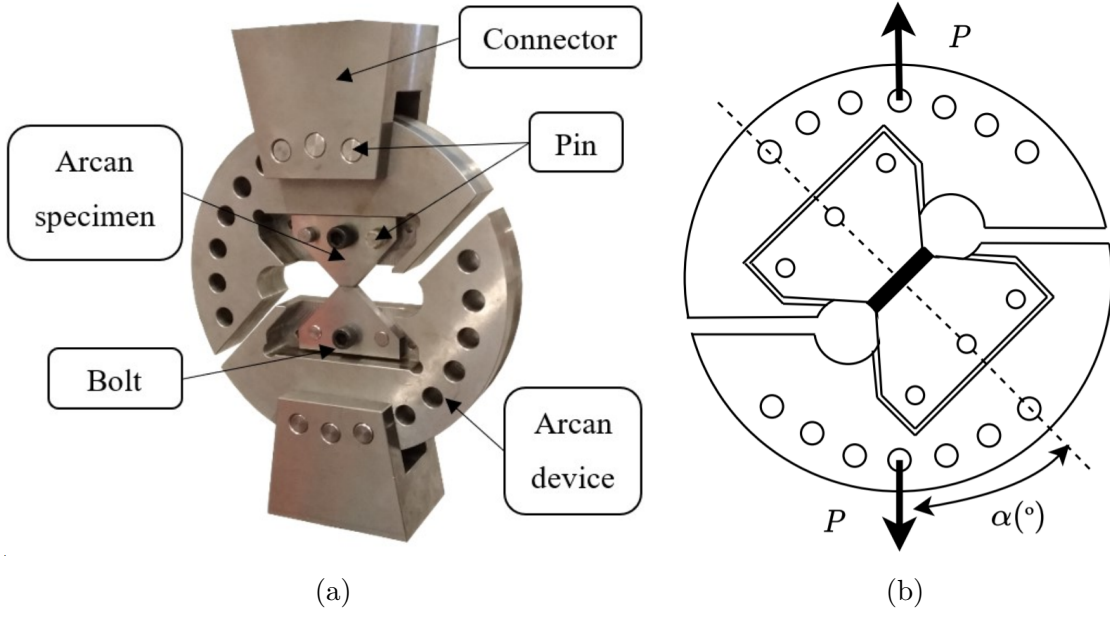


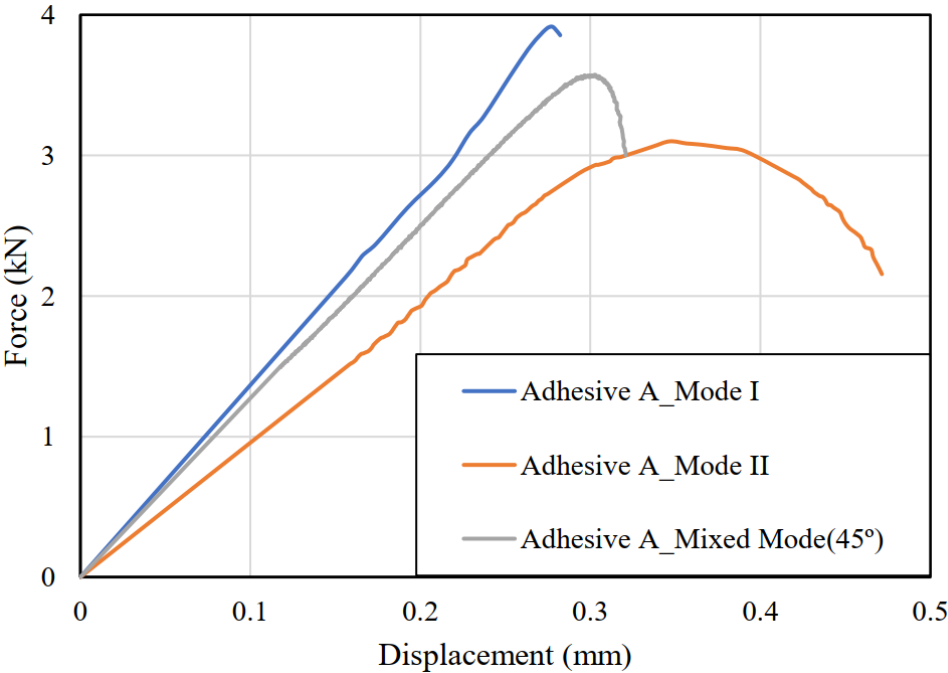
Figure A.3: (a) Arcan apparatus; (b) Load angle definition .

global response of the adhesive is approximately linear. Despite the overall linear behaviour, when the loading is not purely tensile, some plastic deformation appears that increases with load angle. The increase of load angle is also responsible for a decrease on the stiffness of the joint.

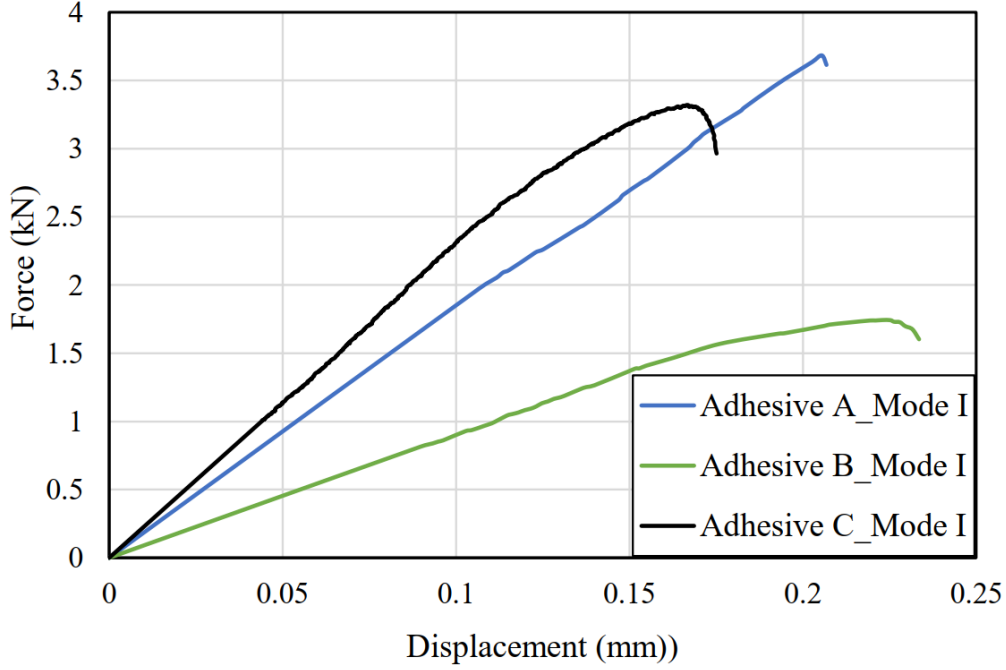
Typical load-displacement curves of the three adhesives tested in mode I are presented in Figure A.4b. All adhesives display an overall linear-elastic behaviour. Based on the results shown in Figure A.4b, adhesive A presents the highest failure load, while adhesive C is the stiffest. Adhesive B has the lowest failure load and stiffness but shows the highest elongation. The difference between its elongation and the one obtained for the other adhesives is not as significant as it is on the bulk results and that may be due to the following reasons. The Arcan specimens exhibit stress concentrations near the free ends due to the singularities which affect the Arcan failure loads, and also the strain rate in the Arcan static tests is 100 times higher than the one used in bulk tests which may influence the Arcan results.

Table A.2: Static results of Arcan specimens.

	Adhesive A			Adhesive B	Adhesive C
	Mode I	Mode II	Mixed mode (45°)	Mode I	Mode I
Failure load (N)	3760±300	3270±180	3480±150	1660±59	3570±286
Average failure strength (MPa)	30.08±2.40	26.16±1.44	Tensile	13.28±0.47	28.56±2.29
			Shear		
			19.70±0.84		
Tested specimens	3	3	4	3	5



(a) Adhesive A under different mode mixities



(b) Three adhesives under mode I static loading conditions.

Figure A.4: Typical force-displacement curve for Arcan joints.

A.3.2 Fatigue results

All the fatigue tests failed cohesively. Typical fatigue failure surfaces of adhesive A, B and C are shown in Figure A.5. A macroscopic analysis of the failure surface for adhesive A reveals a significant difference in the pattern found. Under mode I loading, a smoother failure surface is obtained indicating a straight stable crack propagation around the median plane of the bond line. Under mode II loading condition, a rougher failure surface is found, indicating the formation of shear hackles, also known as “shear cusps” [24], resulting in a wavy crack path. This crack path transition behaviour with the increase of the load angle is in accordance with previous works [25]. For mixed mode joints, the failure mode is similar to mode II and, therefore, the shear component of the load seems to govern failure.

A.3.3 Influence of mode mixity

The fatigue test results obtained for adhesive A are presented in Figure 6 in the form of Load-Cycle (L-N) curves, where the life is plotted against the maximum applied load. Tests with lives higher than 2.5×10^6 cycles were considered as run out in these experiments. It was found that for the same load levels, the increase of the load angle decreases the fatigue life of the joints. The possible reason is the lower static strength of the joints with a high load angle. Accordingly, for the same load level, the joints tested in mode II have experienced a higher load ratio (the ratio of the applied fatigue load to the static strength). Another possible cause for this behaviour is the

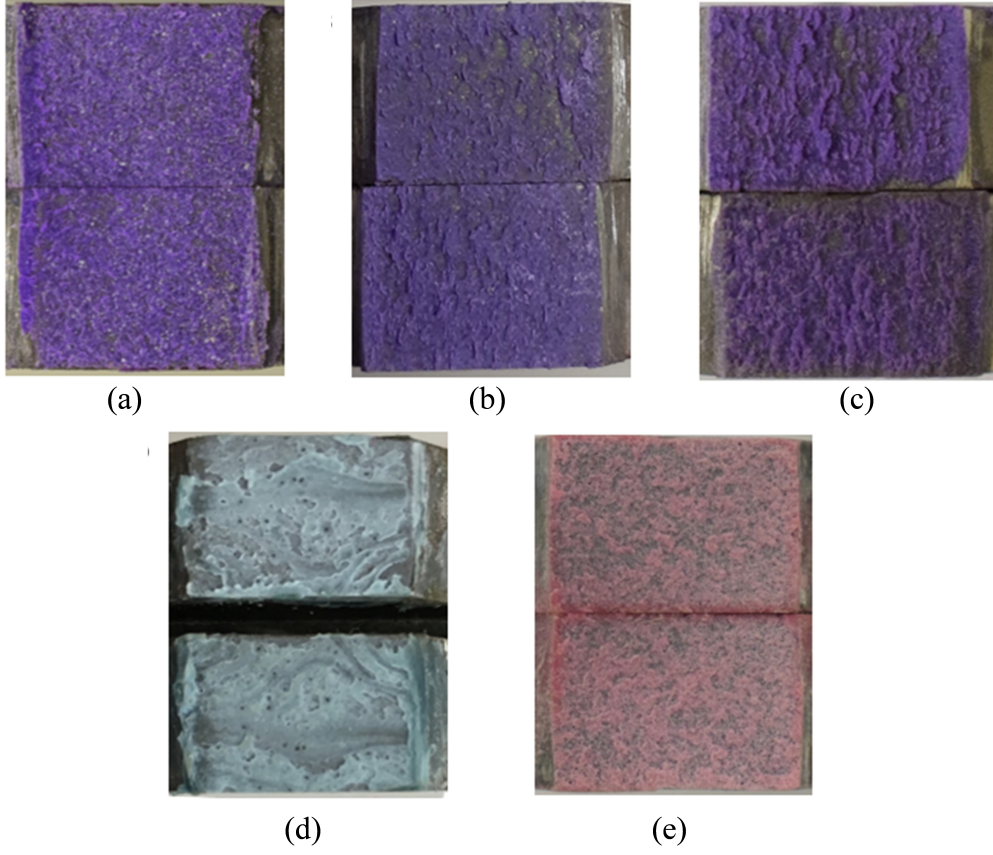


Figure A.5: Fatigue failure surfaces: (a) adhesive A -Mode I; (b) adhesive A -Mode II; (c) adhesive A -Mixed Mode (45°); (d) adhesive B-Mode I; (e) adhesive C-Mode I.

stiffness of the joint which is higher for mode I than for mode II. Subsequently, for the same load level, the displacement obtained for mode I is smaller than the ones for mixed mode and mode II. This means that for the same load level, the amount of energy introduced into the system is higher at each cycle. One important parameter which should be considered is the threshold fracture energy (G_{th}) which is defined as the energy release rate below which the fatigue crack growth is negligible. Based on the previous results already published by the current authors [10], it was shown that for adhesive A, G_{th} in mode I is higher than mode II as shown in Table A.3. This associated with the fact that the energy introduced in the system per cycle increases with the presence of a shear component, aggravates the reduction of the fatigue strength as the load angle increases.

Based on the results shown in Figure A.6, it is shown that the difference between the life obtained for mode I and mode II was not constant along the entire life spectrum. For low cycle fatigue (LCF), in region I depicted in Figure A.6 the difference between mode I and mode II was relatively small (around 2 times), while with the increase of number of cycles that difference increases, being the life for

mode I more than 10 times higher than for mode II, in region II. However, it should be noted that for Arcan joints the tensile load is almost uniformly distributed along the bondline for pure mode I loading conditions. This uniform stress distribution for tensile loading rarely takes place in real applications. In common pure mode I joints, such as DCB and T-peel joints, the resistant area to the applied load is very small and the stress is concentrated at the ends of the overlap (or ahead of the crack tips). For these types of joints, the fatigue strength is usually smaller than the strength of shear lap joints due the stress concentration effects.

Table A.3: Threshold fracture energy for adhesive A (mode I and mode II) and adhesive B (mode I).

	Adhesive A- Mode I	Adhesive A- Mode II	Adhesive B- Mode I
G_{th} [N/mm]	1.58 ± 0.06 [12]	1.44 ± 0.3 [12]	0.95 ± 0.1 [24]

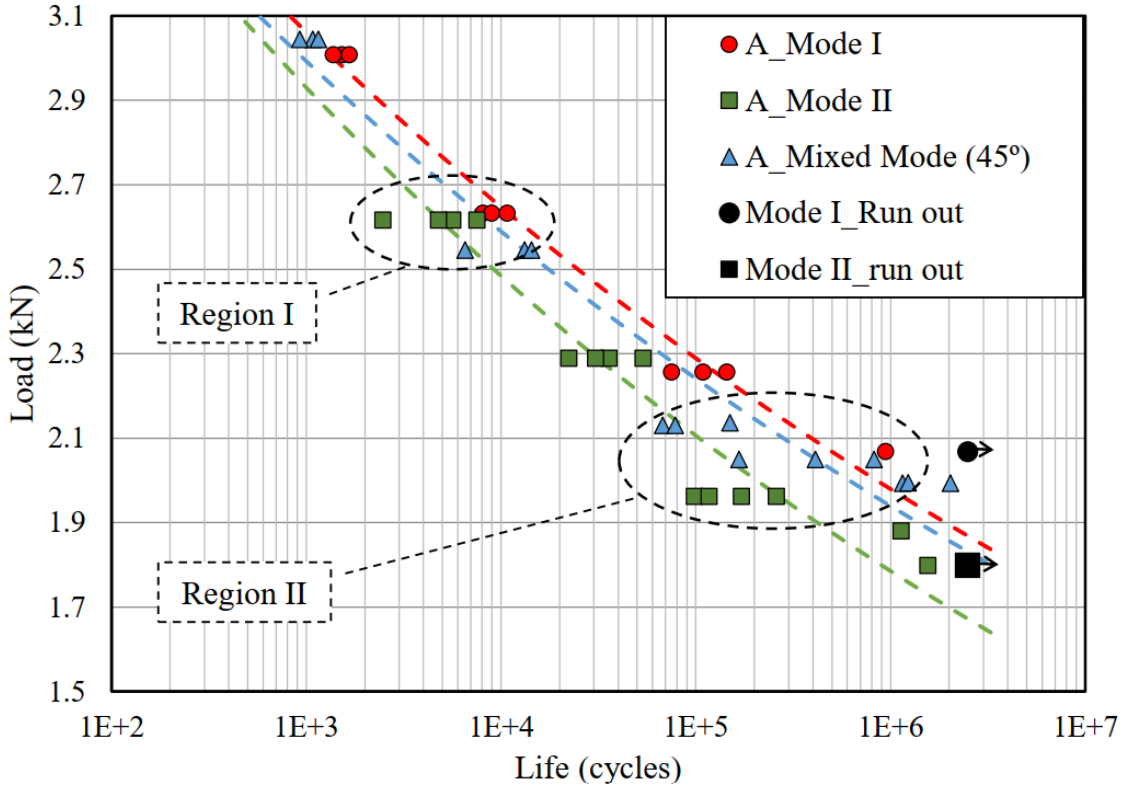


Figure A.6: L-N curves obtained for adhesive A under different mode mixities.

A.3.4 Effect of adhesive system

Three different adhesives, a one-part heat cured epoxy, a two-part room temperature cured epoxy, and an acrylic were used to assess the influence adhesive types on the

tensile fatigue behaviour of Arcan joints. The obtained results are plotted in Figure A.7. In these curves, instead of the usual maximum load, a load ratio was considered which is defined by the ratio of the applied load to the static strength of the joint under mode I loading conditions. As there is a big difference between the tensile static properties of all the adhesives, using load ratio instead of load level will help to have a better comparison between results. It is possible to observe that the fatigue resistance of adhesive B (acrylic) is always lower than the one obtained for adhesives A and C (epoxy adhesives). A reason can be the stiffness of the joint, that is lower for adhesive B and as stated previously, this affects the introduced energy per cycle. According to previous studies [10,26], the threshold fracture energy obtained for adhesive A is higher than the one obtained for adhesive B as presented in Table A.3. These two factors associated may be the cause for a lower fatigue resistance. Regarding the two adhesives with the same adhesive system, no major differences were found in their fatigue behaviour when they are tested at the same load ratio.

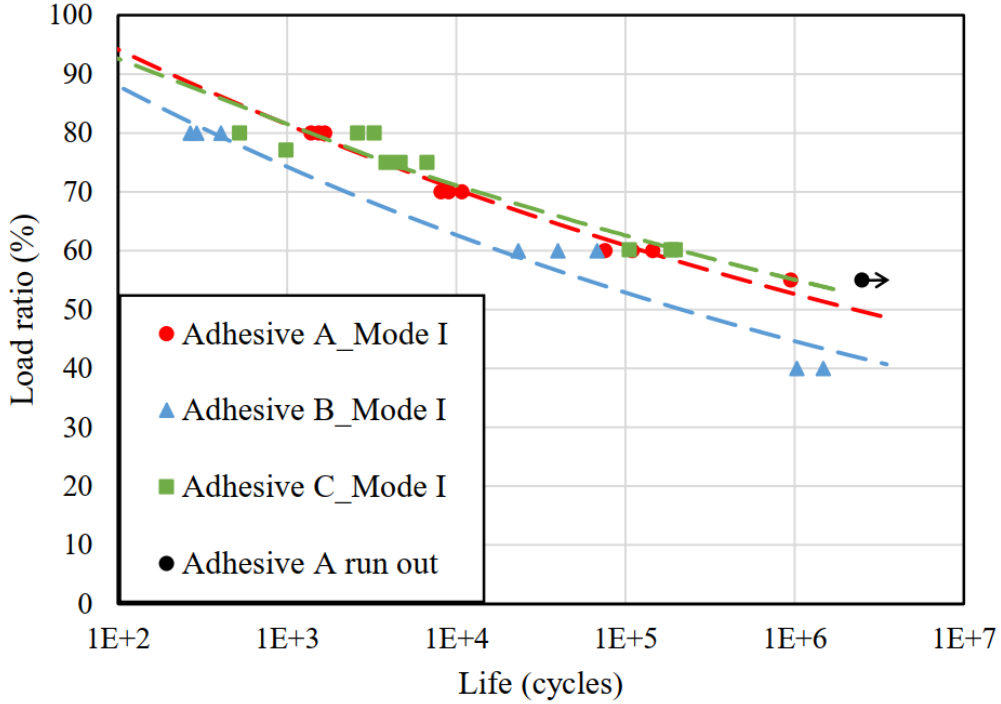


Figure A.7: L-N curves for three adhesives (A, B and C) under mode I loading condition using the load ratio.

A.3.5 Damage evolution

Stiffness (K) degradation of an adhesive joint can be a fatigue damage metric. To analyse the damage evolution during the fatigue life, the stiffness variation of the tested materials was analysed during the tests. Normalised load cycles, defined as the ratio between the current load cycle (N) and the total life (N_f), and normalised

stiffness defined based on Eq.(A.1) were used in this analysis.

$$\frac{K}{K_{0.1}} = \frac{\frac{F_{max}-F_{min}}{x_{max}-x_{min}}}{K_{0.1}}; K_{0.1} = K \left(\frac{N}{N_f} = 0.1 \right) \quad (A.1)$$

where the parameters are defined as follows:

F_{max} : maximum applied load per cycle.

F_{min} : minimum applied load per cycle.

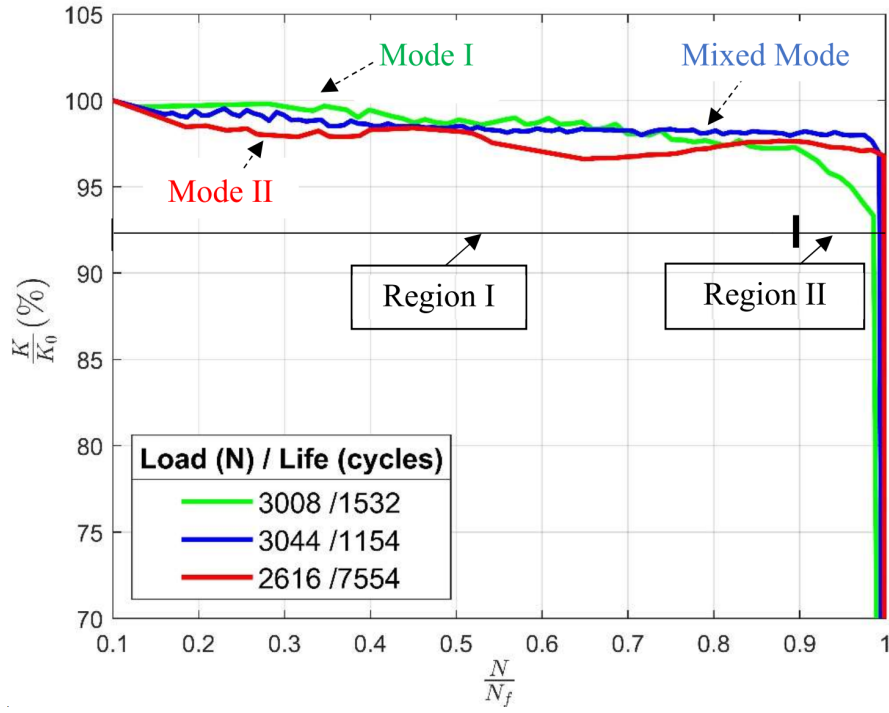
x_{max} : maximum axial displacement per cycle

x_{min} : minimum axial displacement per cycle

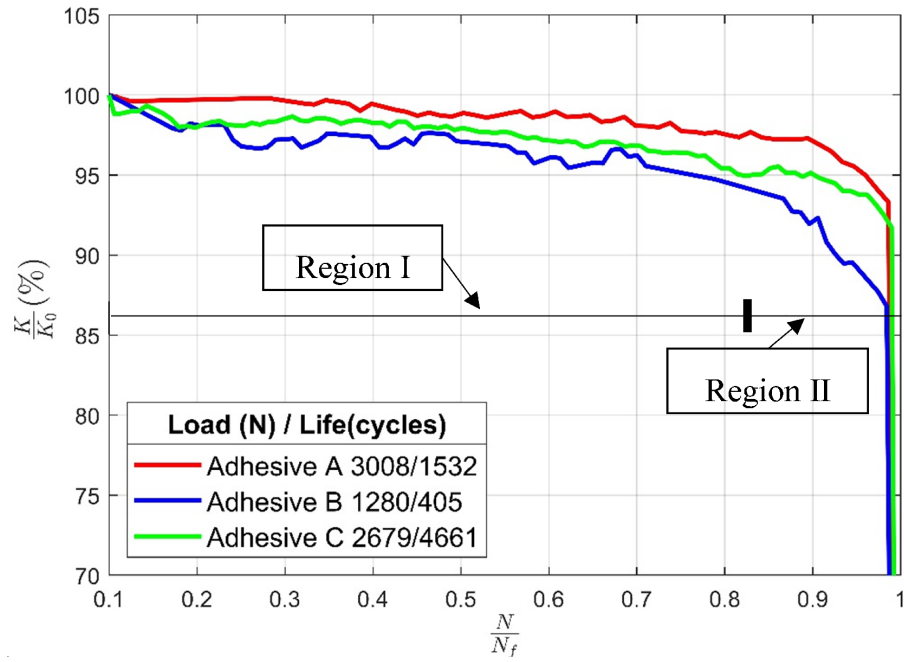
The stiffness degradation curves obtained for adhesive A and for different mode mixities are presented in Figure A.8a. The same analysis was performed for tensile fatigue tests for different adhesives. Results are presented in Figure A.8b. As it is indicated in Figure A.8, the initial 10% of life were not considered in this analysis as usually the loading condition is not fully stable for the initial parts of the tests. Using Figure A.8, it is possible to identify the overall trend of the curves. Similar stiffness degradation behaviour of adhesive joints can be found in literature [27–29].

