International Scholarly Research Network
ISRN Materials Science
Volume 2012, Article ID 746308, 25 pages
doi:10.5402/2012/746308

*Review Article*

# Fatigue in Adhesively Bonded Joints: A Review

**M. M. Abdel Wahab**

*Department of Mechanical Construction and Production, Ghent University, Technologiepark 903, 9052 Zwijnaarde, Belgium*

Correspondence should be addressed to M. M. Abdel Wahab, magd.abdelwahab@ugent.be

Received 22 August 2012; Accepted 3 October 2012

Academic Editors: J. F. Bartolomé, D. Chicot, and J. E. Lowther



This paper presents a literature review on fatigue in adhesively bonded joints and covers articles published in the Web of Science from 1975 until 2011. About 222 cited articles are presented and reviewed. The paper is divided into several related topics such as fatigue strength and lifetime analysis, fatigue crack initiation, fatigue crack propagation, fatigue durability, variable fatigue amplitude, impact fatigue, thermal fatigue, torsional fatigue, fatigue in hybrid adhesive joints, and nano-adhesives. The paper is concluded by highlighting the topics that drive future research.

## 1. Introduction

Adhesive bonding has gained lots of popularity during the last few decades due to the many advantages that it offers when compared to classical mechanical fastening techniques. A major advantage of using adhesives is its higher fatigue resistance and longer fatigue life than conventional joining techniques. Other advantages include its light weight, ability to joint thin and dissimilar components, good sealing, low manufacturing cost, and its good vibration and damping properties. Adhesively bonded joints are widely used in many industries, especially automotive and aerospace due to the requirement of lightweight materials. There is, therefore, no wonder that adhesive bonding is the primary joining technique for carbon fibre reinforced polymer (CFRP) used in the aerospace industry. Many other industries make use of adhesives, for example, civil engineering, transportation, biomechanical, marine, electronics, and so forth. Hybrid joints that consist of the combination of mechanical joining and adhesive bonding have attracted the attention of various automotive and transportation industries during the last few decades due to their enhanced performance when compared to only mechanical joining techniques.

Fatigue is undoubtedly a very important type of loading for many structural components that contain adhesive bonding systems. In a fatigue loading regime, a structure may fail at a small percentage of static strength. Therefore, fatigue analysis and fatigue strength prediction are highly required especially for the case of fail-safe or damage tolerance design. Accurate prediction of fatigue life is a challenge due to the complicated nature of fatigue crack initiation and propagation, geometry of bonded joints, and complex material behaviour under loading and unloading regimes.

This paper covers a literature review on fatigue in adhesively bonded joints during the last few decades and more precisely from 1975 until 2011 (or early 2012). All cited articles, 222 references, are published in the Web of Science (WoS). It is a difficult task indeed to classify these articles because of the overlap between the different topics and because there exist many ways to classify them. The classification chosen in this paper is mainly based on the type of analysis and fatigue loading regime. The topics that can be regarded as classified under type of analysis are (a) fatigue strength and lifetime prediction, (b) fatigue crack initiation, (c) fatigue crack propagation and (d) fatigue durability, while the topic that can be regarded as classified under fatigue loading regime are (a) variable fatigue amplitude, (b) impact fatigue, (c) thermal fatigue, and (d) torsional fatigue. Two additional topics that cannot be classified under those two broad headings are fatigue in hybrid adhesive joints and nanoadhesives.

## 2. Fatigue Strength and Lifetime Analysis

A large number of the WoS articles concentrated on fatigue strength and lifetime prediction of joints. This indicates that there is a need to enhance fatigue strength and prolong fatigue lifetime of adhesively bonded joints. In general, there are two approaches for fatigue lifetime prediction, which have been extensively used in the literature, namely, stress-life approach and fatigue crack initiation/propagation approach. Unless some overlaps take place, this section is mainly dealing with the first approach, while Sections 3 and 4 are presenting the second approach. In the stress-life approach, a series of tests under various loads are performed in order to obtain the plot of stress versus the number of cycles to failure, which is known as S-N curve or Wohler's curve. Theoretically speaking, at a fatigue threshold the structure has an infinite life. However, this is not the case for adhesively bonded joints and the threshold is usually specified at a certain number of cycles, for example, one million cycles. This section is divided into four main parts providing a literature overview on the effect of different aspects on the fatigue strength and lifetime analysis, namely, the effect of geometric parameters, the effect of material parameters, the effect of loading conditions, and the effect of surface treatment and curing conditions.