The curves shown in Figure A.8 present two distinct regions (I and II). It is possible to identify these regions by the change of the slope of the trends of the curves. However, a boundary between the two regions is not perfectly defined. The approximated regions are depicted in Figure A.8. However, it should be noted that the length of each region depends on the mode mixity and on the adhesive considered. The first region (I) corresponds to a very slow degradation rate and in the second zone the stiffness degradation is very fast until a drastic drop that represents final failure. Region I, as shown in Figure A.8, represents a big percentage of the total life for all adhesives and mode mixities. Since any crack propagation leads to a big reduction in the joint stiffness, region I, with a very small stiffness reduction, can be considered as the fatigue initiation life. Given that, it is possible to infer that the initiation phase governs the total fatigue life and the crack propagates very fast until failure for the tested materials and conditions.

Regarding the different adhesives tested, it is shown that adhesives A and C, both epoxy-based, present a very similar behaviour, with a stiffness degradation of less than 9% until final failure. While for adhesive B which is an acrylic system, the second region of the curve begins much earlier and the stiffness degradation is higher than the one obtained for the other adhesives, about 15%.



(a) Adhesive A under different mode mixities.

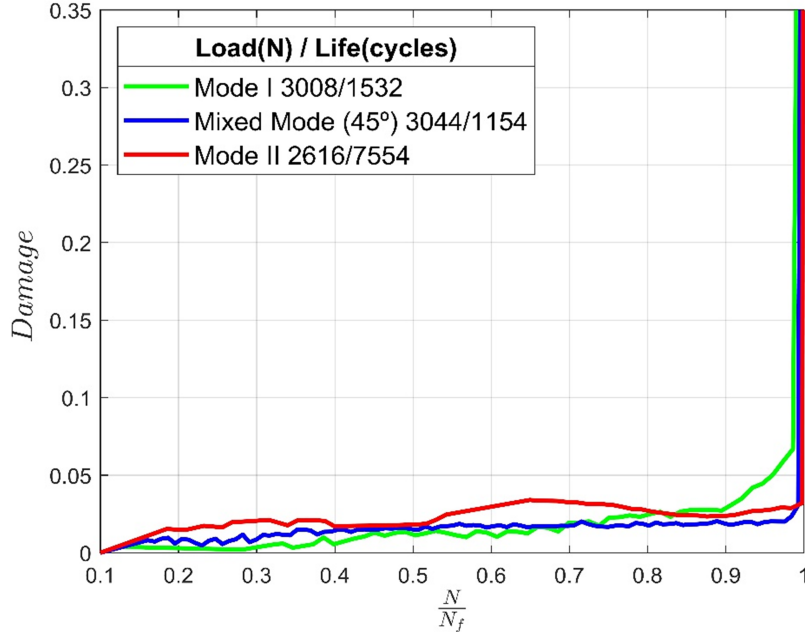


(b) Adhesives A, B and C.

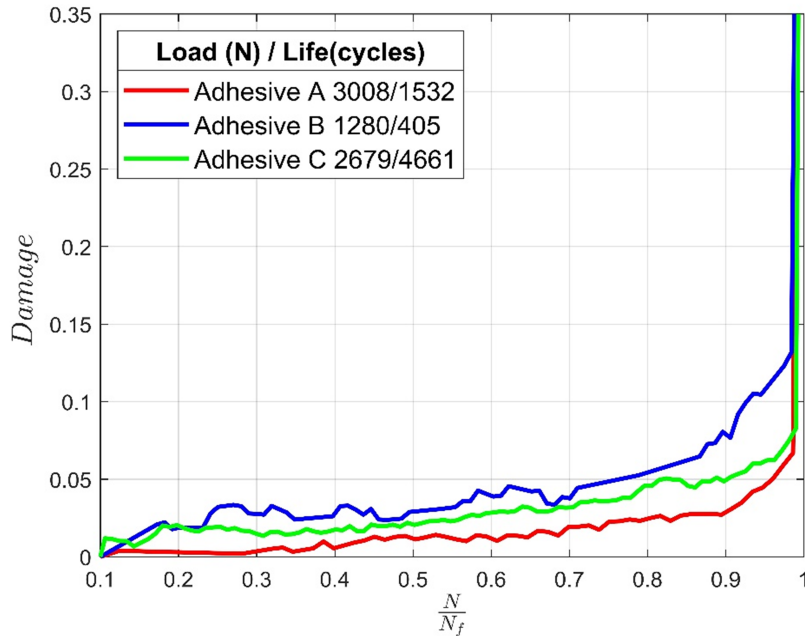
Figure A.8: Stiffness degradation for similar order of magnitude lives.

It is possible to define a fatigue damage variable (D) as: $D = 1 - \frac{K}{K_{0.1}}$, in order to analyse its evolution. Figure A.9 presents the damage evolution for adhesive

A under different mode mixities(A) and for the three adhesives in mode I loading conditions(B).



(a) Adhesive A for different mode mixities.



(b) Adhesives A, B and C.

Figure A.9: Damage evolution.

A.3.6 P-L-N curves

P-L-N curves are necessary during the design of components subjected to cyclic loading. In this section, P-L-N curves were produced for pure mode I test results, for different levels of probability of failure including 90%, 50% and 10%. The results are shown in Figure A.10 for adhesives A, B, and C.

The procedure used was in accordance with the model presented in [30]. The experimental data was assumed to be well represented by a line in a log-log plot. It was presumed that the logarithm of the fatigue life follows a normal distribution, considering a constant standard deviation and with a mean defined as $\mu = \alpha + \beta \times \log_{10} F$, where F is the load applied, and α and β are constant parameters. The latter were estimated using a maximum likelihood procedure.

A.3.7 Fatigue failure envelopes

A curve was fitted to the L-N results of adhesive A for each mode mixity. The fitted curve helps to estimate the fatigue life for the load levels with no experimental results. These data will be used for obtaining the fatigue envelope for any arbitrary fatigue life regime. The fatigue envelope is a curve in which the average shear stress is plotted against the average tensile stress for different mode mixities where the fatigue life is similar. Based on the obtained results, fatigue envelopes for adhesive A were produced for six different fatigue lives including $10^3, 10^4, 10^5, 5 \times 10^5$ and 10^6 cycles.

To obtain a better fit to the experimental L-N data points, two different regions (region a and region b) can be distinguished in L-N curves, as shown in Figure A.11a. The relation used for fitting the curve is $P_{max} = \alpha \times N^\beta$, where α and β are fitting constants, P_{max} is the maximum applied load for N cycles fatigue life. The fitted curves and load-life obtained for each mode mixity are presented in Table A.4. The average shear and tensile stresses were defined as the maximum applied load divided by the bonded area ($A = 125\text{mm}^2$). A schematic representation of the procedure used is presented in Figure A.11a.

Based on the data presented in Table A.4, envelopes were obtained as shown in Figure A.11b. The fatigue envelopes were constructed according to Eq. (A.2).

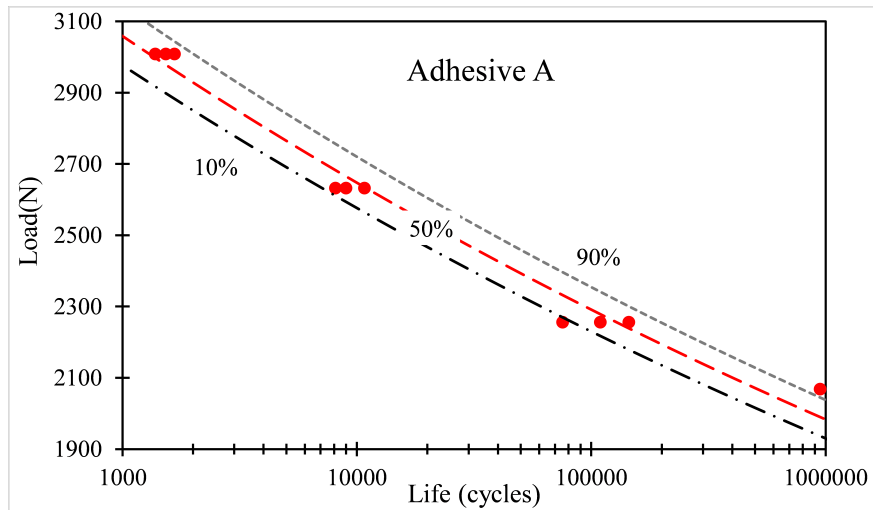
$$1 = \left(\frac{\tau_{ave}^4}{a} + \frac{\sigma_{ave}}{b} \right) \quad (\text{A.2})$$

where the parameters are defined as follows:

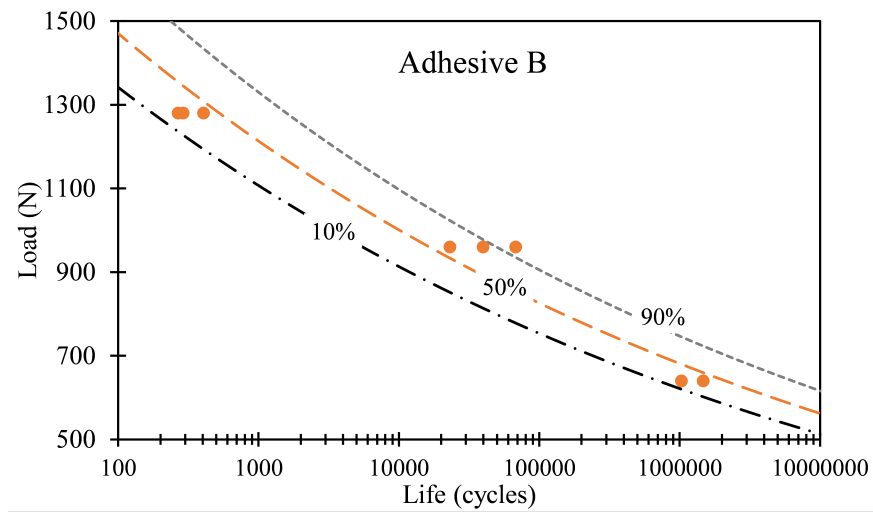
τ_{ave} : average shear stress

σ_{ave} : average tensile stress

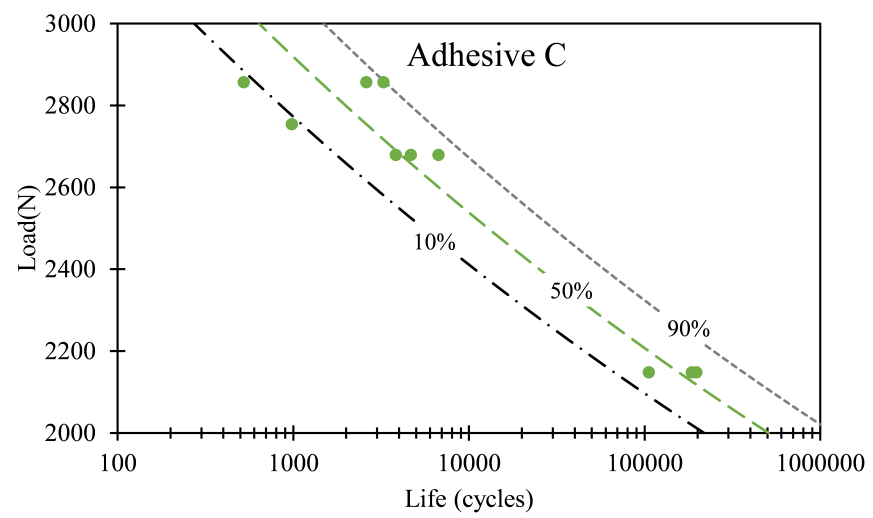
a, b : fitting parameters



(a) Adhesive A.



(b) Adhesive B.



(c) Adhesive C.

Figure A.10: P-L-N curves for adhesives under mode I loading condition.

Table A.4: Equations of the fitted curves and the obtained L-N pairs for different modes.

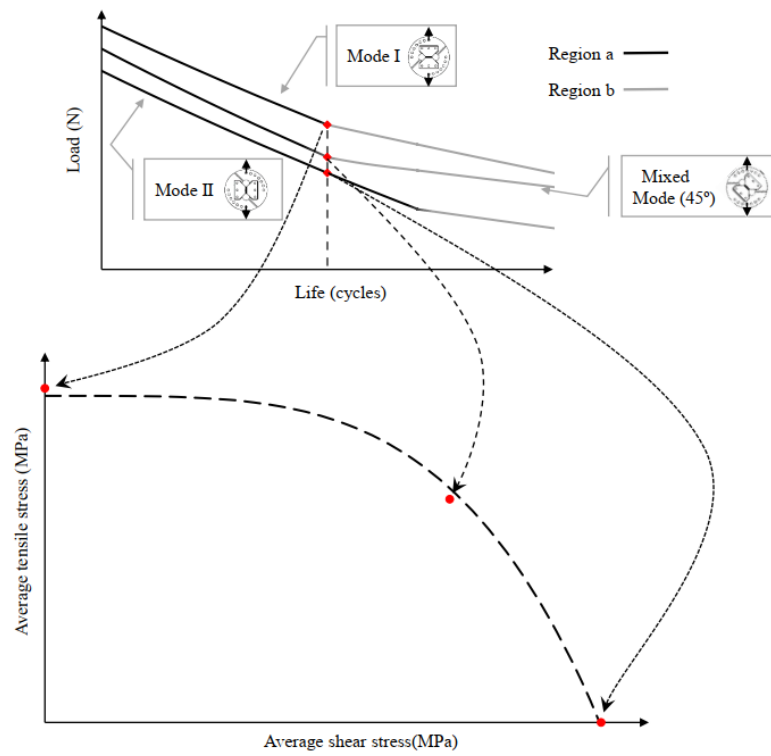
Fitted curve		Life (cycles)	Load (N)
Mode I	$\begin{cases} P = 4912 \times N^{-0.068}; & 0 < N < 10^5 \\ P = 3464 \times N^{-0.037}; & N \geq 10^5 \end{cases}$	10^3	3081
		10^4	2637
		10^5	2258
		5×10^5	2127
		10^6	2073
Mixed Mode (45°)	$\begin{cases} P = 5212 \times N^{-0.078}; & 0 < N < 10^5 \\ P = 2754 \times N^{-0.023}; & N \geq 10^5 \end{cases}$	10^3	3050
		10^4	2551
		10^5	2133
		5×10^5	2050
		10^6	2018
Mode II	$\begin{cases} P = 4945 \times N^{-0.076}; & 0 < N < 10^5 \\ P = 2728 \times N^{-0.028}; & N \geq 10^5 \end{cases}$	10^3	2934
		10^4	2466
		10^5	2072
		5×10^5	1896
		10^6	1860

It is possible to see that for higher values of life, the distance between the envelopes is reduced, which indicates that a small variation in the stress level represent a significant variation of the fatigue life.

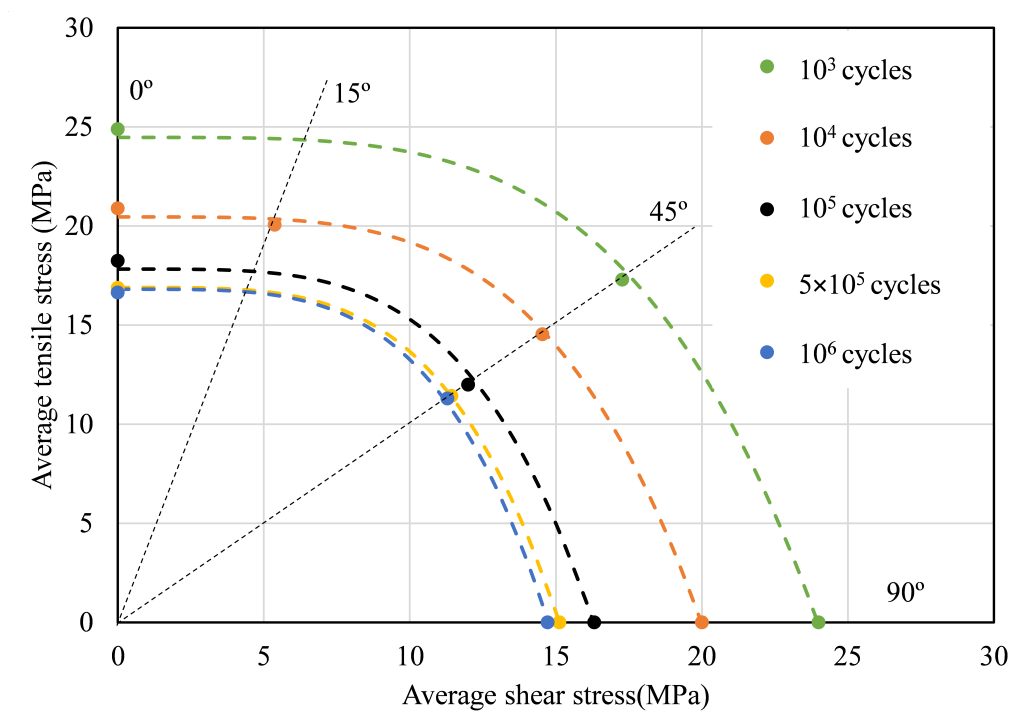
To assess the utility and effectiveness of this tool in giving an estimation of life for different load levels and different mode mixities, two fatigue tests were performed for a joint with a load angle of 15° and the results can be found in Table A.5. This point was added to the envelope as can be seen in Figure 11b. A linear interpolation between the 10^4 cycles and 10^5 cycles envelopes, for a constant value of maximum shear stress, was performed and the estimated life was 27611 cycles as presented in Table A.5. The ratio between the average experimental life and the estimated life is 2.83, which is satisfactory for a fatigue analysis. Therefore, this method allows a rough estimation of the life of a joint under different load angles and load levels.

Table A.5: Results for fatigue tests under mixed mode (15°) conditions.

Load	Average tensile stress (MPa)	Average shear stress (MPa)	Average experimental life (cycles)	Estimated life (cycles)
2596	20.06	5.38	9770	27611



(a) Schematic representation of the fatigue envelope construction procedure



(b) Adhesive A

Figure A.11: Fatigue envelopes.

A.4 Conclusions

In this paper, the influence of mode mixity on the fatigue behaviour of a structural epoxy-based adhesive was studied. Three different adhesive types (one acrylic and two different epoxies) were investigated to study their influence on the total fatigue life.

Out of the obtained experimental and post processing results, the following conclusions can be drawn:

- For the same load level, the presence of shear loading reduces the stiffness of the joint and consequently, a reduction of the fatigue life can be observed compared with pure tensile loading conditions.
- Although mode mixity did not have a big influence for lower fatigue lives, for high cycle fatigue the impact of mode mixity is significant where the ratio of the life obtained for mode I and mode II reached 10.
- The acrylic adhesive provides a lower fatigue strength than the epoxy adhesive even when compared to the static strength. The lower stiffness of the joint can be the reason for this behaviour.
- Stiffness degradation curves suggest that crack propagation concerns a small part of the total life and, therefore, fatigue crack initiation is predominant for the tested adhesive joints.
- Based on the results it was shown that the acrylic adhesive presents a higher stiffness degradation than the epoxy based.
- Fatigue envelopes can be a very useful design tool, giving an estimation of the fatigue life of a joint under different loading conditions and different mode mixities.