*2.1. Effect of Geometric Parameters.* The shape and configuration of an adhesively bonded joint play an important role in its fatigue strength and lifetime. Many researchers have investigated different types of joints and compared their fatigue performances. Some researchers proposed new or modified joints that can provide higher fatigue threshold and longer fatigue life. Jen [1] performed an experimental study in order to determine the fatigue lifetime of adhesively bonded scarf joints (Figure 1) with various scarf angles. His experimental results indicated that the fatigue strength significantly increases when increasing the scarf angle. He also found that the mode of failure changed from adhesive failure for small scarf angles to cohesive failure for large scarf angle.

Altan et al. [2] experimentally studied the effects of butterfly fitting clearances on the fatigue performance. From the experimental results, it was found that adhesively bonded butterfly joints (Figure 2) had a longer fatigue lifetime than those of the bonded butt joints under the same conditions. Fessel et al. [3] proposed a reverse-bent joint geometry (Figure 3) in order to improve fatigue performance of adhesively bonded joints. From their results, high improvement in fatigue performance was obtained.

Underhill et al. [4] investigated the factors affecting the wedge test performance of aluminium (Al) adhesively bonded joints (Figure 4). They found that the specimens having the shortest crack length in the wedge test had the longest fatigue lives with the least amount of scatter.

Zhang et al. [5] experimentally investigated double lap joint (DLJ) and stepped lap joints CFRP adhesively bonded joints (Figures 5(a) and 5(b)) subjected to cyclic tensile loading. They found a critical stiffness for DLJs and a critical

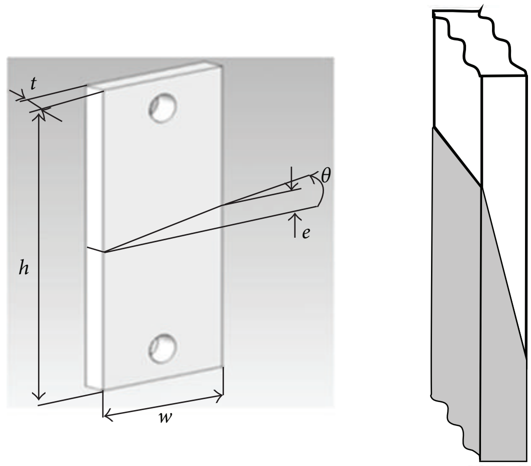



Figure 1: Scarf joints.

Figure 2: Adhesive butterfly joint.

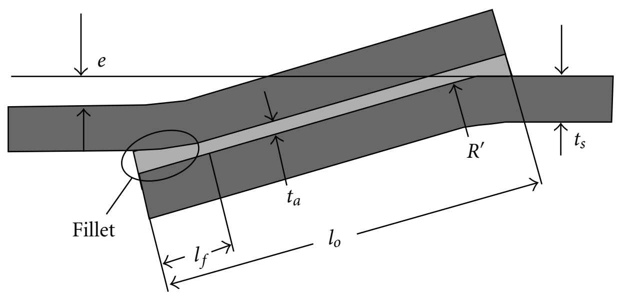



Figure 3: Reverse-bent joint, adopted from [3].

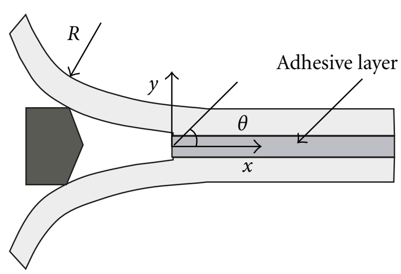
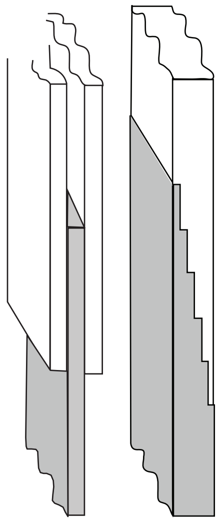



Figure 4: Wedge test.



(a) (b)

Figure 5: (a) Double lap joint and (b) stepped lap joints.

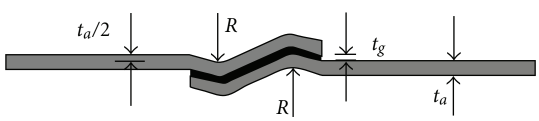



Figure 6: Wavy lap joint, adopted from [9].

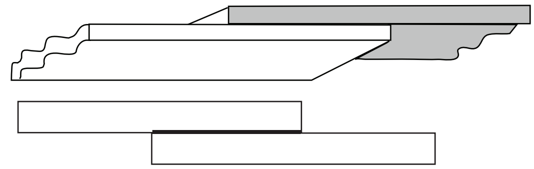


Figure 7: Single lap joints.