References

- [1] da Silva LFM, Öchsner A, Adams R. Handbook of Adhesion Technology. 2nd ed., 2018. https://doi.org/10.1007/978-3-642-01169-6_1.
- [2] Costa M, Viana G, da Silva LFM, Campilho RDSG. Environmental effect on the fatigue degradation of adhesive joints: A review. *J Adhes* 2017;93:127–46. <https://doi.org/10.1080/00218464.2016.1179117>.
- [3] Pereira AM, Reis PNB, Ferreira JAM. Effect of the mean stress on the fatigue behaviour of single lap joints. *J Adhes* 2017;93:504–13. <https://doi.org/10.1080/00218464.2015.1110699>
- [4] Azari S (Shahrokh), Ameli A, Datla N, Papini M, Spelt JK. Effect of substrate modulus on the fatigue behavior of adhesively bonded joints. *Mater Sci Eng A* 2012;534:594–602. <https://doi.org/10.1016/j.msea.2011.12.014>.
- [5] de Barros S, Kenedi PP, Ferreira SM, Budhe S, Bernardino AJ, Souza LFG. Influence of mechanical surface treatment on fatigue life of bonded joints. *J Adhes* 2017;93:599–612. <https://doi.org/10.1080/00218464.2015.1122531>.
- [6] Underhill PR, Duquesnay DL. The dependence of the fatigue life of adhesive joints on surface preparation. *Int J Adhes Adhes* 2006;26:62–6. <https://doi.org/10.1016/j.ijadhadh.2005.03.006>.
- [7] Zhang Z, Shang JK, Jr. FVL. A Backface Strain Technique for Detecting Fatigue Crack Initiation in Adhesive Joints. *J Adhes* 1995;49:23–36. <https://doi.org/10.1080/00218469508009975>.
- [8] Shenoy V, Ashcroft IA, Critchlow GW, Crocombe AD, Abdel Wahab MM. An investigation into the crack initiation and propagation behaviour of bonded single-lap joints using backface strain. *Int J Adhes Adhes* 2009;29:361–71. <https://doi.org/10.1016/J.IJADHADH.2008.07.008>.
- [9] Abdel Wahab M. Fatigue in Adhesively Bonded Joints: A Review. *ISRN Mater Sci* 2012;2012. <https://doi.org/10.5402/2012/746308>.
- [10] Monteiro J, Akhavan-Safar A, Carbas R, Marques E, Goyal R, El-zein M, et al. Influence of mode mixity and loading conditions on the fatigue crack

- growth behaviour of an epoxy adhesive. *Fatigue Fract Eng Mater Struct* 2020;43:308–16. <https://doi.org/10.1111/ffe.13125>.
- [11] Rocha AVM, Akhavan-Safar A, Carbas R, Marques EAS, Goyal R, El-Zein M, et al. Paris law relations for an epoxy-based adhesive. *Proc Inst Mech Eng Part L J Mater Des Appl* 2020;234:291–9. <https://doi.org/10.1177/1464420719886469>.
- [12] Rocha AVM, Akhavan-Safar A, Carbas R, Marques EAS, Goyal R, El-zein M, et al. Numerical analysis of mixed-mode fatigue crack growth of adhesive joints using CZM. *Theor Appl Fract Mech* 2020;106:102493. <https://doi.org/https://doi.org/10.1016/j.tafmec.2020.102493>.
- [13] Monteiro J, Akhavan-Safar A, Carbas R, Marques E, Goyal R, El-zein M, et al. Mode II modeling of adhesive materials degraded by fatigue loading using cohesive zone elements. *Theor Appl Fract Mech* 2019;103:102253. <https://doi.org/https://doi.org/10.1016/j.tafmec.2019.102253>.
- [14] <https://doi.org/https://doi.org/10.1016/j.tafmec.2019.102253>. [14] Ebadi-Rajoli J, Akhavan-Safar A, Hosseini-Toudeshky H, Silva] LFM [da. Progressive damage modeling of composite materials subjected to mixed mode cyclic loading using cohesive zone model. *Mech Mater* 2020;143:103322. <https://doi.org/https://doi.org/10.1016/j.mechmat.2020.103322>.
- [15] Ajdani A, Ayatollahi MR, Akhavan-Safar A, da Silva] LF [Martins. Mixed mode fracture characterization of brittle and semi-brittle adhesives using the SCB specimen. *Int J Adhes Adhes* 2020;101:102629. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2020.102629>.
- [16] Tserpes K, Floros I. Fatigue crack growth simulation in adhesively bonded composite joints. *Fatigue Fract Eng Mater Struct* 2019;42:1430–40. <https://doi.org/10.1111/ffe.12969>.
- [17] Akhavan-Safar A, Salamat-talab M, Ajdani A, Ayatollahi MR, da Silva LFM. Mode II fracture energy characterization of brittle adhesives using compliance calibration method. *Fatigue Fract Eng Mater Struct* n.d.;n/a. <https://doi.org/10.1111/ffe.13244>.
- [18] Ayatollahi MR, Ajdani A, Akhavan-Safar A, Silva] LFM [da. Effect of notch length and pre-crack size on mode II fracture energy of brittle adhesives. *Eng Fract Mech* 2019;212:123–35. <https://doi.org/https://doi.org/10.1016/j.engfracmech.2019.03.024>.
- [19] Jen Y-M. Fatigue life evaluation of adhesively bonded scarf joints. *Int J Fatigue* 2012;36:30–9. <https://doi.org/https://doi.org/10.1016/j.ijfatigue.2011.08.018>.

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- [20] Imanaka M, Iwata T. Fatigue Failure Criterion of Adhesively-Bonded Joints Under Combined Stress Conditions. *J Adhes* 1996;59:111–26. <https://doi.org/10.1080/00218469608011081>.
- [21] Imanaka M, Iwata T. Estimation of Fatigue Strength for Adhesively-Bonded Lap Joints Based on Fatigue Failure Criterion Under Multiaxial Stress Conditions. *J Adhes* 1998;65:7–24. <https://doi.org/10.1080/00218469808012236>.
- [22] Beber VC, Fernandes PHE, Schneider B, Brede M, Mayer B. Fatigue life-time prediction of adhesively bonded joints: An investigation of the influence of material model and multiaxiality. *Int J Adhes Adhes* 2017;78:240–7. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2017.08.007>.
- [23] Li H, Zhang J, Shen HZ, Wei XL. Multiaxial fatigue experiments and life prediction for silicone sealant bonding butt-joints. *Theor Appl Fract Mech* 2019;103:102245. <https://doi.org/10.1016/j.tafmec.2019.102245>.
- [24] Hiley MJ. Fractographic study of static and fatigue failures in polymer composites. *Plast Rubber Compos* 1999;28:210–27. <https://doi.org/10.1179/146580199101540358>.
- [25] Fleck NA, Hutchinson JW, Zhigang S. Crack path selection in a brittle adhesive layer. *Int J Solids Struct* 1991;27:1683–703. [https://doi.org/https://doi.org/10.1016/0020-7683\(91\)90069-R](https://doi.org/https://doi.org/10.1016/0020-7683(91)90069-R).
- [26] Rocha A, Akhavan-Safar A, Carbas R, Marques E, Goyal R, El-Zein M, et al. Fatigue crack growth analysis of different adhesive systems: Effects of mode mixity and load level. *Fatigue Fract Eng Mater Struct* 2019. <https://doi.org/10.1111/ffe.13145>.
- [27] Ferreira JAM, Reis PN, Costa JDM, Richardson MOW. Fatigue behaviour of composite adhesive lap joints. *Compos Sci Technol* 2002;62:1373–9. [https://doi.org/https://doi.org/10.1016/S0266-3538\(02\)00082-9](https://doi.org/https://doi.org/10.1016/S0266-3538(02)00082-9).
- [28] Harris JA, Fay PA. Fatigue life evaluation of structural adhesives for automotive applications. *Int J Adhes Adhes* 1992;12:9–18. [https://doi.org/https://doi.org/10.1016/0143-7496\(92\)90003-E](https://doi.org/https://doi.org/10.1016/0143-7496(92)90003-E).
- [29] Pereira AM, Ferreira JM, Antunes F V, Bártolo PJ. Study on the fatigue strength of AA 6082-T6 adhesive lap joints. *Int J Adhes Adhes* 2009;29:633–8. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2009.02.009>.
- [30] Paolino DS, Chiandussi G, Rosseto M. A unified statistical model for S-N fatigue curves: probabilistic definition. *Fatigue Fract Eng Mater Struct* 2013;36:187–201. <https://doi.org/10.1111/j.1460-2695.2012.01711.x>.

Appendix B

Paper 2

Fatigue life estimation of adhesive joints at different mode mixities

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Abstract

Fatigue life prediction of adhesive joints is a concern when using this bonding technique in structural components where the joints are subjected to multiaxial stress states. Thus, the development of a fatigue failure criterion that accounts for the effect of mode mixity is crucial. The main aim of the present study is to develop a fatigue model to be able to predict the fatigue life of an epoxy-based adhesive loaded at different mode mixities. For this purpose, Arcan joints were manufactured and tested in pure modes (I and II), and mixed mode loading conditions. Using the obtained experimental data for pure mode loading conditions, a master S-N curve was constructed based on a proposed effective stress. According to this curve and by considering the numerical simulations, the fatigue lives of the joints under mixed mode conditions were estimated. Two different relations (Basquin and Stromeyer) were considered in this study. The influence of the number of load levels considered for the master curve was also analysed. It was found that more experimental results for the reference samples do not necessarily lead to a better estimation. Results show a good agreement between the experimental data and the predicted fatigue lives based on the proposed model.

B.1 Introduction

The rise in popularity that adhesive joints have been subjected in the last decades is not unfounded, due to the many advantages that this bonding technique presents. Adhesive joints are nowadays a very important joining method in a wide range of sectors such as civil engineering, automotive, aerospace and shoe manufacturing [1,2]. They can be used to produce multimaterial structures with a better strength-to-weight ratio. They also offer a more uniform stress distribution than conventional fastening methods, resulting in a higher stiffness and a superior fatigue strength [3–5].

In real applications, adhesively bonded components commonly experience fatigue loading conditions. Despite the enhanced fatigue strength, their mechanisms of long-term cyclic behaviour are not yet completely defined. Thus, it is important to develop fatigue life prediction methodologies to deal with the nefarious impact that such fatigue regime has in bonded structures [6]. Fatigue life consists of two sequential stages. The initial stage is the fatigue life part prior to the crack nucleation, commonly denominated as crack initiation. The second one is labelled as crack propagation and corresponds to the propagation of the crack until final failure occurs [7]. Efforts have been done to understand which percentage of the fatigue life is spent at each stage. This has been investigated using the back-face strain technique [8–10]. These studies show that generally, at lower load levels, where the applied load is well below the yielding point of the adhesive, life is dominated by the initiation stage, while for higher load levels the crack propagation is prevailing. The existence of these two stages of the fatigue life has influence on how fatigue failure criteria are categorised.

The failure of engineering materials is usually assessed using criteria that are distinguished according to the nature of the parameter being used and are therefore classified as stress, strain or energy based [11]. However, in the fatigue context it is more interesting to categorise the approaches undertaken to develop fatigue failure criteria into three different groups: fracture mechanics methods, damage mechanics based and total life models. In the first, only the fatigue crack propagation life is considered and the difficulty of dealing with the crack nucleation is put aside. This topic has been vastly studied in the literature both experimentally and numerically, including studies that deal with the influence of mode mixity [12–17]. The damage mechanics based methods can deal with both fatigue life phases as it allows to model the progressive degradation of adhesives [4,18]. The last method is also denominated as the S-N approach where a load-related variable is plotted against the number of cycles until failure through experimental testing. The main difficulty when handling this approach is the transferability of the S-N results to different geometries and loading conditions. To deal with this disadvantage, an effective stress or strain (or a combination of both) is commonly considered. It is the combination of two different aspects, the equivalent parameter that governs the fatigue failure and the point

where this parameter should be measured. The second can be either the maximum value or a smaller value measured at a specific distance away from the maximum points. This distance is called critical distance and has been already investigated in the literature [19].

Despite some constraints, the S-N method remains a simple powerful tool and has been used widely by many authors to investigate the fatigue life of adhesive joints. Imanaka and Iwata [20] tested scarf and butterfly type joints subjected to fatigue loading with different mode mixities. They studied the effect of such loading conditions on the endurance limit of adhesively bonded joints. They considered different effective stresses including the maximum principal stress, the von Mises stress and the maximum shear stress, all measured at the uniform region of the stress distribution. They found a relation between these three types of effective stresses at the endurance limit where the fatigue life is around 107 cycles. The method was then extended by considering the point stress criterion where the endurance limit of single and double lap joints was predicted [21]. Jen [22] analysed the fatigue behaviour of scarf joints and found that an increase in the scarf angle is responsible for a change of the failure mechanism from adhesive to cohesive, resulting in an increase in the fatigue strength. They proposed a fatigue life prediction using two distinct effective stresses according to the failure mechanism: the maximum interfacial peel stress for adhesive failure and the maximum von Mises stress for cohesive failure. Results reflected the importance of considering an effective stress representative of the failure mechanism. Shahani and Pourhosseini [23] investigated both experimentally and numerically the influence of adherend thickness on the fatigue behaviour of thin aluminium single lap joints bonded by an epoxy structural adhesive film. The fatigue lifetime prediction was carried using the Smith, Watson, Topper (SWT) criterion that considers the mean stress and the plastic strain effects. The SWT parameters were extracted at the maximum principal strain location using a finite element analysis. Drucker-Prager equivalent stress along with a critical distance approach were considered by Beber et al. [24] to analyse the stress concentration effects on fatigue life prediction of adhesive joints. To achieve this, they tested three different notched bulk specimens and a single lap joint. The results showed good correlation between the experimental data and the estimated results.

The S-N approach has in its simplicity, the reason why it is still very relevant today. The importance of such design methodology is undeniable, specifically in the design of bonded structures for industrial applications. Although some researchers have dealt with the effect of mode mixity on adhesive joints, a life prediction model, based on the total life method, that accounts for the influence of all mode mixities from pure mode I to pure mode II on the fatigue life of adhesive joints has not been studied. The aim of the current work is to develop a fatigue model able to predict the fatigue life of an epoxy based adhesive joint under different mode mixities. To achieve this, Arcan joints were manufactured and tested under fatigue loading at different load levels and different mode mixities. A Finite Element Analysis (FEA)

was carried to attain the proposed effective stress. The model was validated by estimating the life of the joints subjected to mixed mode fatigue loading conditions. The curve fitting approach and the number of experimental data points used for the construction of the master curve have key roles in the precision of the results. Both parameters have been considered in this study.

B.2 Experimental details

B.2.1 Materials and joint preparation

A high performance and impact resistant one-component structural epoxy-based adhesive was used to bond high strength steel substrates. In a previous study [15], the adhesive behaviour was characterised in terms of mechanical properties. A typical tensile stress-strain curve is shown in Figure B.1. The mechanical properties of the adhesive are presented in Table B.1.

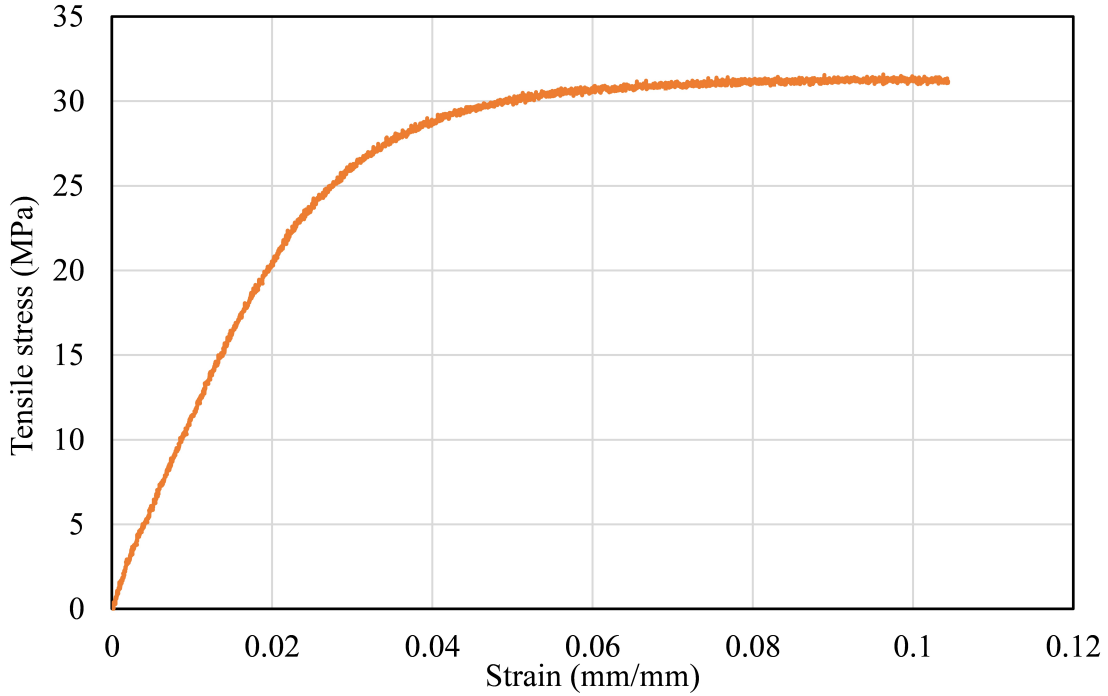


Figure B.1: Typical tensile stress-strain curve [15].

High strength steel Arcan specimens with a thickness of 10 mm (shown in Figure B.2) were used as substrate.

For surface treatment the substrates were sandblasted and then cleaned with acetone. The mould shown in Figure 3 was used to control the geometry in the manufacturing process. As shown in Figure 3 the adhesive thickness was controlled using a 0.2 mm calibrated metal spacer.

Table B.1: Adhesive mechanical properties [15].

Adhesive properties	
Maximum tensile strength (MPa)	31.3 ± 0.6
Maximum tensile strain (%)	10.4 ± 0.5
Maximum shear strength (MPa)	23.1 ± 0.5
Maximum shear strain (%)	43.3 ± 0.9
Young's Modulus (MPa)	1159 ± 29.3
Shear Modulus (MPa)	440 ± 8.7
Poisson's ratio, ν	0.32 ± 0.03

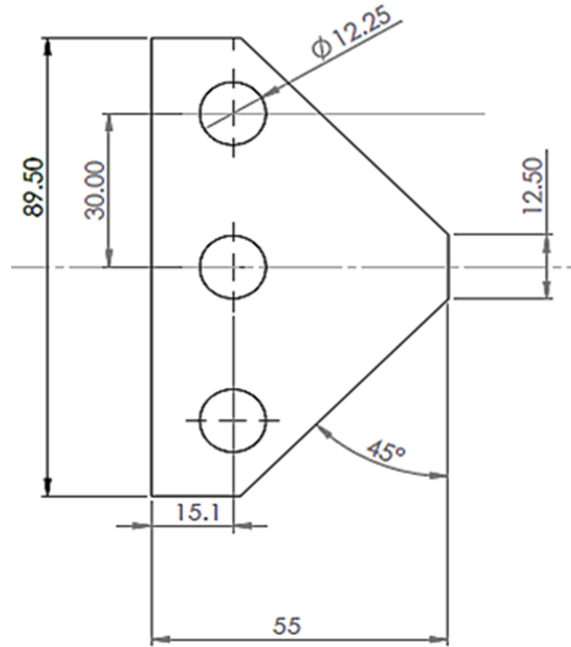


Figure B.2: Arcan specimen (only half is represented) (dimensions in mm).

The curing temperature was set to 210°C for a period of 65 min and was applied using a hot plate press. The pressure was applied on the joints to prevent joints misalignment during the heat curing process. The cured specimens were then kept at room conditions for 5 days. Before testing, a metal file was used to remove the excess adhesive around the overlap.

B.2.2 Testing conditions

Static tests were initially conducted in Arcan joints to assess the influence of mode mixity on the static strength and to define the load levels at which the fatigue tests should be conducted. Both the static and fatigue tests were performed at room

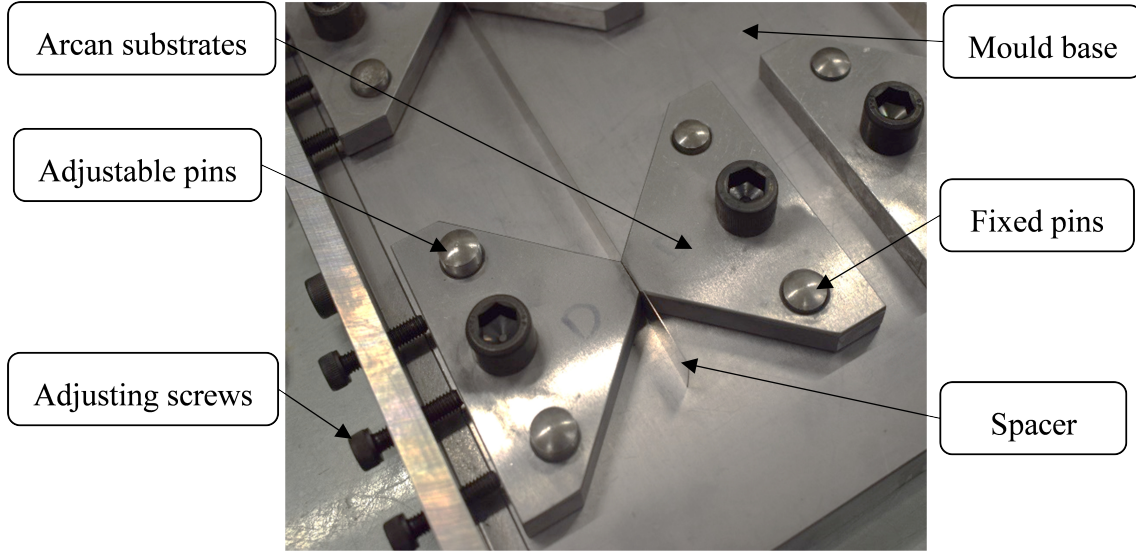


Figure B.3: Arcan specimens manufacturing mould.

conditions using an Instron 8801 servo-hydraulic testing machine. The Arcan joints were mounted on the testing machine using the apparatus presented in Figure B.4. Two pins were used for load transmission along with a bolt that was used to prevent out of plane misalignments of the sample during the tests. To analyse the effect of mode mixities, three loading angles defined in Figure B.5 were considered. The studied angles were 0° (mode I), 45° and 90° (mode II).

Fatigue tests were carried under load control condition, with a sinusoidal waveform, at a loading frequency of 10 Hz and a load ratio (R) of 0.1 where $R = F_{min}/F_{max}$. In this relation, F_{max} and F_{min} denote the maximum and minimum applied loads, respectively. Static tests were controlled by displacement where the rate of the loadline displacement was set to 1 mm/min.

B.3 Proposed fatigue model

The proposed fatigue model consists of two major components: the prediction procedure and the proposed effective stress, which are separately discussed below.

B.3.1 Fatigue life prediction procedure

The fatigue life prediction procedure has two main steps. The first one is obtaining a master curve. Based on the proposed method, the master curve is obtained through experimental testing of Arcan joints in pure modes I and II loading conditions. For each mode mixity three fatigue data points should be obtained experimentally at arbitrary load levels. However, as it is discussed in Section B.5.3, the load levels should be selected so that they can cover fatigue lives from 10^3 to 10^6 cycles. To obtain a master curve, an effective fatigue stress should be considered. In this study

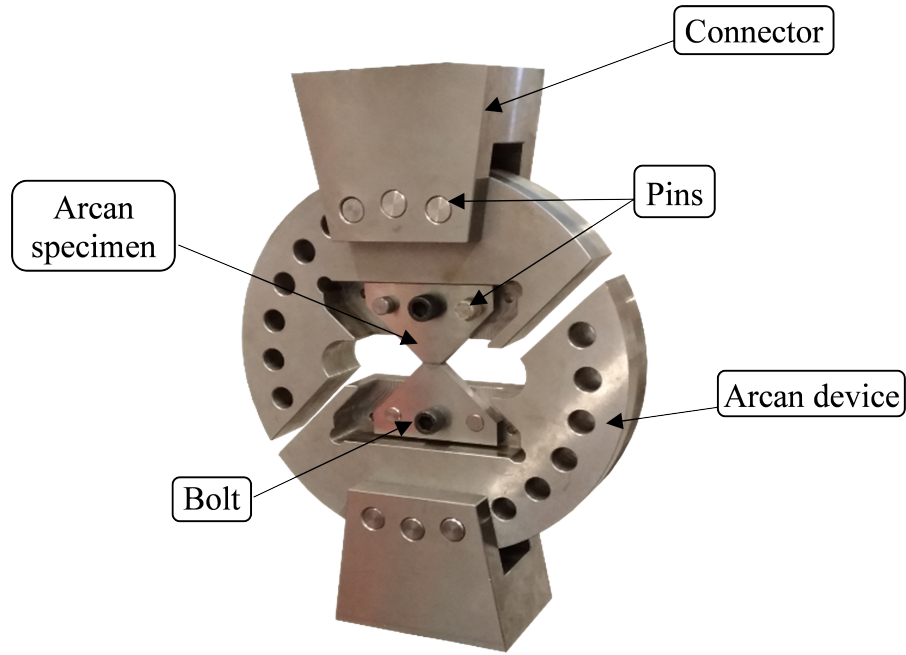


Figure B.4: Arcan apparatus.

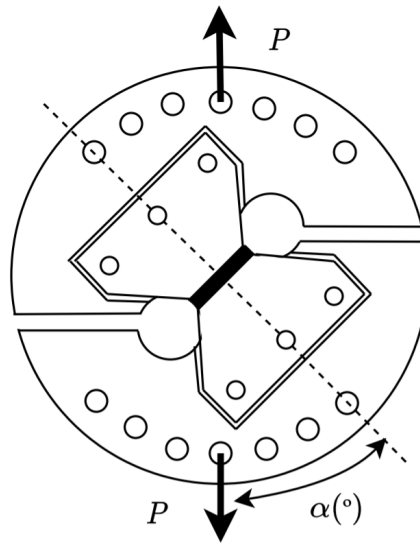


Figure B.5: Load angle definition.

an effective stress is proposed based on the von Mises and the hydrostatic stresses as discussed in the next section.

Using the experimental data for pure modes I and II, a 2D linear elastic FEA should be carried out to measure the effective stress for the tested conditions. Then the effective stress should be plotted as a function of the corresponding fatigue life for each test condition, originating the reference points. Next, a curve should be fitted to the reference points using the most common relation (Basquin). Some important aspects of the construction of the master curve are the number of considered load

levels, the effect of finite element model, mesh size, and the relation that should be used to fit the experimental results. The effects of these parameters have been analysed in this study.

The second step is measuring the effective stress in a joint in which the fatigue life should be predicted. For this purpose, again only a 2D linear elastic FEA is required. Once the effective stress for the joint under analysis is calculated, it should be compared to the master curve previously generated. A value of effective stress corresponds to a specific value of life. Due to that, obtaining the effective stress for the desired joint configuration means that an estimation of its fatigue life is achieved. It should be noted that the proposed model is intended for adhesive joints that fail cohesively. The prediction procedure is schematically shown in Figure B.6.

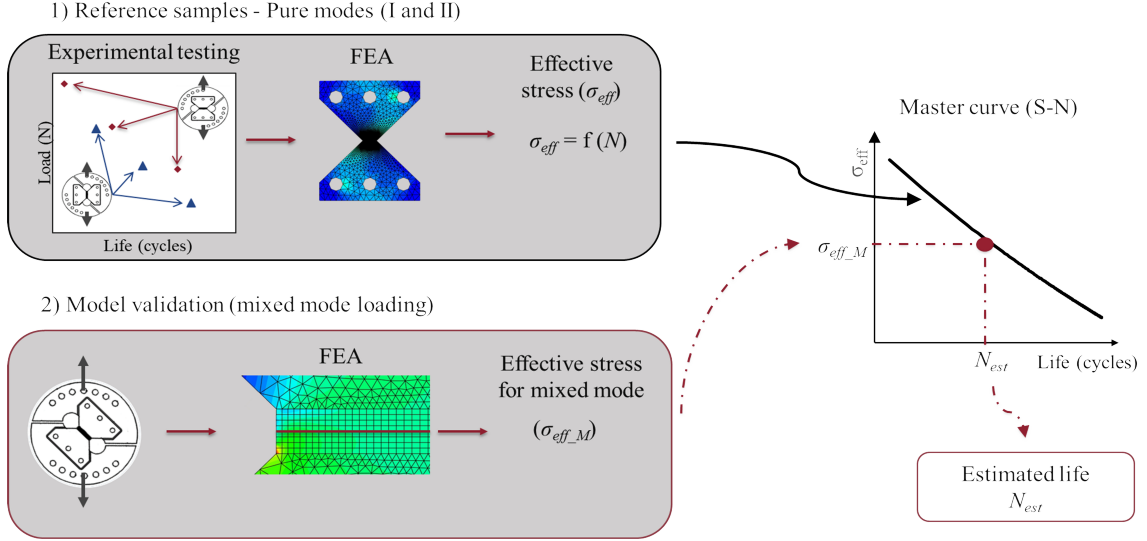


Figure B.6: Schematic representation of the estimation procedure.

B.3.2 Effective stress

A new effective stress composed by parameters that play a key role in the fatigue behaviour of adhesive joints is proposed in Eq. (B.1).

$$\sigma_{eff} = \sigma_{VM} + (\sigma_H \times S) \quad (B.1)$$

where:

σ_{eff} : Effective stress

σ_{VM} : von Mises stress

σ_H : Hydrostaic stress

The proposed effective stress is the combination of the von Mises stress, the hydrostatic stress and the stress triaxiality (S). Stress triaxiality is defined as the ratio between hydrostatic stress and von Mises stress ($\frac{\sigma_H}{\sigma_{VM}}$). The von Mises stress is commonly used for metals, however, it has been proven to be inaccurate for adhesives for not taking in account the effect of hydrostatic stress. Hydrostatic stress is the stress responsible for volume change without changing the shape [4,25]. It is widely acknowledged that polymers and adhesives behaviour exhibit a hydrostatic stress dependence. This is due to two main reasons. Firstly, the yield stress in compression is different from the one obtained in tension. The second reason is due to the crazing as a failure phenomenon that consists in the formation of microvoids under tensile loads. Microvoids grow and develop thin fibrils and then originate a crack [26,27]. The stress triaxiality, also known as the triaxiality ratio [28], is a parameter that quantifies the multiaxial stress state within the adhesive layer. The adhesive is subjected to a multiaxial stress state, in part caused by the constraints imposed by the substrates [25]. Moreover, stress triaxiality is also related to crack initiation as it linked to the void growth [28]. Higher stress triaxiality values show that the role of the hydrostatic stresses in adhesive fatigue failure is more significant than the von Mises stress. It has also been shown that the stress triaxiality plays a key role in adhesives tensile fracture energy (G_{IC}) [29].

Another crucial part of the effective stress is the location where this stress should be measured. According to the proposed model, to obtain the fatigue effective stress, the von Mises stress and the hydrostatic stress should be measured along the adhesive mid-plane, at the location where the maximum principal stress is higher, as shown in Figure B.7. The maximum principal stress as an important stress has been already used as an equivalent stress in some fatigue life prediction models [24]. For more brittle materials it is assumed that a crack propagates in a direction perpendicular to the maximum principal stress direction, which makes the point with the highest value of the maximum principal stress a critical location.

B.4 FEA details

According to the proposed model, FEA should be performed on the reference joints to measure the effective stress values at critical points. This analysis intends to obtain the maximum principal stress, the von Mises stress and the hydrostatic stress distribution along the mid-plane of the bondline, shown in Figure B.8. In this study, the reference joints are the Arcan joints under pure modes I and II loading conditions. A 2D linear elastic FEA was performed which allows a short computation time. This type of analysis only needs two adhesive behaviour parameters, Young's modulus, obtained from the bulk test and the Poisson's ratio obtained from the relation between the Young's modulus and the shear modulus. The considered mesh configuration is presented in Figure 8 where two types of solid elements were used: 3-node (triangular shaped) plain strain elements for the substrates and 4-node plain

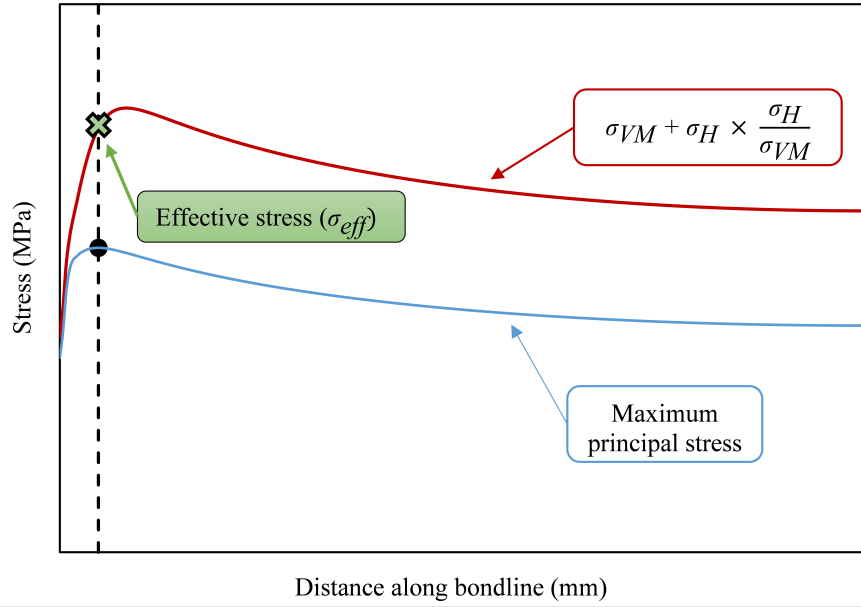


Figure B.7: Effective stress determination.

strain elements on the bondline. In the latter, eight elements were used along the thickness and a mesh refinement was carried out near the free ends, as can be seen in Figure B.8b.

Regarding the boundary conditions used, they aim to describe accurately the real conditions found on the experimental setup. As shown in Figure B.9, only the movement in the perpendicular direction to the applied load was restricted. The load was applied to the region of the substrate holes that are in contact with the pins. The FEA analysis of the joints was carried out at the maximum applied load during each fatigue test.

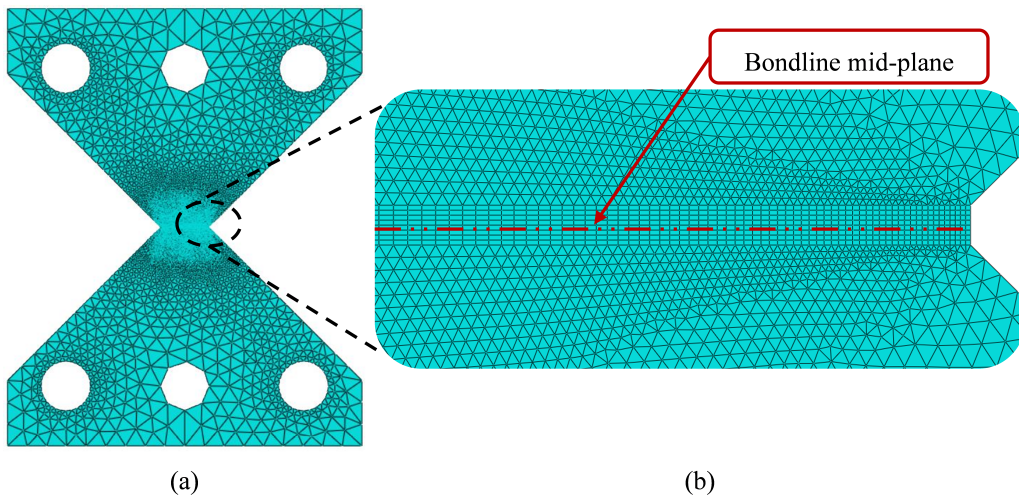


Figure B.8: (a) Mesh used for 2D simulation; (b) bondline mesh detail.

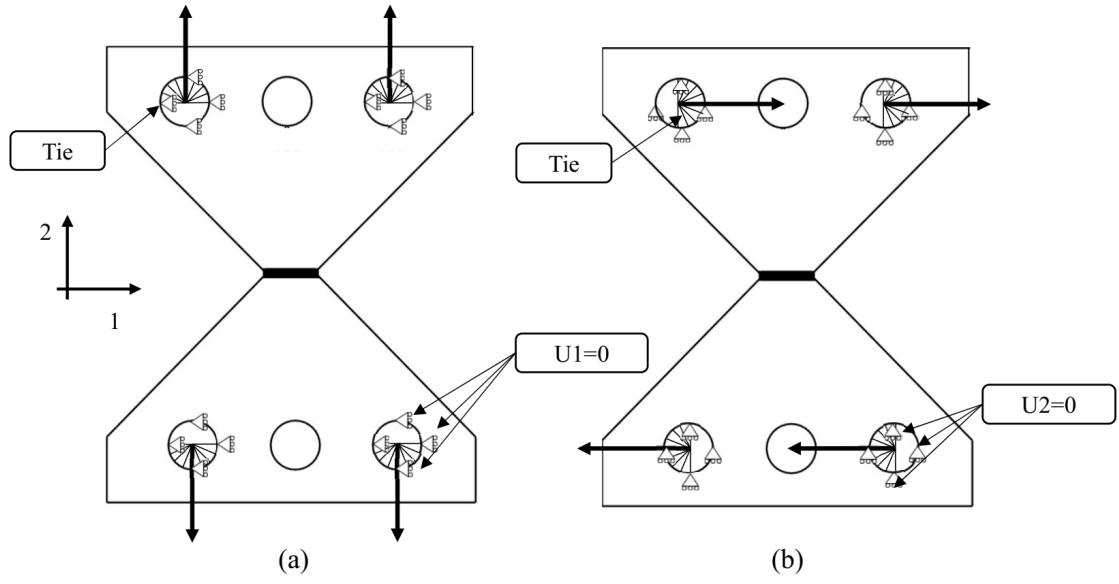


Figure B.9: Boundary conditions for pure mode loading conditions: (a) Mode I; (b) Mode II.

B.5 Results and discussion

B.5.1 Experimental results

The average static strength (average failure load divided by the bonded area A ($A = 125\text{mm}^2$)) are presented in Table B.2. For the mixed mode condition, the average failure strength was divided into two components, tensile and shear. These two components can be obtained by multiplying the average failure strength by the cosine or sine of the load angle for the shear tensile component, respectively. It is possible to observe a reduction in strength with the increase of load angle.

Table B.2: Static failure loads.

	Mode I	Mode II	Mixed mode (45°)	
Failure load (N)	3760 ± 300	3270 ± 180	3480 ± 150	
Average failure strength (MPa)	30.08 ± 2.40	26.16 ± 1.44	Tensile	Shear
			19.70 ± 0.84	19.70 ± 0.84
Number of tested specimens	3	3	4	

Fatigue tests were then performed at different load levels by taking in account the static results and to cover different fatigue lives from 10^3 cycles to 2.5×10^6 cycles. The fatigue tests results for different mode mixities are presented in Figure B.10. In Figure B.10 the vertical axis is the maximum applied load and the horizontal axis

is the total fatigue life. In these experiments, tests with lives higher than 2.5×10^6 cycles were considered as run outs. Results show that for similar load levels, the increase of load angle causes a reduction in fatigue strength. Such behaviour may be a consequence of the reduction of static strength since at the same load level, joints with greater load angles (closer to mode II) are subjected to a higher load ratio (the ratio of the applied load to the static strength).

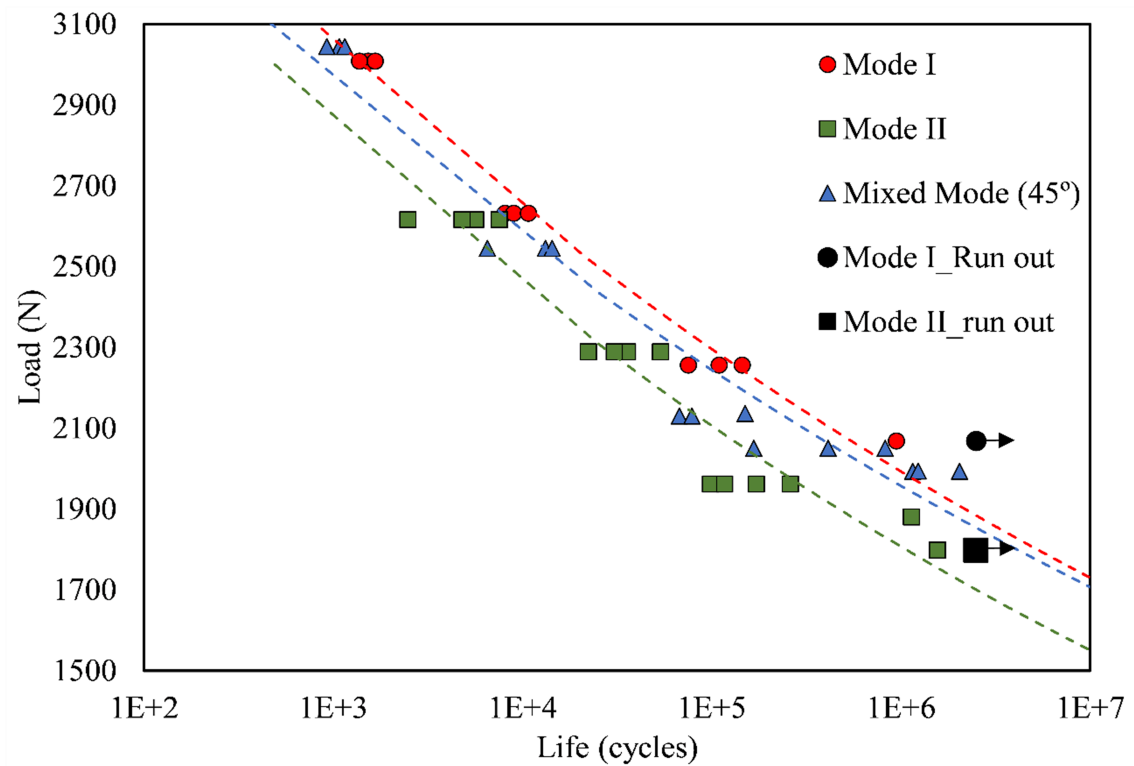


Figure B.10: - L-N curve for different mode mixities.

All the tests exhibited cohesive failure in the adhesive. The fatigue failure surfaces for different mode mixities are shown in Figure 11. A difference can be found between the failure surfaces for mode I and the surfaces obtained for the modes with a shear component. While for pure tensile loading, the failure surface is smoother, for mode II and mixed mode (45°) a rougher surface is found, indicating the formation of shear hackles.

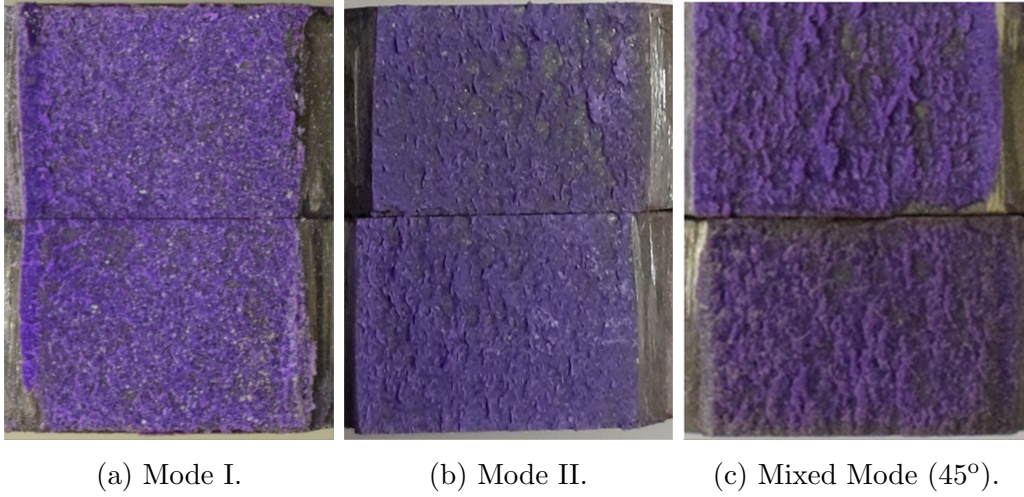


Figure B.11: Fatigue failure surfaces

B.5.2 Master curve and fatigue life prediction

To predict the fatigue life of the joints subjected to mixed mode loading conditions, two analysis steps should be followed. According to the proposed approach the first step is to obtain a master curve. To achieve this and based on the procedure defined before, the effective stresses for three load levels for pure modes I and II conditions were determined. The load levels selected were the ones with higher load values shown in Figure B.10, since using experimental data with shorter life would require less experimental effort. To attain the effective stress, distributions of the maximum principal, the von Mises and the hydrostatic stresses along the adhesive mid-plane were obtained using FEA. Using these data and based on Eq. (B.1), the effective stress was calculated for each data point (see Table B.3). Then the obtained effective stresses were plotted against the average failure life of the correspondent load levels. Basquin relation, defined as Eq. (B.2), was employed to fit a curve to the obtained data points and shape the master curve. The Basquin's constants and the master curve are presented in Table B.3 and Figure B.13a respectively.

$$\sigma_{eff} = \alpha \times N^{\beta} \quad (B.2)$$

where:

σ_{eff} : Effective stress

N : Fatigue life

α, β : Material constants

The second step is the determination of the effective stress for the mixed mode testing condition. The procedure to obtain the effective stress for mixed mode conditions was the same used for the reference samples. The distribution of both

Table B.3: Reference points used for the master curve and Basquin's constants.

Mode I		Mode II		Basquin's constants	
Life (cycles)	σ_{eff} (MPa)	Life (cycles)	σ_{eff} (MPa)	α	β
1526	40.7	12	38.4		
9295	35.6	35670	33.6	69.17	-0.071
109968	30.5	162270	28.8		

the von Mises stress and the hydrostatic stress are shown in Figure B.13a for mixed mode (45°). The mesh used was equal to the one used for the pure mode conditions, depicted in Figure 8. The boundary conditions are shown in Figure 12. Using the obtained effective stress for each load level the fatigue lives were predicted.

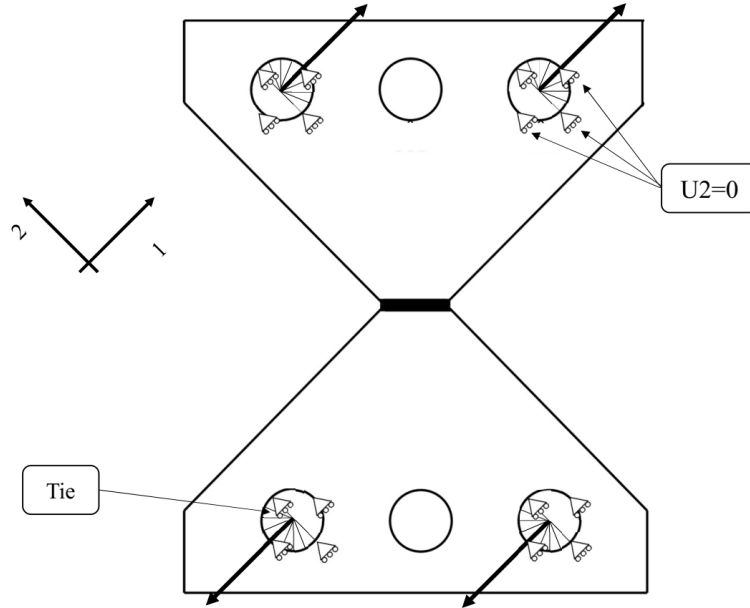
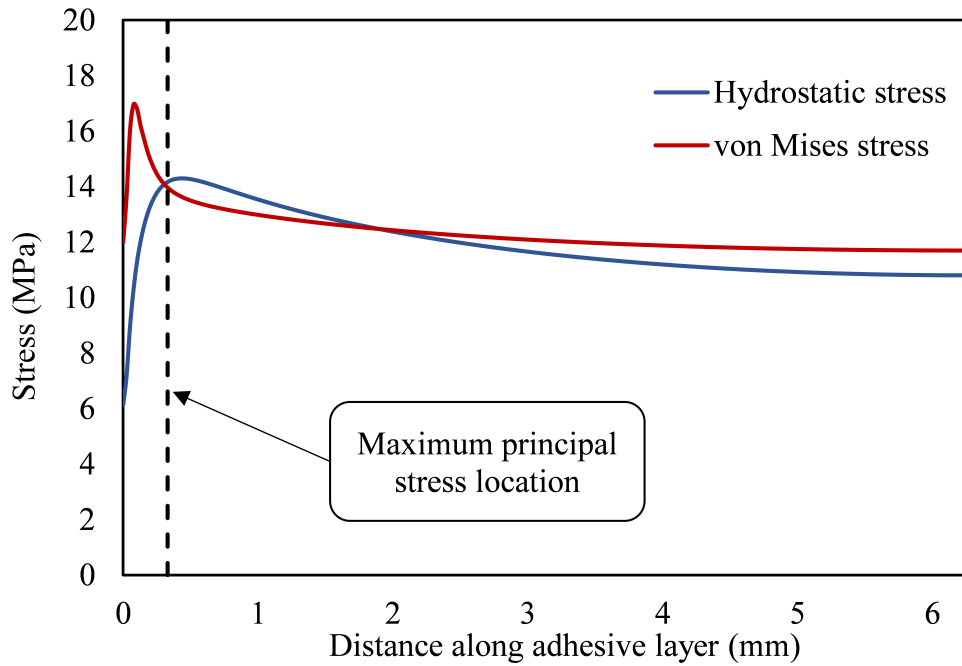
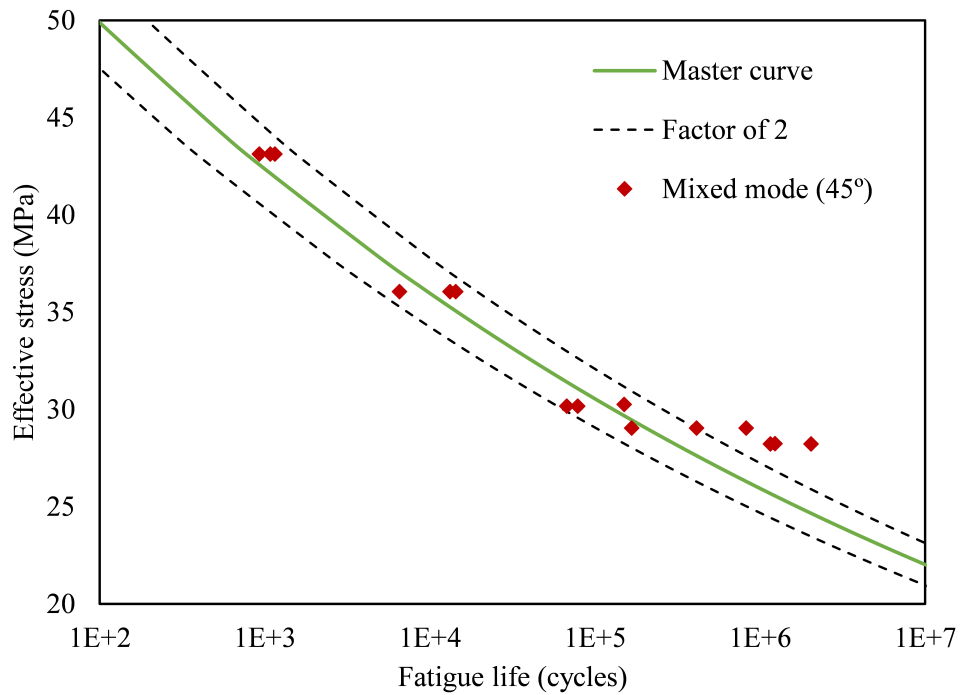


Figure B.12: Boundary conditions used for mixed mode loading conditions.

The estimation results are presented in Figure B.13b. The boundaries where the life differs two times from the estimated one is also shown. As can be seen, predictions show good agreement with the experimentally obtained values. Until 10^6 every point lies within the factor of two boundaries. However, for higher values of life, the accuracy decreases. This is due to the way the master curve is constructed. Different approaches could be taken for the master construction to address this issue. Further investigations on this matter are performed in the next section.



(a) Stress distribution: von Mises and hydrostatic.



(b) Comparing the predicted and the experimental fatigue lives for the Arcan joints subjected to mixed mode (45°).

Figure B.13: Fatigue life prediction procedure.

B.5.3 Master curve construction approaches

A very important part of the life estimation procedure, apart from the calculation of the effective stress, is the definition of the master curve. There are two relevant aspects that affect the master curve construction and consecutively the accuracy and the applicability of the fatigue model. The first is the number and the corresponding fatigue life of the load levels used to produce the master curve. To assess the influence of this aspect, three different alternatives (A, B and C) were considered, as listed in Table B.4. The points are labelled according to Figure B.14 and they represent the average value of fatigue life obtained for each load level. The alternative A consists of the first three points of each mode and does not consider any points in the very high cycle fatigue region ($N > 1 \times 10^6$ cycles). Alternative B is composed of three points, 1 and 2 and 4 of each mode. Alternative C considers all the experimentally obtained data points.

Table B.4: Reference points used for the master curve and Basquin's constants.

Alternative	Points used (for each mode)
A	1,2,3
B	1,2,4
C	All

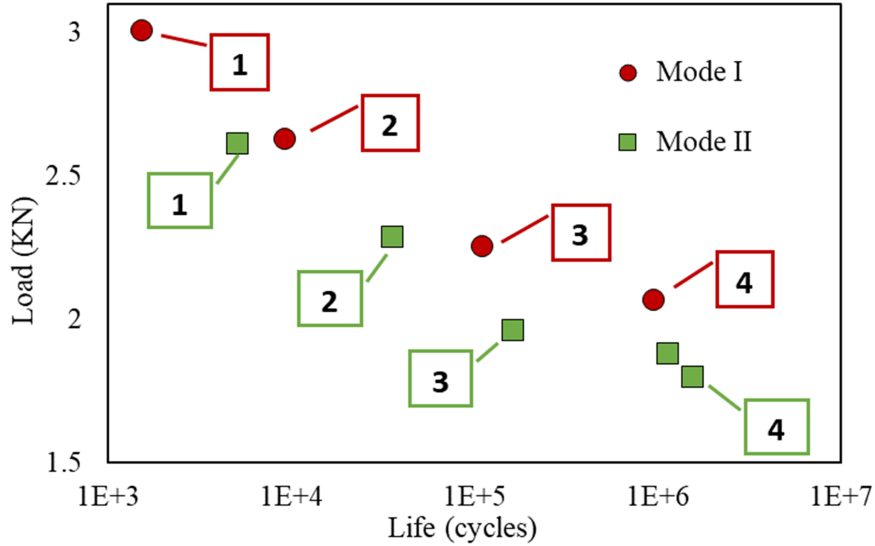


Figure B.14: Points used for fitting.

The second relevant aspect is the type of relation used to fit the experimental points. To obtain a good estimation it is very important to use a relation capable of precisely describing the behaviour of the adhesive. Accordingly, two different relations were used: Basquin, and Stromeyer (defined as Eqs. (B.2) and (B.3), respectively). The Stromeyer function is an empirical relation that extends the Basquin relation to the high-cycle fatigue region. It is important to highlight that although the fact that the material constants α and β are commonly represented using the same symbol for both relations, they do not have neither the same value nor geometrical meaning [30].

$$\sigma_{eff} = \alpha \times N^\beta + C \quad (B.3)$$

where the parameters are defines as follow:

σ_{eff} : Effective stress

N : Fatigue life

α, β, C : Material constants

The two referred aspects (three alternatives for the number of data points, and two relations for the curve fitting) were analysed and accordingly six cases were considered shown in Table B.5. To understand which case figures as a better estimation procedure, the root-mean-square deviation (RMSD), defined as Eq. (B.4), was used. It has already been used by different authors as an error metric of a prediction model [31]. Smaller values of RMSD indicate a better estimation procedure.

$$RMSD = \sqrt{\frac{\sum_{i=1}^n (\log_{10} N_i^{exp} - \log_{10} N_i^{est})^2}{n}} \quad (B.4)$$

where the parameters are defines as follow:

N_i^{est} : Estimated life

N_i^{exp} : Experimentally obtained life

n : Total number of experiments

The analysis performed based on all the cases shown in Table B.5. As it is shown in Table B.5, the obtained values of RMSD for the different cases show that using the Stromeyer relation always produces better results, unless when alternative A is considered, where the RMSD is the same. The reason for this is that the fitted line does not change when only the three initial points are considered. Such behaviour is in accordance with what was expected, given that the main difference between the two relations is in the high cycle fatigue (HCF) region. The resulting master curve as well as the mixed mode (45°) experimental results obtained for each effective stress are presented in Figure B.15. It shows that up to 10^5 cycles every point is

within the factor of two boundaries. However, for HCF, the master curve is not able to accommodate the experimental points. This limitation may be justified by the fact that none of the points used for the master curve fitting is near the HCF region. In Table B.5 it is possible to see that, for both relations, alternative B represents a significant improvement when compared to alternative A in terms of the RMSD value. The difference between these two alternatives is the inclusion of a fitting point in the HCF region. Therefore, it is possible to conclude that if one wants to estimate the fatigue life of a joint under mixed mode in the HCF fatigue region, the reference samples should include experimental results in this part of the fatigue life as well. Such is needed, given that adhesives can exhibit different behaviours in this region. Adhesive joints usually do not exhibit an endurance limit [6]. However, in some adhesives, as the one being studied, the fatigue strength loss (FSL), defined as the fatigue strength lost by moving one decade in the fatigue life, is smaller in the HCF region than for lower lives. For this reason, it is important to have experimental points that characterise the adhesive behaviour in the HCF region.

Table B.5: Cases considered and its respective RMSD.

Case N°	Relation	Alternative\points	RMSD
1	Basquin	A/ 1,2,3	0.376
2		B/ 1,2,4	0.303
3		C / All	0.314
4	Stromeyer	A/ 1,2,3	0.376
5		B/ 1,2,4	0.292
6		C / All	0.286

Another important aspect that the results present in Table B.5 is that, contrary to expectations, for Basquin relation, increasing the number of points does not necessarily mean an improvement of the estimation. While for Stromeyer relation, by using more load levels a decrease of the RMSD is denoted. To further investigate this behaviour, the curves obtained using alternatives B and C for Basquin and Stromeyer relations are plotted in Figures B.16a and B.16b, respectively. Out of this analysis, it can be understood that for Basquin relation, its inability to accommodate the points in region I, makes the curve shift down and because of that it moves away from the points inside region II resulting in a higher RMSD. However, since Stromeyer best describes the behaviour of the adhesive, it improves its estimation in region I without compromising region II. Despite the above-mentioned considerations, the accuracy of the model using alternative B is satisfactory and therefore having experimental results for the reference samples in the medium range of the fatigue life is not of major importance.

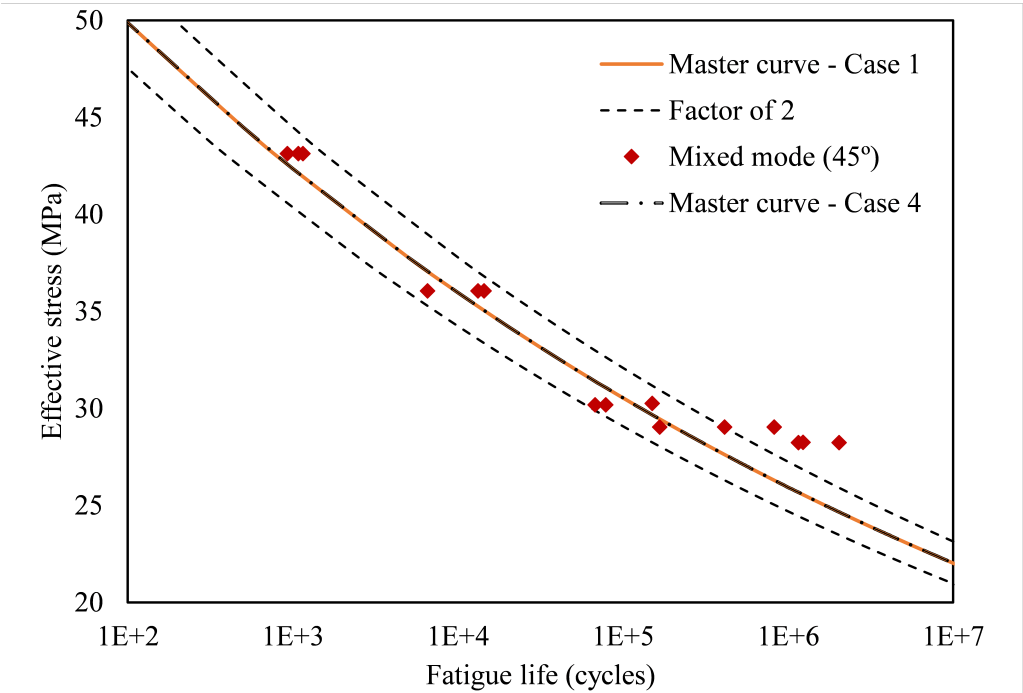
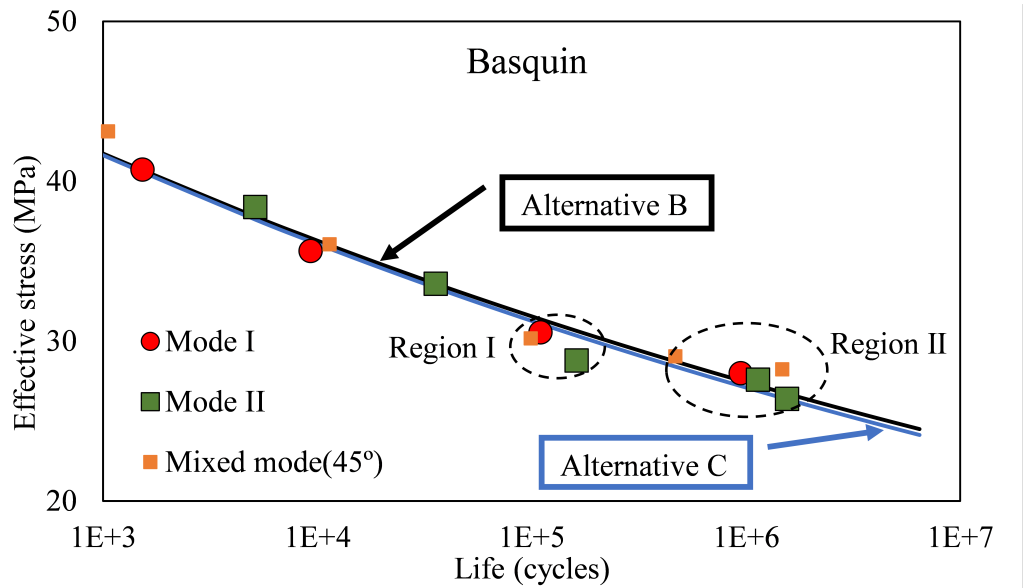
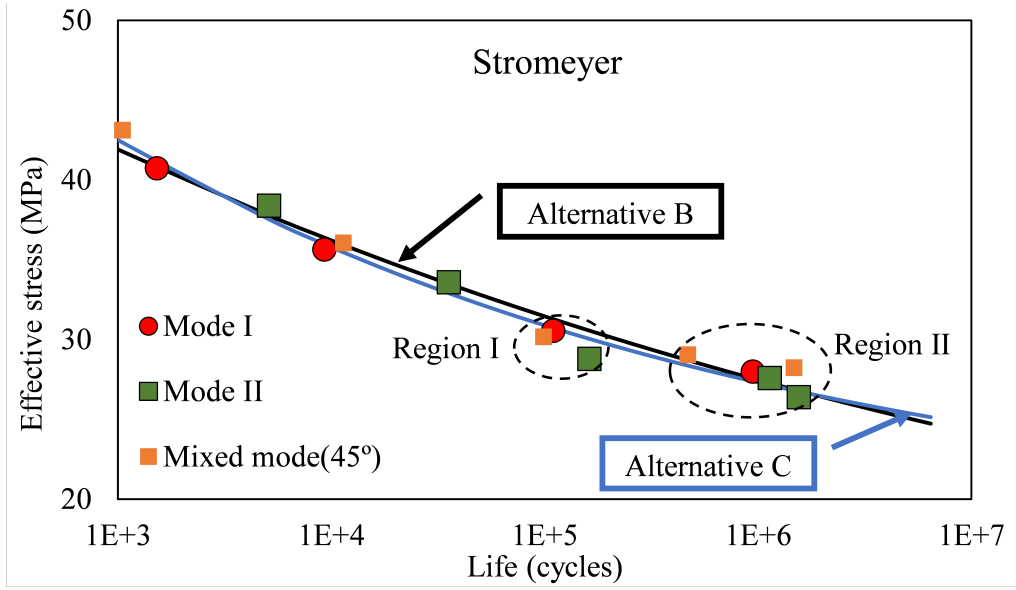


Figure B.15: Master curve for cases 1 and 4.



(a) Basquin.



(b) Stromeyer.

Figure B.16: Master curves using alternative B and C.

Based on RMSD results shown in Table B.5, the best case for Basquin is case 2 while for the Stromeyer, case 6 gives the best results. Comparing the best cases of the two models show an improvement of 6% by using Stromeyer which is a considerable enhancement. This improvement is more evident when the two curves are plotted as shown in Figure B.17. This shows the higher adaptability of the Stromeyer model to different cases. For allowing an improvement of the estimation and maintaining the simplicity, Stromeyer is assumed to be the most adequate for the procedure.

From the previous analysis it is possible to define the following rules that generate a simple and accurate estimation procedure:

- At least three load levels should be tested under pure modes I and II conditions. These load levels should be spaced by a minimum of one decade.
- If one wants to estimate the fatigue life of a component in the region of HCF, it is very important to have experimental results for the reference joints in that region.
- The medium range results only cause a slight difference in the estimation accuracy. Given this, it is recommended to have results for two load levels for lower cycle fatigue lives (around 10^3 and 10^4 cycles) and one for higher cycle fatigue (near 10^6 cycles).
- By being the relation that best describes the adhesive behaviour and that shows higher adaptability to different alternatives, Stromeyer is the most reliable relation to use based on the considered conditions.

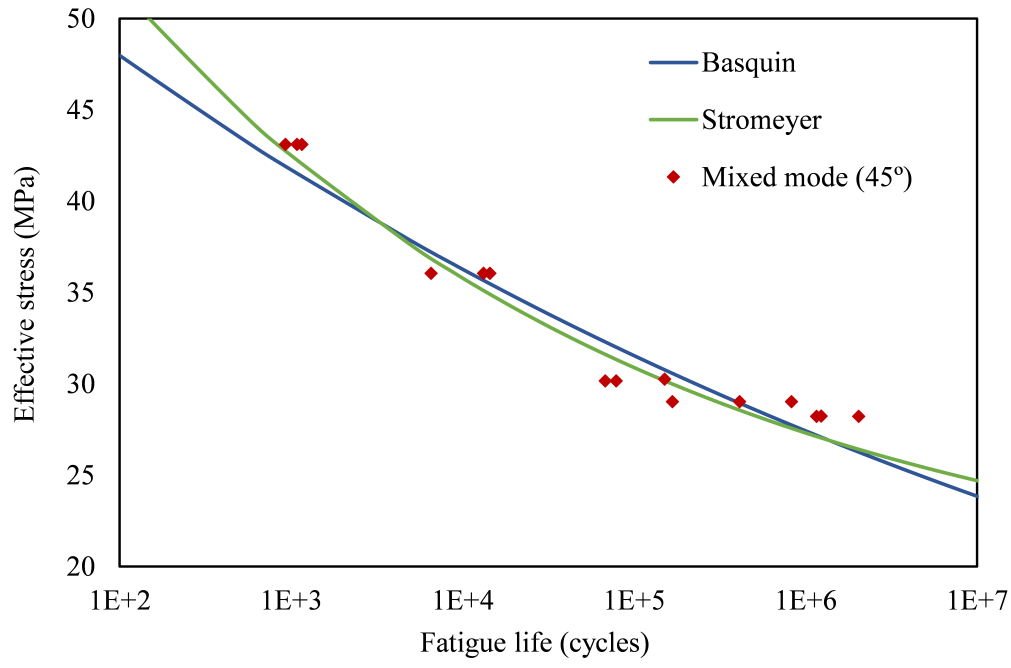


Figure B.17: Stromeyer (alternative C) vs Basquin (alternative B).

The master curve that best estimates the life of the joints under mixed mode loading conditions, case 6, is given in Figure B.18, and a good correlation between the experimental data and the estimated life is found. The majority of the experimental results lie within the factor of two boundaries, which shows the accuracy of the proposed model. It should be noted that the results that have a life ratio, defined as the ratio between the experimentally obtained life and the estimated life, higher than two are located in the HCF region. This lower accuracy is caused by the big scatter that the experimental results exhibit in this region. In some load levels, the ratio between the biggest and the shortest life obtained is higher than four. This big dispersion of data is very common because of the higher sensitivity to the presence of defects due to manufacturing issues.

B.5.4 Influence of mesh size and model type (2D vs 3D)

As stated previously, a mesh sensitivity analysis was performed in order to determine the effect of element size (X) on the results of the proposed criterion. The number of elements along the thickness were consecutively doubled in each step and the analysis was stopped as soon as a variation inferior to 1% was detected in the effective stress. Table B.6 shows the dimensions of the elements for different steps. The evolution of the effective stress with the number of elements along the thickness is presented in Table B.6. It is seen that the value of the effective stress is not significantly influenced by the mesh size which can be considered as an advantage of the proposed effective stress.

To validate the 2D plane strain assumption, a 3D linear elastic analysis for

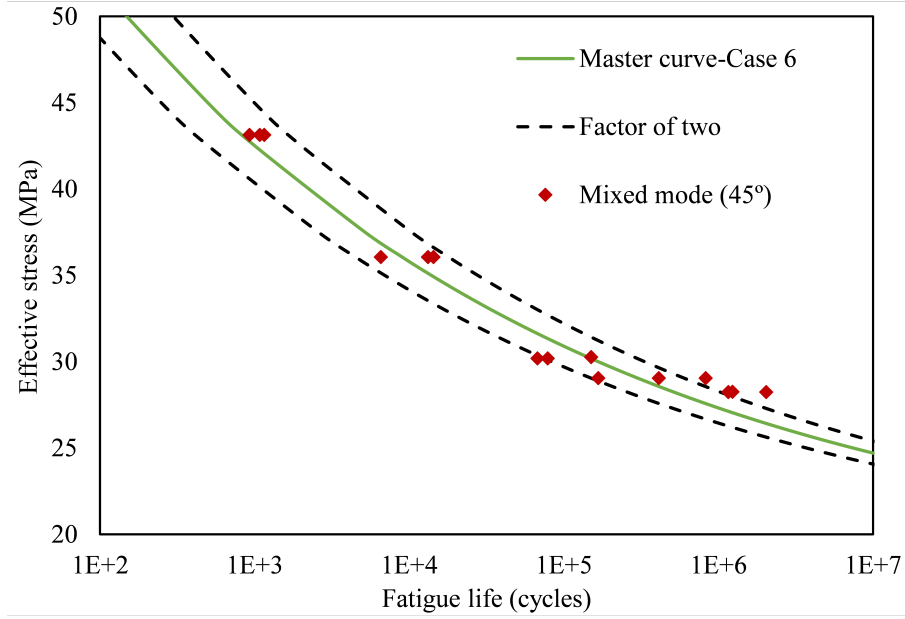


Figure B.18: Master curve: case 6.

Table B.6: Mesh sensitivity analysis.

Step No.	Number of Elements (along the adhesive thickness)	X (mm)	Effective stress (MPa)
1	2	0.1	28.43
2	4	0.05	26.73
3	8	0.025	27.08
4	16	0.0125	27.04

mode I loading conditions was performed. The mesh used is presented in Figure 19. The dimensions of the elements used for the adhesive layer is the same as the 2D analysis. The number of elements along the substrate thickness (w) was set to 20. The elements used for the substrates were 8-node 3D linear elements with reduced integration, while for the adhesive layer 20-node 3D quadratic elements with reduced integration were employed. The boundary conditions defined are similar to the ones defined for the 2D analysis. The effective stress for both type of analysis was then compared. For the 3D analysis, this parameter was obtained at the middle of the adhesive thickness (t) and at the middle of the substrate thickness, for a $w/2 = 5mm$, as shown in Figure B.19. The results are shown in Table B.7. It is seen that the effective stress values for both 2D and 3D analyses are in good agreement. The difference between both is 2.6%, which is insignificant when compared to the computation time saved by this assumption. For that reason, it is assumed that a 2D plane strain assumption is valid for obtaining the effective stress values for Arcan joints. It should be noted that for the 2D analysis, two different assumptions can be

made, plane strain or plane stress. However, one of the parameters that composes the proposed effective stress is the stress triaxiality, that represents the multiaxial stress state. Consequently, a 2D plane stress assumption, that considers a biaxial stress state is not applicable to the proposed fatigue model.

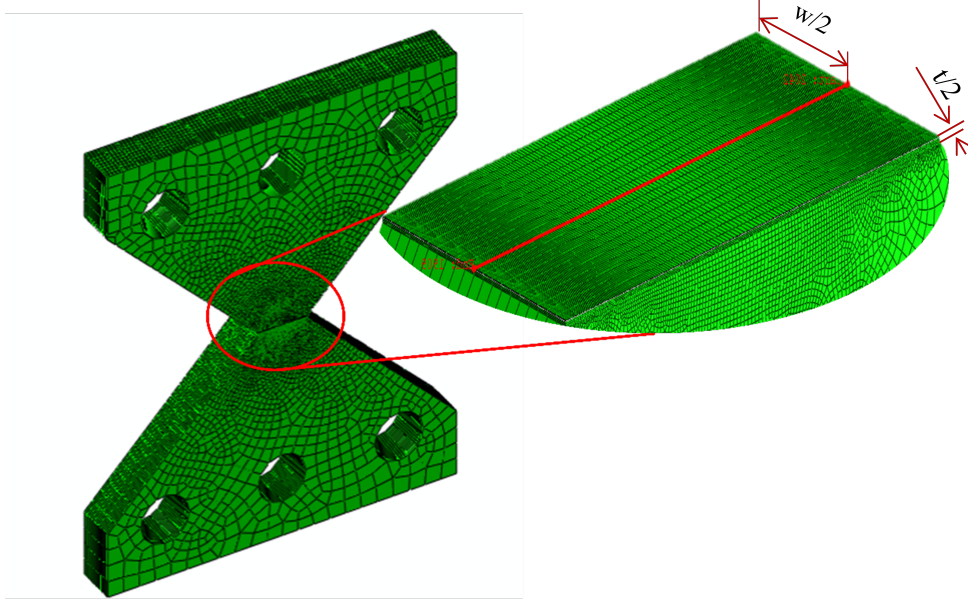


Figure B.19: Mesh used for 3D simulation.

Table B.7: 2D plane strain vs 3D model type comparison.

Analysis type	Effective stress (MPa)
3D	27.08
2D-Plane strain	27.81

B.6 Conclusions

In this paper, a simple method was proposed to estimate the fatigue of adhesively bonded joints subjected to different mode mixities. For this purpose, a new effective stress composed by key stress parameters that govern the failure of adhesive joints was introduced. Different types of FEA and two fatigue models (Basquin and Stromeier) were considered in this study. Out of the presented research the following conclusions can be drawn:

- The proposed fatigue model was able to precisely predict the fatigue life of an Arcan adhesive joints subjected to mixed mode fatigue loading conditions.

- Based on the proposed effective fatigue stress, it was found that a combination of von Mises stress and stress triaxiality play a key role in fatigue response of the considered adhesive joints.
- According to the FEA results it was found that a 2D linear elastic analysis proves to be sufficient. This can be considering an advantage of the proposed model, for allowing short simulation times.
- Stromeier relation provided the most precise estimations comparing with the Basquin model.
- By considering the experimental tests performed on the reference samples on the HCF region, a significant increase in the prediction accuracy was observed using Stromeier.
- More experimental results for the reference samples do not necessarily mean that better estimation accuracy will be obtained.
- Mesh sensitivity analysis showed that the mesh size doesn't have a significant influence on the obtained effective stress.

References

- [1] Machalická K, Vokáč M, Kostecká M, Eliášová M. Structural behavior of double-lap shear adhesive joints with metal substrates under humid conditions. *Int J Mech Mater Des* 2018. <https://doi.org/10.1007/s10999-018-9404-y>.
- [2] Paiva RMM, António CAC, da Silva LFM. Multiobjective optimization of mechanical properties based on the composition of adhesives. *Int J Mech Mater Des* 2017;13:1–24. <https://doi.org/10.1007/s10999-015-9313-2>.
- [3] Adams R. *Structural Adhesive Joints in Engineering*. 1st ed. Springer Netherlands; 1984. <https://doi.org/10.1007/978-94-009-5616-2>.
- [4] da Silva LFM, Öchsner A, Adams R. *Handbook of Adhesion Technology*. 2nd ed., 2018. https://doi.org/10.1007/978-3-642-01169-6_1.
- [5] Gonçalves VM, Martins PAF. Joining stainless steel parts by means of weld bonding. *Int J Mech Mater Des* 2006;3:91–101. <https://doi.org/10.1007/s10999-006-9015-x>.
- [6] Abdel Wahab M. Fatigue in Adhesively Bonded Joints: A Review. *ISRN Mater Sci* 2012;2012. <https://doi.org/10.5402/2012/746308>.
- [7] Olajide SO, Arhatar BD. Recent progress on damage mechanisms in polymeric adhesively bonded high-performance composite joints under fatigue. *Int J Fatigue* 2017;95:45–63. <https://doi.org/10.1016/j.ijfatigue.2016.10.009>.
- [8] Shenoy V, Ashcroft IA, Critchlow GW, Crocombe AD, Abdel Wahab MM. An investigation into the crack initiation and propagation behaviour of bonded single-lap joints using backface strain. *Int J Adhes Adhes* 2009;29:361–71. <https://doi.org/10.1016/J.IJADHADH.2008.07.008>.
- [9] Zhang Z, Shang JK, Jr. FVL. A Backface Strain Technique for Detecting Fatigue Crack Initiation in Adhesive Joints. *J Adhes* 1995;49:23–36. <https://doi.org/10.1080/00218469508009975>.
- [10] Zamani P, Jaamialahmadi A, da Silva LFM, Farhangdoost K. An investigation on fatigue life evaluation and crack initiation of Al-GFRP

- bonded lap joints under four-point bending. *Compos Struct* 2019;229:111433. <https://doi.org/10.1016/j.compstruct.2019.111433>.
- [11] Moradi A, Carrère N, Leguillon D, Martin E, Cognard J-Y. Strength prediction of bonded assemblies using a coupled criterion under elastic assumptions: Effect of material and geometrical parameters. *Int J Adhes Adhes* 2013;47:73–82. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2013.09.044>.
- [12] Rocha AVM, Akhavan-Safar A, Carbas R, Marques EAS, Goyal R, El-Zein M, et al. Paris law relations for an epoxy-based adhesive. *Proc Inst Mech Eng Part L J Mater Des Appl* 2020;234:291–9. <https://doi.org/10.1177/1464420719886469>.
- [13] Rocha AVM, Akhavan-Safar A, Carbas R, Marques EAS, Goyal R, El-zein M, et al. Numerical analysis of mixed-mode fatigue crack growth of adhesive joints using CZM. *Theor Appl Fract Mech* 2020;106:102493. <https://doi.org/https://doi.org/10.1016/j.tafmec.2020.102493>.
- [14] Monteiro J, Akhavan-Safar A, Carbas R, Marques E, Goyal R, El-zein M, et al. Mode II modeling of adhesive materials degraded by fatigue loading using cohesive zone elements. *Theor Appl Fract Mech* 2019;103:102253. <https://doi.org/https://doi.org/10.1016/j.tafmec.2019.102253>.
- [15] Monteiro J, Akhavan-Safar A, Carbas R, Marques E, Goyal R, El-zein M, et al. Influence of mode mixity and loading conditions on the fatigue crack growth behaviour of an epoxy adhesive. *Fatigue Fract Eng Mater Struct* 2020;43:308–16. <https://doi.org/10.1111/ffe.13125>.
- [16] Rocha A, Akhavan-Safar A, Carbas R, Marques E, Goyal R, El-Zein M, et al. Fatigue crack growth analysis of different adhesive systems: Effects of mode mixity and load level. *Fatigue Fract Eng Mater Struct* 2019. <https://doi.org/10.1111/ffe.13145>.
- [17] Thäsler T, Holtmannspötter J, Gudladt H-J. Monitoring the fatigue crack growth behavior of composite joints using in situ 2D-digital image correlation. *J Adhes* 2019;95:595–613. <https://doi.org/10.1080/00218464.2018.1562923>.
- [18] Costa M, Viana G, Créac’hcadec R, Silva] LFM [da, Campilho RDSG. A cohesive zone element for mode I modelling of adhesives degraded by humidity and fatigue. *Int J Fatigue* 2018;112:173–82. <https://doi.org/https://doi.org/10.1016/j.ijfatigue.2018.03.014>.
- [19] Akhavan-Safar A, Silva] LFM [da, Ayatollahi MR. An investigation on the strength of single lap adhesive joints with a wide range of materials and dimensions using a critical distance approach. *Int J Adhes Adhes* 2017;78:248–55. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2017.08.009>.

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- [20] Imanaka M, Iwata T. Fatigue Failure Criterion of Adhesively-Bonded Joints Under Combined Stress Conditions. *J Adhes* 1996;59:111–26. <https://doi.org/10.1080/00218469608011081>.
 - [21] Imanaka M, Iwata T. Estimation of Fatigue Strength for Adhesively-Bonded Lap Joints Based on Fatigue Failure Criterion Under Multiaxial Stress Conditions. *J Adhes* 1998;65:7–24. <https://doi.org/10.1080/00218469808012236>.
 - [22] Jen Y-M. Fatigue life evaluation of adhesively bonded scarf joints. *Int J Fatigue* 2012;36:30–9. <https://doi.org/https://doi.org/10.1016/j.ijfatigue.2011.08.018>.
 - [23] Shahani AR, Pourhosseini SM. The effect of adherent thickness on fatigue life of adhesively bonded joints. *Fatigue Fract Eng Mater Struct* 2019;42:561–71. <https://doi.org/10.1111/ffe.12931>.
 - [24] Beber VC, Schneider B, Brede M. Efficient critical distance approach to predict the fatigue lifetime of structural adhesive joints. *Eng Fract Mech* 2019;214:365–77. <https://doi.org/https://doi.org/10.1016/j.engfracmech.2019.03.022>.
 - [25] Wang CH, Rose LRF. Determination of triaxial stresses in bonded joints. *Int J Adhes Adhes* 1997;17:17–25. [https://doi.org/https://doi.org/10.1016/S0143-7496\(96\)00028-0](https://doi.org/https://doi.org/10.1016/S0143-7496(96)00028-0).
 - [26] Ward IM. Review: The yield behaviour of polymers. *J Mater Sci* 1971;6:1397–417. <https://doi.org/10.1007/BF00549685>.
 - [27] García JA, Chiminelli A, García B, Lizaranzu M, Jiménez MA. Characterization and material model definition of toughened adhesives for finite element analysis. *Int J Adhes Adhes* 2011;31:182–92. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2010.12.006>.
 - [28] Abdel Wahab M, Hilmy I, Ashcroft I, Crocombe A. Damage Parameters of Adhesive Joints with General Triaxiality Part I: Finite Element Analysis. *J Adhes Sci Technol - J ADHES SCI TECHNOL* 2011;25:903–23. <https://doi.org/10.1163/016942410X534939>.
 - [29] Akhavan-Safar A, Ayatollahi MR, Moazzami M, Silva] LFM [da. The role of T-stress and stress triaxiality combined with the geometry on tensile fracture energy of brittle adhesives. *Int J Adhes Adhes* 2018;87:12–21. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2018.09.008>.
 - [30] Kohout J, Vechet S. A new function for fatigue curves characterization and its multiple merits. *Int J Fatigue* 2001;23 : 175~83.[https://doi.org/https://doi.org/10.1016/S0142-1123\(00\)00082-7](https://doi.org/https://doi.org/10.1016/S0142-1123(00)00082-7).

REFERENCES

- [31] Beber VC, Fernandes PHE, Schneider B, Brede M, Mayer B. Fatigue life-time prediction of adhesively bonded joints: An investigation of the influence of material model and multiaxiality. *Int J Adhes Adhes* 2017;78:240–7. <https://doi.org/https://doi.org/10.1016/j.ijadhadh.2017.08.007>

Appendix C

Paper 3

Fatigue life estimation of single lap adhesive joints using a critical distance approach

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Abstract

The fatigue life prediction of adhesive joints still remains as one of the most challenging issues. Given the increasing need for safer and more efficient industrial bonded structures, the development of simple fatigue design methodologies is of primordial relevance. In this work, a model based on the S-N approach for the estimation of the fatigue life of single lap adhesive joints with different geometries is proposed. Steel substrates and an epoxy adhesive were considered to manufacture joints with different overlap lengths, adherend thicknesses and widths. The joints were tested under static and fatigue loading conditions. A critical distance approach based on a recently developed effective stress is proposed to deal with the effect of stress concentrations exhibited by this type of joints. The results showed a good correlation between the experimental and the estimated fatigue lives.

C.1 Introduction

Nowadays, adhesive joints are extensively used in a wide range of applications in different industries due to their multiple merits. One of the main characteristics commonly attributed to this bonding technique is its more uniform stress distribution that results in higher fatigue strength when compared to the conventional joining techniques such as welding, riveting and other fastening methods [1; 2]. Despite the enhanced fatigue strength, the failure mechanisms of adhesive joints are not completely understood. While the static strength prediction of adhesives is quite developed, the same cannot be said to the fatigue failure of this kind of joints. This issue still remains as one of the obstacles to a wider use of this technology in long-term cyclic applications.

The fatigue strength of adhesive joints depends on many factors, namely: material, surface preparation, environmental conditions, mean stress and frequency [3–5]. Another factor that markedly affects the fatigue behaviour of adhesive joints, mainly because of its multimaterial nature, is the joint geometry. Many joint configurations are available, however, due to its simplicity, single lap joints (SLJ) are the most common, both for research purposes and for industrial applications. Given this, several studies have been devoted to the effect of multiple geometry parameters on the fatigue strength of adhesively bonded SLJs. For an efficient estimation, these factors should be taken into account in the conceptualization of fatigue life prediction methodologies. Jen and Ko [6] studied experimentally the effect of adhesive thickness and overlap length on the fatigue strength of aluminium SLJs. They concluded that for a fixed average shear stress, the fatigue strength increases as the adhesive thickness decreases. They also found that increasing the overlap length decreases the fatigue strength with the exception of a joint with an adhesive thickness of 0.5mm. However, the failure mode was mostly adhesive failure. Ferreira et al. [7] studied the influence of overlap length in fatigue strength of composite SLJs. They concluded that, for a given value of average shear stress, a reduction in fatigue is found when moving from 30mm to 60mm overlap. da Costa Mattos [8] studied the effect of bonded area on the fatigue life of composite SLJs. They found that a shape factor can be used to correlate the fatigue strength of two joints with a brittle-elastic adhesive, with different bonded areas. Shahani and Pourhosseini [9] studied the effect of substrate thickness on the fatigue strength of SLJs and concluded that an increase in substrate thickness increases the fatigue strength of the joint. They also observed that the failure mode changed from adherent to cohesive as a result of the increase of the adherend thickness.

Another important factor that should be taken into account is the material behaviour. Adhesives commonly exhibit a considerable amount of plastic deformation [10]. For this reason, some studies have been performed using elastoplastic models [11–13]. However, this type of analysis requires a long computation time and the definition of the material properties can be quite complex. These factors, make

its usage impracticable in conceptual design phases of industrial applications. For these purposes, a linear-elastic analysis is often preferred. However, linear-elastic analysis presents some problems, specially when dealing with stress concentrations. It is widely recognized that the fatigue strength is not governed by the maximum stress originated from a linear elastic analysis, and considering the peak values originates over-conservative criteria [14]. However, most adhesive joints present stress concentration near the bonding ends and these have a significant influence on the fatigue strength of adhesive joints as these are directly linked to the fatigue crack initiation. Despite the influence of the static strength, stress concentrations have a more nefariously impact on the fatigue behaviour of adhesive joints [15].

A possible approach to deal with the influence of the stress concentration is using a critical distance technique. This technique was first introduced by Neuber [16] and Peterson [17] to deal with the effect of stress concentrations on the fatigue behaviour of notched metallic components. Recently, Taylor [18] merged the concepts used in this approach and defined the Theory of Critical Distances (TCD). He defined TCD as a non-mechanistic approach that relies on a length parameter, called critical distance, that is factor that represents all the mechanisms at the microstructural level that govern the failure of a certain component. The main difficulty associated with this method is the definition of the critical distance, usually obtained experimentally. Critical distance usually is a function of many factors such as the material properties, geometry, fatigue life and the type of loading [14; 19]. For metallic materials, this approach has been vastly used, even under fatigue conditions [19].

For adhesive joints, this approach has not been considered widely. In most cases the TCD has been applied to joints subjected to static loading conditions, with satisfactory results [20–23]. Ayatollahi and Akhavan-Safar [24] proposed a model for the failure load prediction of SLJs based on a critical distance approach. The proposed method states that the failure occurs when the longitudinal strain reaches a critical value at a critical distance, along the adhesive mid-plane. It was shown that this method is able to predict the static strength of SLJs with different overlaps. This method was then applied to SLJs with different adherend [25] and adhesive [26] thicknesses. This criterion was further developed and applied to SLJs with multiple material properties and dimensions [27] and more recently, it was extended to cover the failure load prediction of SLJs made of dissimilar materials [28]. However, for fatigue life prediction of adhesive joints this approach has been significantly less studied. Imanaka and Iwata [29], applied a criterion based on the TCD to estimate the endurance limit of single lap and single-step double-lap joints. Beber et al. [30] conducted a parametric study and found that the optimal critical distance value was different for SLJs and scarf joints, which shows that this parameter depends on the joint configuration. Beber et al. [31] predicted the fatigue life of SLJs by the Drucker-Prager equivalent stress measured at a fixed distance of 0.1mm. The reference samples used were notched bulk specimens.

Although many studies have been conducted to understand and predict the fa-

tigue behaviour of adhesive joints, there is no fatigue life prediction methodology universally accepted. For this reason, the development of a simple and accurate fatigue model able to predict adhesive joints with different configurations is still of prime importance to design efficient and safe structures. The aim of the present work is to extend a model based on the S-N approach, proposed by the same authors [32], to predict the fatigue life of SLJs with different overlap lengths, joint width, and adherend thicknesses, using a critical distance approach. To achieve this, three different configurations of SLJ were manufactured and tested under fatigue loading conditions. A linear-elastic finite element analysis (FEA) was performed to assess the distribution of the proposed effective stress. To determine the location where it should be measured, a critical distance approach was used. The model was then validated with the experimental results.

C.2 Experimental details

SLJs were manufactured using steel substrates bonded by a one component structural epoxy-based adhesive. The mechanical properties of the adhesive were obtained experimentally in a previous study [33]. A typical tensile stress-strain curve is shown in Figure C.1. The tensile and shear properties of the adhesive are presented in Table C.1.

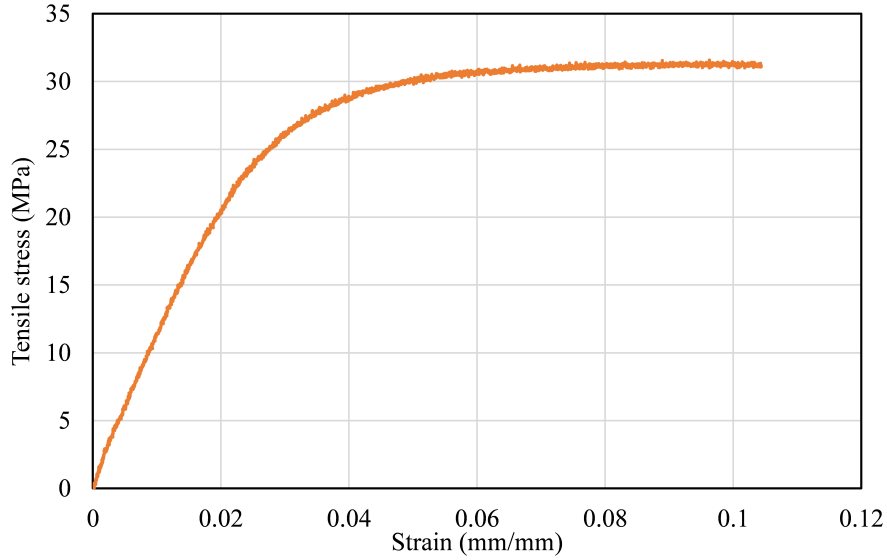


Figure C.1: Typical tensile stress-strain curve [33].

Three different SLJ configurations were considered for the present study, see Figure C.2.

To guarantee a clean bonding surface and improve the adhesion properties, the substrates were sandblasted and then degreased using acetone. To control the geometry of the specimens, a mould already used by some authors [34] was considered

Table C.1: Adhesive mechanical properties [33].

Adhesive properties	
Maximum tensile strength (MPa)	31.3 ± 0.6
Maximum tensile strain (%)	10.4 ± 0.5
Maximum shear strength (MPa)	23.1 ± 0.5
Maximum shear strain (%)	43.3 ± 0.9
Young's Modulus (MPa)	1159 ± 29.3
Shear Modulus (MPa)	440 ± 8.7
Poisson's ratio, ν	0.32 ± 0.03

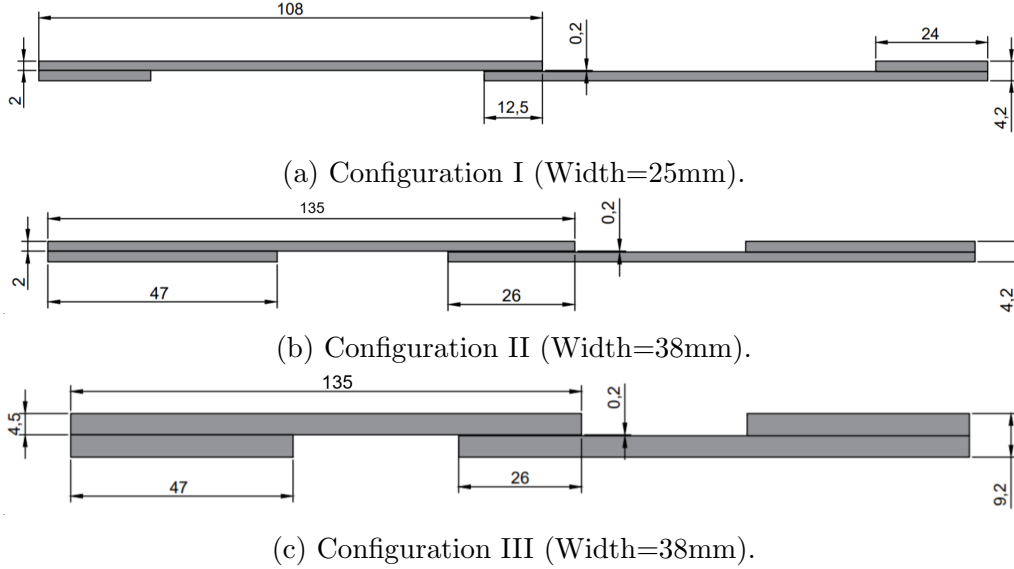


Figure C.2: Studied SLJ configurations (dimensions in mm).

in this study. The mould is presented in Figure C.3. For all the configurations, the adhesive thickness was controlled using calibrated shims and metal strips, as illustrated in Figure C.3.

The specimens were cured at 210°C for 65 min. Pressure was also applied to prevent joints misalignment. Both temperature and pressure were controlled using a hot-plate press. The specimens were then left at room conditions for a period of 5 days. Before testing, the excess adhesive was removed using a file.

C.2.1 Testing conditions

Both static and fatigue tests were conducted at room conditions for all the tested configurations, using an Instron 8801 servo-hydraulic testing machine. Clamps were used to connect the specimens to the testing apparatus. Two tabs were added to

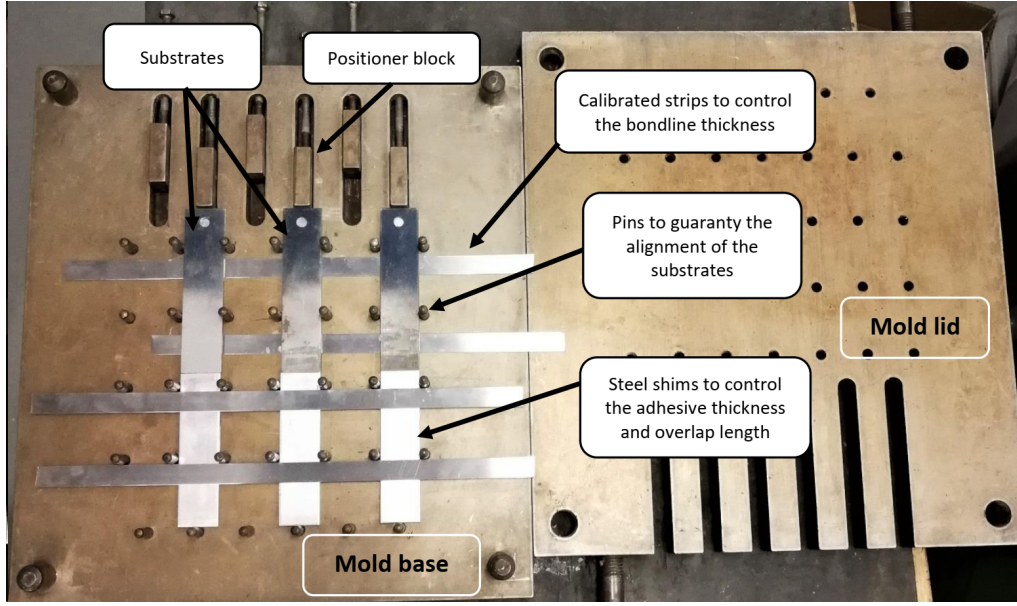


Figure C.3: Mould used to manufacture the SLJ specimens [34].

the extremities of the specimens to ensure the alignment between the adhesive's mid-plane and the applied load.

The static tests were performed to define the load levels at which the fatigue tests should be conducted. The test were performed under displacement control conditions with a crosshead speed of 1mm/min.

The fatigue tests were carried under load control conditions with a sinusoidal waveform at a frequency of 10 Hz and a load ratio (R) of 0.1. Load ratio is defined as the ratio of the maximum applied load to the minimum applied load for each cycle. Several load levels were considered to cover a range of fatigue life between 10^3 to 2.5×10^6 cycles.

C.3 Proposed fatigue model

In a previous study [32], a fatigue life prediction model able to deal with the effect of mode mixity was proposed by the current authors. This fatigue model is based on an effective stress, defined as Eq.(C.1). The effective stress is a function of some key parameters that govern the failure of adhesive joints, measured at the peak of the maximum principal stress point. According to this approach, two reference samples (Arcan joints under pure mode I and pure mode II loading conditions) are tested under fatigue loading conditions. Then, a FEA is used to obtain the effective stress. After obtaining the effective stress, it is used to create a master S-N curve where the number of cycles to failure is plotted against the effective stress. Then, to predict the fatigue life of a joint under mixed mode loading conditions, the effective stress should be assessed using a FEA and then should be compared to the master S-N curve. A schematic representation of the previously proposed fatigue model is

presented in Figure C.4.

$$\sigma_{eff} = \sigma_{VM} + \sigma_H \times S \quad (C.1)$$

Where σ_{eq} is the effective stress, σ_{VM} corresponds to the von Mises stress, σ_H is the hydrostatic stress and S represents the stress triaxiality $\left(\frac{\sigma_H}{\sigma_{VM}}\right)$.

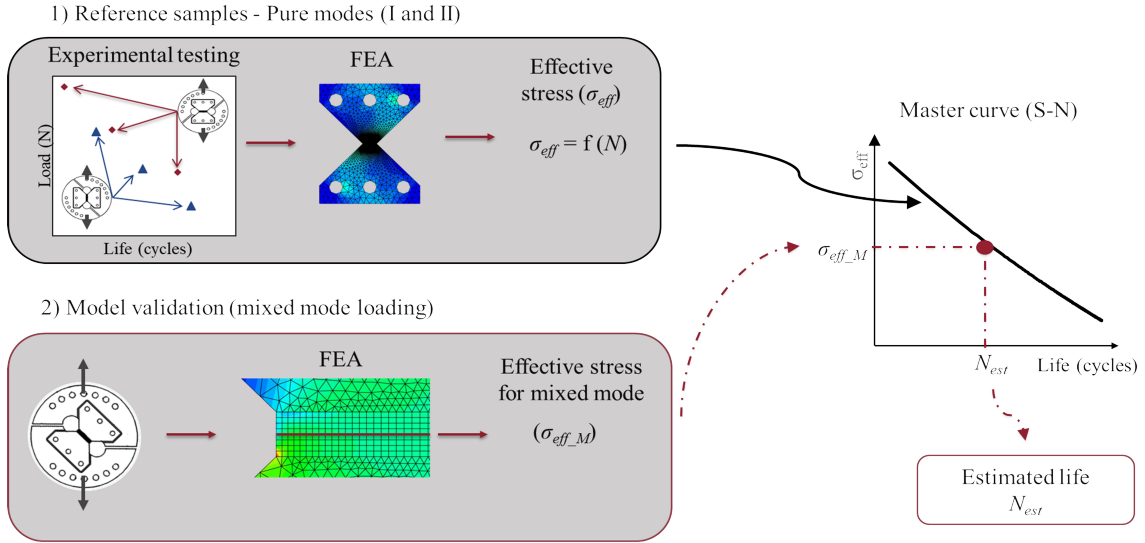


Figure C.4: Schematic overview of previously proposed fatigue model.

However, Arcan joints present an almost uniform stress distribution. While most adhesive joints exhibit stress concentration near the free ends due to its geometry. This issue has a great impact on the fatigue strength. Thus, it is necessary to consider them in fatigue life prediction models. For this reason, the previously proposed model was extended to predict the fatigue life of SLJs. To achieve this, a change in the location where the effective stress should be measured was implemented. Although the equivalent stress is the same, Eq. (C.1), the location where this should be assessed was modified to take into account the stress concentration exhibited by SLJs. Instead of measuring the effective stress at the peak point of the maximum principal stress, a critical distance approach, denominated Equivalent Notch Approach (ENA) is adopted to determine this location. This method is based on the idea of what would be the size of a hypothetical notch to cause the stress concentration of the SLJ under study. Having this in mind, the stress concentrations of all the configurations, obtained by means of a FEA, are compared to a reference state. The chosen reference state was a theoretical case of an infinite plate under remote uniaxial tension, containing an elliptical hole, as illustrated in Figure C.5. For this case, the stress concentration is given by Eq.(C.2) [35].

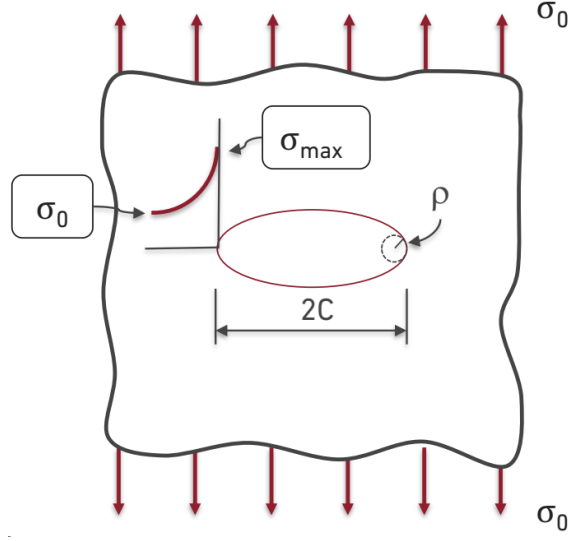


Figure C.5: Infinite plate under remote uniaxial tension, containing an elliptical hole.

$$K_t = \frac{\sigma_{max}}{\sigma_0} = 1 + 2 \times \sqrt{\frac{C}{\rho}} \quad (C.2)$$

Where K_t is the stress concentration, C represents half of the notch diameter and ρ stands for the notch root radius.

To apply to a SLJ, some modifications were made to this relation. One of these modifications is the definition of the stress concentration (K_t). Here the stress concentration is given as the ratio between the maximum value of the maximum principal stress ($\sigma_{1,max}$) measured at the adhesive mid-plane and the maximum principal stress measured at the center of the overlap length ($\sigma_{1,mid}$), Eq.(C.3). The parameter C is replaced by a factor that is the load ratio (LR) multiplied by K_t and by an empirical constant, M , that should be determined experimentally. The parameter ρ represents the critical distance (L) normalised by the overlap length (L_P). The relation used to determine the normalized critical distance is presented in Eq. (C.4)

$$K_t = \frac{\sigma_{1,max}}{\sigma_{1,mid}} \quad (C.3)$$

$$\rho = \frac{L}{L_P} = \frac{LR \times K_t \times M}{(\frac{K_t-1}{2})^2} \quad (C.4)$$

To summarize, the following steps should be followed to obtain a prediction of the fatigue life of SLJs. First, fatigue tests should be performed in Arcan joints under pure mode I and pure mode II loading conditions, at least at three different load levels. Then a FEA should be carried out to obtain the effective stress for Arcan joints (effective stress at the peak location of the maximum principal stress). Once the effective stresses are obtained, it is possible to generate a master S-N curve

that relates the effective stress to the fatigue life. Next, to estimate the fatigue life of SLJs, the effective stress and the maximum principal stress distributions at the adhesive mid-plane should be attained using a 2D linear-elastic FEA. Afterwards, the ENA should be applied to determine the critical distance. For this purpose, it is necessary to have an estimation of the failure load of the joint. This can be obtained either by performing experimental tests or by using one of the available static strength prediction criteria. It is also required to perform one fatigue test for each configuration, at any load level to determine the empirical constant M . By substituting the above-mentioned parameter in Eq.(C.4), and by multiplying ρ by the overlap length, the critical distance is determined. Next, the effective stress at this critical location should be determined. By comparing this effective stress to the reference S-N curve previously generated, an estimation of the fatigue life of the joint is then obtained. A schematic overview of the proposed model is shown in Figure C.6.

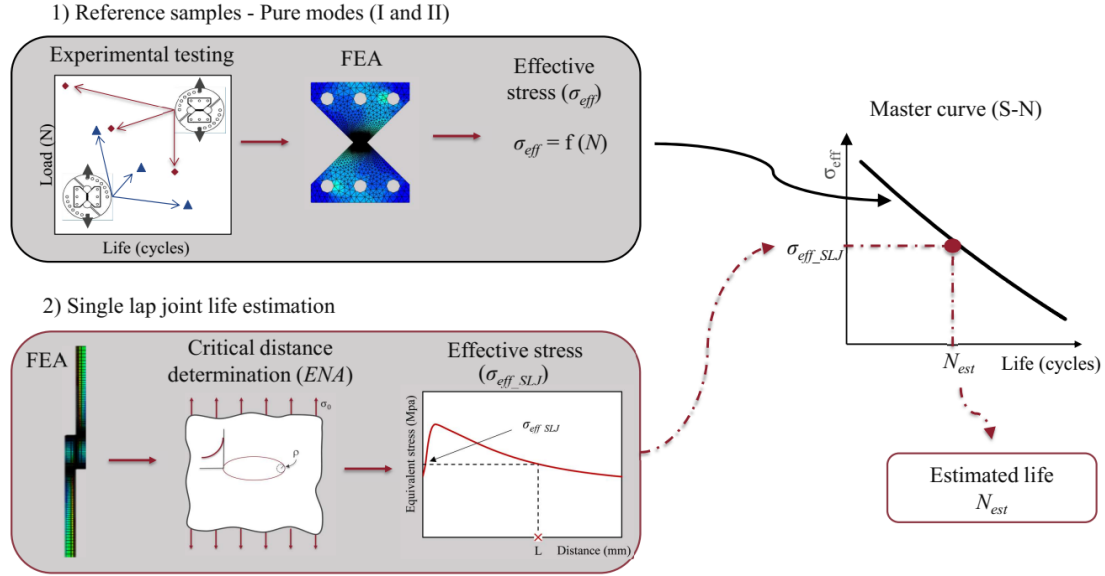


Figure C.6: Schematic overview of the fatigue life estimation procedure.

C.4 Results and discussion

C.4.1 Experimental results

Static results

The average static failure loads and the average shear stress, defined as the ratio between the applied load and the bonded area A ($A_I = 312.5\text{mm}^2$; $A_{II} = A_{III} = 988\text{mm}^2$) are presented in Table C.2. The average elongation at break is also presented.

It is possible to observe that increasing the overlap length, causes a decrease in the static average shear strength. The increase in adherend thickness (T) is responsible for an almost negligible increase in the static strength. Typical load-displacement curves for all the configurations are shown in Figure C.7.

Table C.2: Static failure loads.

Configuration	I	II	III
Failure load (N)	9775.5 ± 199.8	29735.5 ± 1238.8	30273.1 ± 1466.9
Average shear strength (MPa)	31.3 ± 0.6	30.1 ± 1.3	30.6 ± 1.5
Elongation at break (mm)	0.82 ± 0.03	0.71 ± 0.03	0.56 ± 0.02
Number of tested specimens	3	3	3

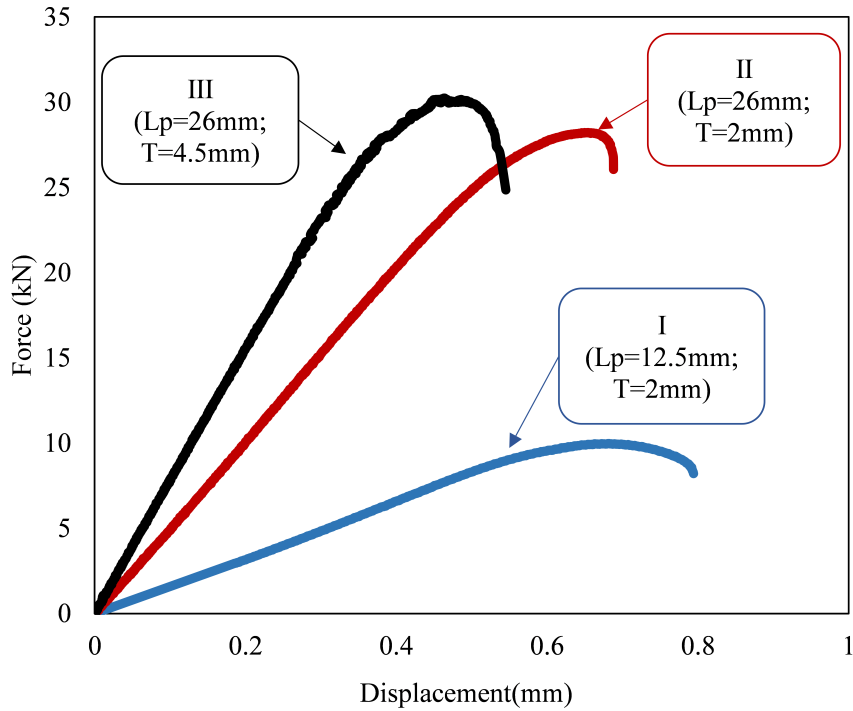


Figure C.7: Typical force-displacement curves for different configurations.

Fatigue results

The fatigue results are presented in Figure C.8, in the form of L-N curves, where the vertical axis is the load ratio (maximum fatigue load divided by the static failure load). From the experimental results, it is possible to conclude that, although for the static results a small increase in strength is observed for the joints with higher

adherend thickness, for fatigue, this increase in thickness is responsible for a significant increase in the fatigue life for the same load ratio. The joint with lower overlap length, for the same load ratio, also presents a higher fatigue strength.

A fatigue failure surface representative of all the fracture surfaces obtained for all the considered configurations is presented in Figure C.9. It shows that the failure was cohesive. The fatigue failure surfaces seem to indicate that the failure begins near the bondline ends, where the tensile forces are higher and propagates near the surface through the adhesive and then moves towards the center of the joint, as suggested by Underhill and Duquesnay [36].

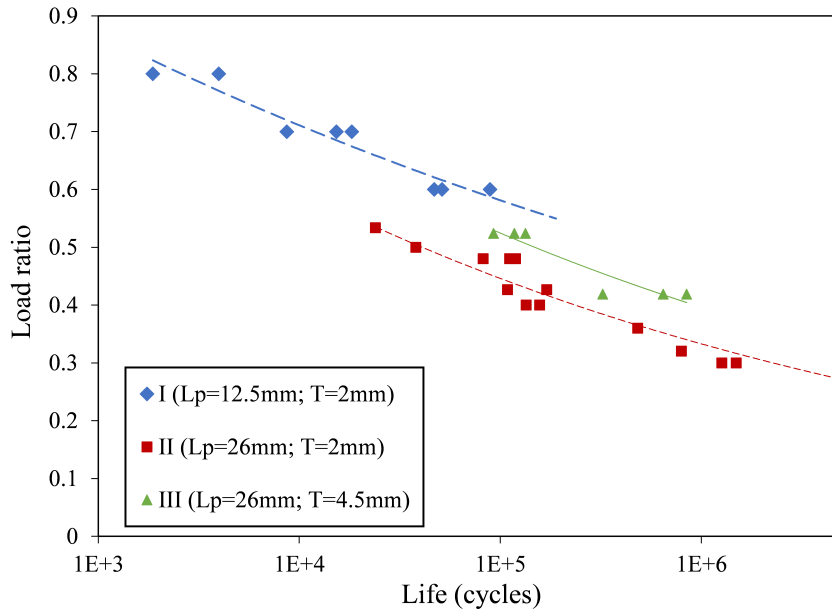


Figure C.8: L-N curve for different configurations.



Figure C.9: Fatigue failure surfaces.

C.4.2 Fatigue life prediction

To validate the proposed fatigue model, the procedure defined in Section C.3 was applied. According to the proposed fatigue model, three main steps should be followed. The first one, is the determination of the master S-N curve. The master S-N curve established in a previous study [32] was used. The second step, is performing

a FEA to assess the effective stress and the maximum principal stress distributions along the adhesives mid-plane defined as shown in Figure C.10. The third one is the calculation of the critical distance using ENA and the determination of the effective stress.

FEA details

Out of FEA, the stress distributions of the maximum principal stress, the von Mises stress and the hydrostatic stress along the adhesive mid-plane were obtained. A 2D linear elastic FEA with a plain strain assumption was chosen for allowing short computation times. To perform this analysis, two types of mechanical properties are required: Young's modulus and Poisson's ratio. The former was obtained from the bulk tests. Poisson's ratio is calculated based on the relation between the Young's modulus and the shear modulus obtained from a thick adherend shear test (TAST). These properties are presented in Table C.1.

A mesh composed of 4-node plain strain elements was used. Near the bonding ends, a refined mesh was used due to the higher stress gradients. Along the adhesive thickness, eight elements were used. This number of elements along the thickness was defined after a mesh sensitivity analysis, that is presented in Section C.4.4. The mesh is presented in Figure C.10.

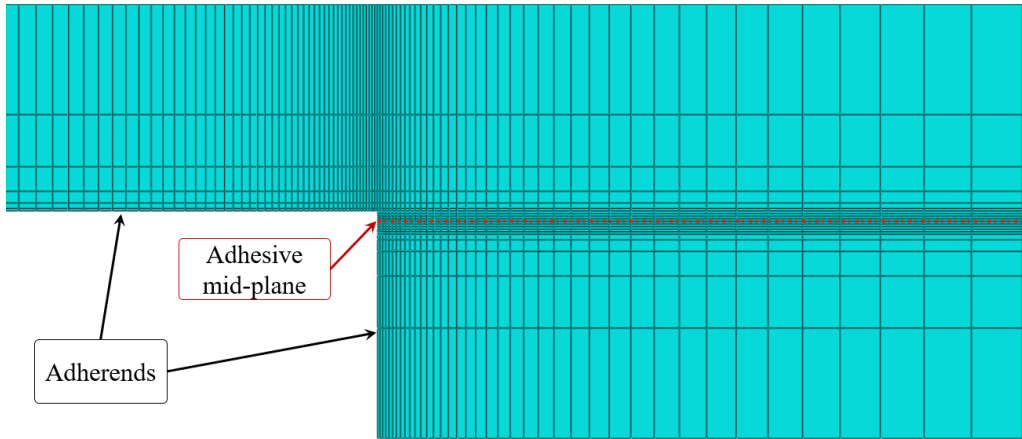


Figure C.10: Mesh configuration used for the simulation of SLJs.

The boundary conditions applied for the simulation are presented in Figure C.11. A pressure load was applied to both ends and a vertical displacement constraint was applied to the clamped region. The applied pressure load was correspondent to the maximum applied load during each fatigue test.

It is important to highlight that for SLJs the stress at a point is not directly proportional to the applied load. This happens due to a geometric non linearity. For this reason, the applied bending moment depends not only on the load applied but also on the deflection of the joint. Therefore, this effect should be considered on the simulation.

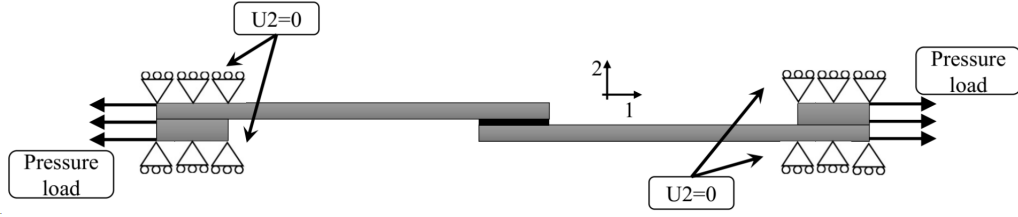


Figure C.11: Boundary conditions used for the simulation of SLJs.

Critical distance determination

To determine the critical distance at which the effective stress should be measured, the procedure stipulated in Section C.3. was followed. From the FEA results, the stress concentration, defined in Eq. (C.4) was calculated. The load ratio was determined using the average static failure loads presented in Table C.2. The empirical constant M was determined using a randomly selected experimental fatigue data point from the highest load levels tested for each configuration. The highest load levels were selected since the testing time is short and requires less effort. The points used are circled in Figure C.12. M was calculated so that the selected point would be exactly on the master S-N curve. By knowing the life obtained experimentally it is possible to estimate the ideal effective stress. Then, by analysing the effective stress distribution, the critical distance that gives the ideal effective stress is determined. The critical distance divided by the overlap length gives ρ . Next, by introducing this value in Eq. (C.4), the M is obtained. The values of M obtained for each configuration are presented in Table C.3. It is important to highlight that other points could be used for this estimation.

Table C.3: M values determined for different configurations.

Configuration	I	II	III
M	0.399	0.424	0.445

With all the parameters defined as described previously, it is possible to determine ρ for all the load levels and configurations. Then, this distance should be multiplied by the overlap length to obtain the critical distance. Having L determined, it is only required to attain the value of the effective stress at this distance using FEA. Finally, by introducing this value in the master S-N curve, a prediction of the fatigue life of the joint for those loading conditions is obtained.

The results are shown in Figure C.12. The points represent the experimental results for each condition and the master curve is the estimated life. The majority of the experimental results lie within the factor of two boundaries, showing good correlation between the estimated life and the experimentally obtained one.

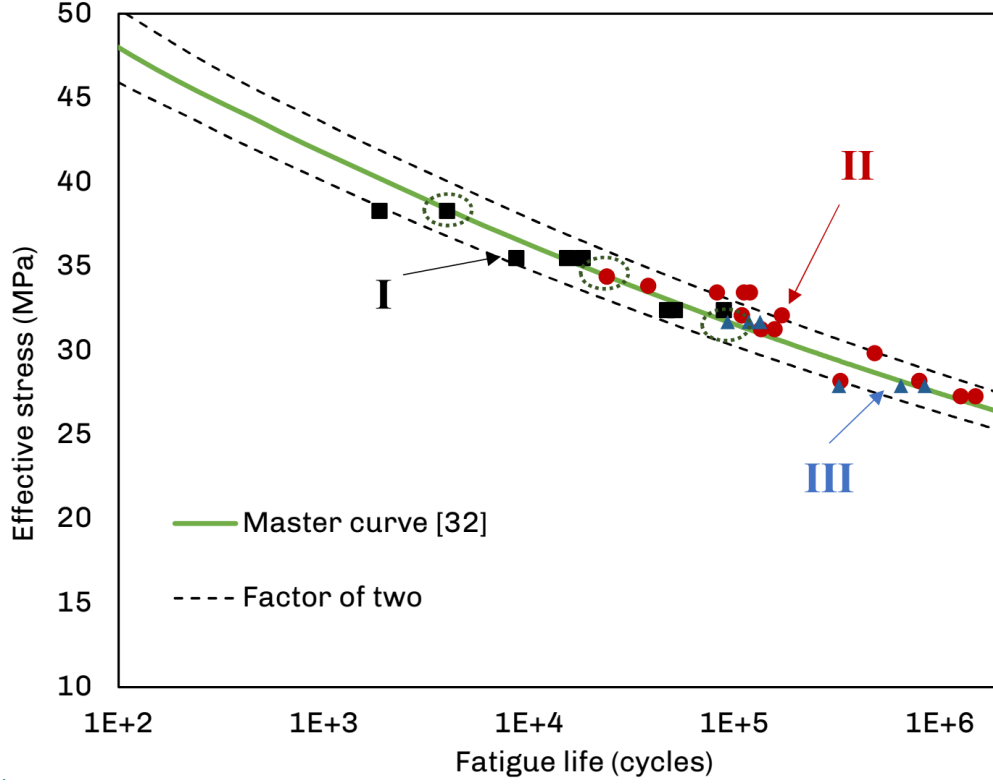
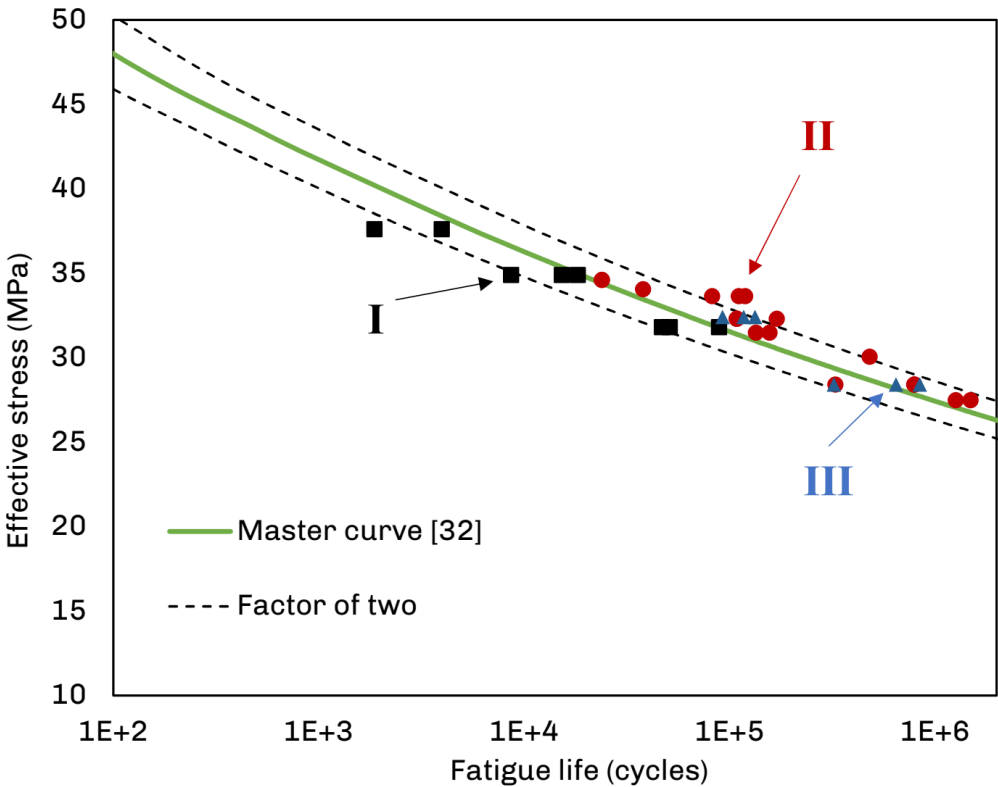


Figure C.12: Fatigue life estimation results.

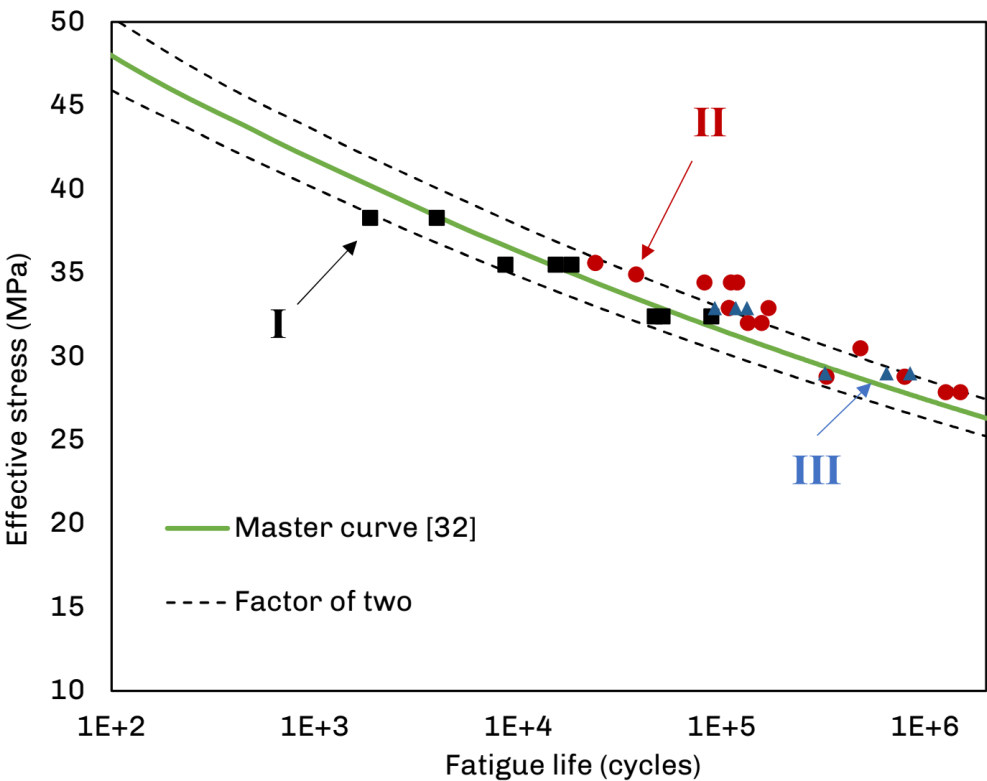
C.4.3 Influence of the value of M on the prediction

As shown in Table C.3 the value of M is similar for different configurations, which indicates that this parameter is not highly influenced by different overlap lengths, substrate thickness and joint width. To assess if this assumption is valid, an estimation of the fatigue life was performed using the same value of M for all the configurations. The value initially selected was the one from configuration II used in the previous analysis. For this point, M takes the value of 0.424. The estimation results are presented in Figure C.13a.

The results show that the overall accuracy loss is almost negligible for a fatigue context. To analyse the sensitivity of the model to the reference points used, the M values calculated for configuration I and III were used. For the results shown in Figure C.13b, a M value of 0.399 was used for all the configurations. While in Figure C.13c the used value was $M = 0.445$.



(a) $M = 0.424$.



(b) $M = 0.399$.

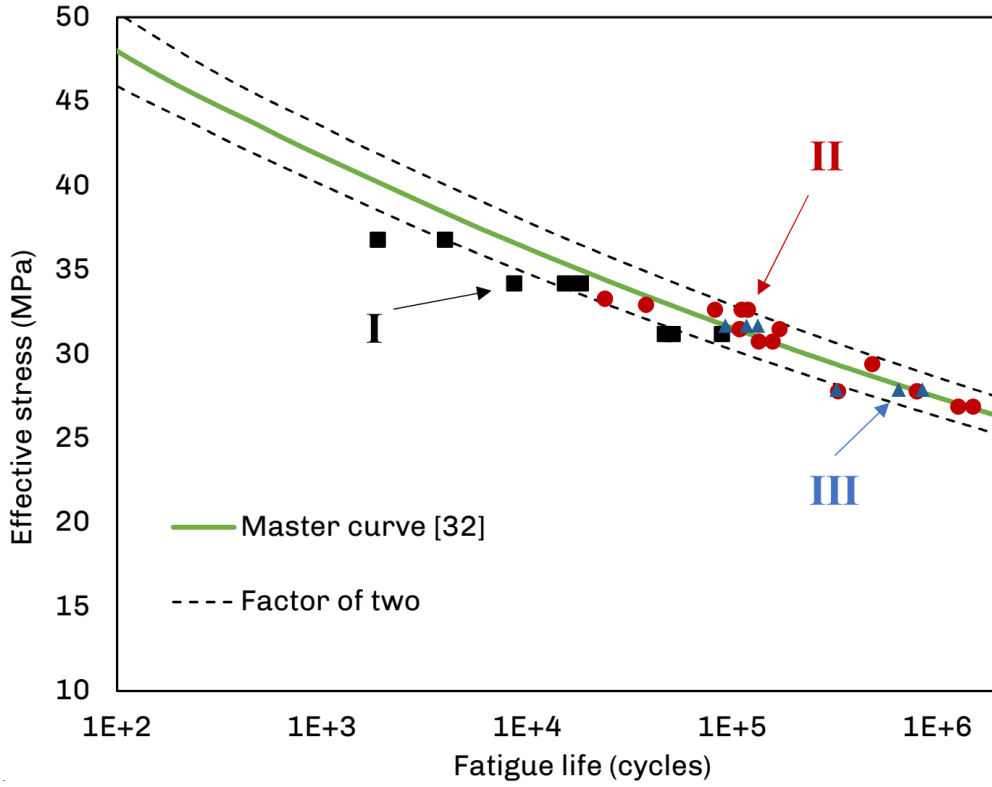
(c) $M=0.445$

Figure C.13: Fatigue life estimation results for a constant M for different configurations.

Results show that even by changing the reference point, using a M value constant for all the configurations still produces accurate results. Therefore, it is assumed that using a constant value of M for all the configurations is a valid approximation. This represents one advantage of the model as by performing only one fatigue test for one configuration it is possible to have an estimation of the fatigue life for different joint's configurations. It is important to highlight that further validation is required to understand if this parameter is a function of other factors that influence the fatigue life of SLJs, namely the adhesive thickness and the materials used (both adhesive and adherend). It is obvious that using one M value for each configuration increases the robustness of the model, resulting in safer estimations but requiring more experimental work.

C.4.4 Mesh sensitivity analysis

As stated in Section C.4.2, a mesh sensitivity analysis was performed to assess the influence of the mesh size (X) on the effective stress. The number of elements along the adhesive thickness was doubled at each step and the analysis stopped once a change less than 1 % on both the effective stress and critical distance was detected. This analysis was performed on for the highest load level experimentally tests from

configuration I. The value of M has no influence on the mesh sensitivity analysis and was arbitrarily set to 0.4. The evolution of the effective stress for each step is presented in Table C.4. The results show that, except for the first step where only two elements were used along the thickness, the mesh size has as almost negligible influence on the effective stress. The effective stress distribution for all the mesh's sizes considered is presented in Figure C.14. It can be seen that the distribution for the meshes used on steps three and four are almost coincident. Given this, it is possible to conclude that the mesh size has an insignificant influence on the proposed fatigue model. This is one the advantages commonly associated with the critical distance approach.

Table C.4: Mesh sensitivity analysis.

Step No.	No. Elements (along the adhesive thickness)	X (mm)	Effective stress (MPa)	Critical distance
1	2	0.1	36.7	4.54
2	4	0.05	38.14	4.08
3	8	0.025	38.3	3.98
4	16	0.0125	38.26	4.01

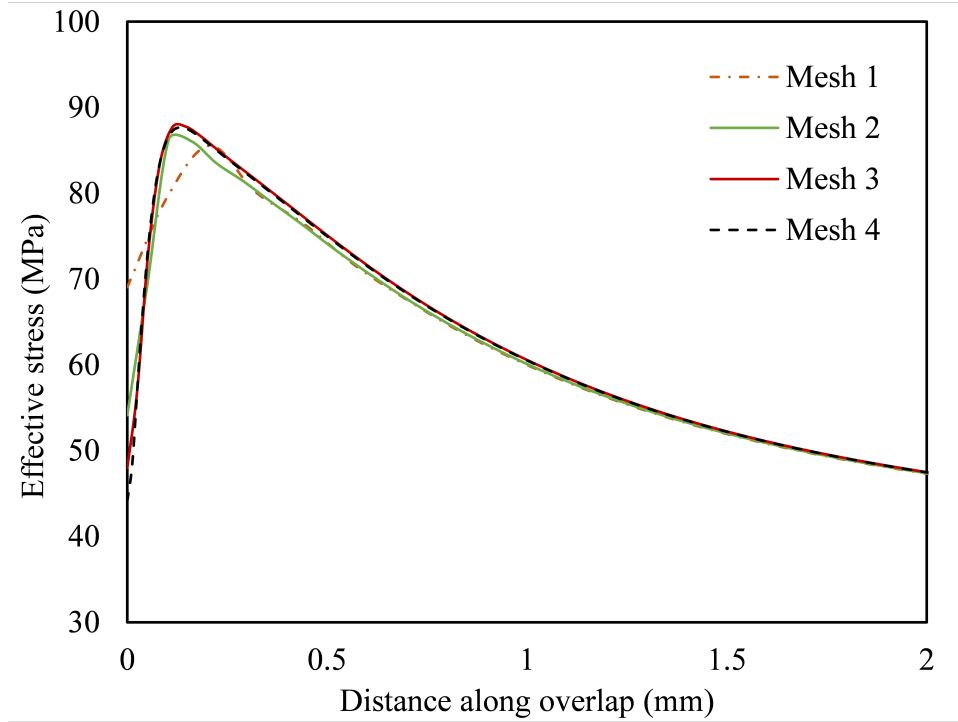


Figure C.14: Effective stress distribution for different mesh sizes.

C.5 Conclusions

In this paper, a novel fatigue life estimation model able to deal with the effect of mode mixities was extended to be able to account for the stress concentrations present in single lap adhesive joints. To achieve this, a critical distance approach was developed and validated on SLJs with different dimensions: overlap length, joint width and substrate thickness. The influence of an empirical constant needed to apply the proposed critical distance approach was also assessed. Out of the present work the following conclusions can be drawn:

- The proposed fatigue model was able to predict accurately the fatigue life of three SLJs with different configurations.
- As expected, the adherend thickness had a bigger impact on the fatigue behaviour than on the static behaviour of the joints. An increase in the adherend thickness improved significantly the fatigue life.
- The empirical constant, M , necessary to calculate the normalised critical distance was shown to be not influenced by different overlap lengths, the adherend thicknesses nor the joint width. Therefore, using the same value of M to predict the life of different configurations is a reasonable approximation. This is one advantage of the model since performing only one fatigue test would give an estimation of the life of SLJs with different geometries.
- A mesh sensitivity analysis indicated that the influence of the mesh size on the fatigue model is almost negligible.

References

- [1] L. F. M. da Silva, Andreas Öchsner, and R Adams. Handbook of Adhesion Technology. 2nd edition, 2018.
- [2] J. Machado, E. Marques, A. Barbosa, and L. F. M. da Silva. Fatigue performance of single lap joints with CFRP and aluminium substrates prior and after hygrothermal aging. *Fatigue Fract. Eng. Mater. Struct.*, 42, 2019.
- [3] L.F.M. da Silva and Andreas Öchsner. *Modeling of Adhesively Bonded Joints*. 01 2008.
- [4] M. Costa, G. Viana, L. F. M. da Silva, and R. D. S. G. Campilho. Environmental effect on the fatigue degradation of adhesive joints: A review. *J. Adhes.*, 93(1-2):127–146, jan 2017.
- [5] M. D. Banea, L. F. M. da Silva, R. J. C. Carbas, D. K. K. Cavalcanti, and L. F. G. de Souza. The effect of environment and fatigue loading on the behaviour of TEPs-modified adhesives. *J. Adhes.*, 96(1-4):423–436, 2020.
- [6] Y. Jen and C. Ko. Evaluation of fatigue life of adhesively bonded aluminum single-lap joints using interfacial parameters. *Int. J. Fatigue*, 32(2):330–340, 2010.
- [7] J. A. M. Ferreira, P. N. Reis, J. D. M. Costa, and M. O. W. Richardson. Fatigue behaviour of composite adhesive lap joints. *Compos. Sci. Technol.*, 62(10):1373–1379, 2002.
- [8] H. S. da Costa Mattos, A. H. Monteiro, and R. Palazzetti. Failure analysis of adhesively bonded joints in composite materials. *Mater. Des.*, 33:242–247, 2012.
- [9] A. R. Shahani and S. M. Pourhosseini. The effect of adherent thickness on fatigue life of adhesively bonded joints. *Fatigue Fract. Eng. Mater. Struct.*, 42(2):561–571, 2019.
- [10] M. Abdel Wahab. Fatigue in adhesively bonded joints: A review. *ISRN Materials Science*, 2012, 11 2012.

- [11] S. Kumar and P. C. Pandey. Fatigue life prediction of adhesively bonded single lap joints. *Int. J. Adhes. Adhes.*, 31(1):43–47, 2011.
- [12] V. Beber, P. Fernandes, J. Espada Fragato, B. Schneider, and M. Brede. Influence of plasticity on the fatigue lifetime prediction of adhesively bonded joints using the stress-life approach. *Appl. Adhes. Sci.*, 4, 2016.
- [13] S. Kumar and P. Pandey. Cyclic-fatigue performance of adhesively bonded lap joint. In *Fail. Mech. Lett.*, volume 1, pages 541–546, 2006.
- [14] M. Braun, A. Müller, A. Milaković, W. Fricke, and S. Ehlers. Requirements for stress gradient based fatigue assessment of notched structures according to theory of critical distance. *Fatigue Fract. Eng. Mater. Struct.*, 2020.
- [15] Douglas Y. Wang. Influence of stress distribution on fatigue strength of adhesive-bonded joints. *Exp. Mech.*, 4(6):173–181, 1964.
- [16] H. Neuber. *Theory of notch stresses: Principles for exact calculation of strength with reference to structural form and material*. Springer, Berlin, 1958.
- [17] R. E. Peterson. Notch sensitivity. In J.L. Sines, G. and Waisman, editor, *Met. Fatigue*, pages 293–306. McGraw Hill, New York, 1959.
- [18] D. Taylor. *The Theory of Critical Distances: A New Perspective in Fracture Mechanics*. Elsevier Science, 2007.
- [19] L. Susmel. The theory of critical distances: a review of its applications in fatigue. *Eng. Fract. Mech.*, 75(7):1706–1724, 2008.
- [20] Yasuaki Suzuki. Adhesive Tensile Strengths of Scarf and Butt Joints of Steel Plates (Relation Between Adhesive Layer Thicknesses and Adhesive Strengths of Joints) : Solid-Mechanics, Strength of Materials. *JSME Int. J.*, 30(265):1042–1051, 1987.
- [21] S. J. John, A. J. Kinloch, and F. L. Matthews. Measuring and predicting the durability of bonded carbon fibre/epoxy composite joints. *Composites*, 22(2):121–127, 1991.
- [22] A. D. Crocombe. Global yielding as a failure criterion for bonded joints. *Int. J. Adhes. Adhes.*, 9(3):145–153, 1989.
- [23] Ph. Martiny, F. Lani, A. J. Kinloch, and T. Pardoen. A maximum stress at a distance criterion for the prediction of crack propagation in adhesively-bonded joints. *Eng. Fract. Mech.*, 97:105–135, 2013.
- [24] M. R. Ayatollahi and A. Akhavan-Safar. Failure load prediction of single lap adhesive joints based on a new linear elastic criterion. *Theor. Appl. Fract. Mech.*, 80:210–217, 2015.

-
- [25] H. Khoramishad, A. Akhavan-Safar, M. R. Ayatollahi, and L. F. M. da Silva. Predicting static strength in adhesively bonded single lap joints using a critical distance based method: Substrate thickness and overlap length effects. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, 2016.
- [26] A. Akhavan-Safar, M. R. Ayatollahi, and L. F. M. da Silva. Strength prediction of adhesively bonded single lap joints with different bondline thicknesses: A critical longitudinal strain approach. *Int. J. Solids Struct.*, 109:189–198, 2017.
- [27] A Akhavan-Safar, L. F. M. da Silva, and M. R. Ayatollahi. An investigation on the strength of single lap adhesive joints with a wide range of materials and dimensions using a critical distance approach. *Int. J. Adhes. Adhes.*, 78:248–255, 2017.
- [28] C. E. Cruz-G, A. Akhavan-Safar, L. F. M. da Silva, and M. R. Ayatollahi. On the evaluation of a critical distance approach for failure load prediction of adhesively bonded dissimilar materials. *Contin. Mech. Thermodyn.*, 2020.
- [29] Makoto Imanaka and Takayoshi Iwata. Estimation of Fatigue Strength for Adhesively-Bonded Lap Joints Based on Fatigue Failure Criterion Under Multiaxial Stress Conditions. *J. Adhes.*, 65(1-4):7–24, 1998.
- [30] V. C. Beber, P. H. E. Fernandes, B. Schneider, M. Brede, and B. Mayer. Fatigue lifetime prediction of adhesively bonded joints: An investigation of the influence of material model and multiaxiality. *Int. J. Adhes. Adhes.*, 78:240–247, 2017.
- [31] V. C. Beber, B. Schneider, and M. Brede. Efficient critical distance approach to predict the fatigue lifetime of structural adhesive joints. *Eng. Fract. Mech.*, 214:365–377, 2019.
- [32] F. Castro Sousa, A. Akhavan-Safar, R. Goyal, and L.F.M. da Silva. Fatigue life estimation of adhesive joints at different mode mixities. *The Journal of Adhesion. Manuscript submitted for publication.*, 2020.
- [33] J. Monteiro, A. Akhavan-Safar, Marques E. Carbas, R., R. Goyal, M. El-zein, and L. F.M. da Silva. Influence of mode mixity and loading conditions on the fatigue crack growth behaviour of an epoxy adhesive. *Fatigue and Fracture of Engineering Materials and Structures*, 43(2):308–316, 2020.
- [34] A. Akhavan-Safar, A. Q. Barbosa, M. R. Ayatollahi, and L. F. M. da Silva. Influence of microcork particles on the lap shear strength of an epoxy adhesive subjected to fatigue loading and different environmental conditions. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, 234(6):851–858, 2020.
- [35] Chun-Hui Wang. *Introduction to Fracture Mechanics*. 1996.

REFERENCES

- [36] P. R. Underhill and D. L. Duquesnay. The dependence of the fatigue life of adhesive joints on surface preparation. *Int. J. Adhes. Adhes.*, 26(1-2):62–66, feb 2006.