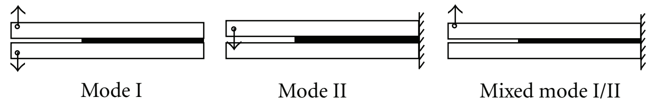



Figure 8: DCB joints.

elongation for stepped lap joints, at which failure occurred regardless of load level.

Tenchev and Falzon [6] carried out experimental fatigue tests on composite adhesively bonded stepped joints. They showed that this type of adhesive joint, widely used in repairs, significantly reduced the static strength as well as the fatigue life of the composite. Marcadon et al. [7] tested a vinylester adhesive T-joint for a structural part of a ship under fatigue loading conditions. From the results, it was concluded that the fatigue lifetime of such adhesive T-joints was separated into two phases: (a) the initiation phase, which is about the third of the fatigue lifetime, and (b) the propagation phase for the remaining lifetime up to failure. Zhou and Keller [8] presented studies on the fatigue behaviour of full scale adhesively bonded FRP bridge deck and steel girder connections. Zeng and Sun [9] introduced a wavy lap joint (Figure 6) and claimed that it was much stronger than the conventional flat joint. They performed fatigue tests and compared the results of the wavy lap joint with those of the conventional SLJ. They concluded that the wavy lap joint had a much longer fatigue life than the conventional SLJ.

Imanaka et al. [10] proposed to use the stress singularity parameters to evaluate the endurance limits of adhesively bonded single lap joint (SLJ) (Figure 7), cracked SLJs, and single-step DLJs. The stress singularity fields are given by

$$\sigma_{ij} = \frac{K_{ij}}{r^{\lambda}}, \quad (1)$$

where $\sigma_{ij}$ is the stress component and $r$ the distance from the singular point. The stress intensity factor, $K_{ij}$, and the order of stress singularity, $\lambda$, could be used to estimate the strength of adhesive joints and crack initiation lifetime.

The effect of overlap length and bonding area on the fatigue strength has been studied by many authors. Depending on the type of joint, the type of substrate, and adhesive thickness, different results may be obtained. da Costa Mattos et al. [11] performed experimental static and fatigue tests of carbon/epoxy laminates bonded with epoxy adhesively bonded SLJ for different bonding areas. They found that a shape factor could be used to correlate fatigue lifetimes of two joints with different adhesive areas.

Jen and Ko [12] studied the effect of adhesive dimensions on the fatigue strength of adhesively bonded Al SLJs. From their experimental results, it was found that the fatigue resistance decreased as the overlap length increased except for the specimens with an adhesive thickness of 0.5 mm. From finite element analysis (FEA), they concluded that the interfacial peeling stress was the main driving force of the fatigue failure of the SLJs. Bernasconi et al. [13] conducted fatigue experimental tests on adhesive lap joints of thick composite laminates. They tested specimens of different overlap length, with and without tapers using different substrate materials, that is, composite to composite and composite to steel. Melander et al. [14] tested a number of fatigue specimens containing artificial bond defects with different configurations. They found that the stiffness and the fatigue strength have been substantially affected by bond defects. Mazumdar and Mallick [15] studied the static and fatigue behaviour of adhesively bonded SLJs in sheet moulding compound (SMC) composites. They investigated the effects of overlap length, adhesive thickness, surface preparation, test speed, and water exposure on the joint performance. From the results, they found that overlap length and adhesive thickness have negligible effect on the ratio of fatigue strength to static strength and the fatigue strength was approximately 50% to 54% of the static strength.

Bond-line thickness has a significant effect on static and fatigue behaviour of adhesively bonded joints. It should be optimised in order to maximize the fatigue strength of a joint. Azari et al. [16, 17] studied the effect of bond-line thickness in the range of 0.13 mm to 0.79 mm on the fatigue


Figure 9: ADCB joints.

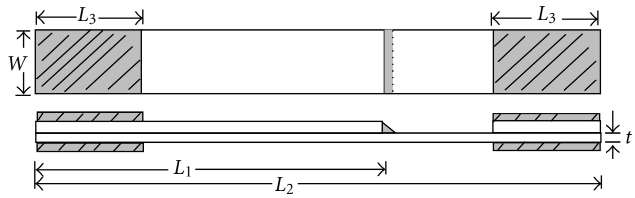



Figure 10: CLS or LSJ (uncracked) joint.

and quasistatic fracture behaviour of Al adhesively bonded joints. They used a toughened epoxy adhesive and double cantilever beam DCB (Figure 8) and asymmetric double cantilever beam ADCB (Figure 9) specimens under mode I and mixed mode loading, respectively. They found that the fatigue threshold strain energy release rate decreased for very thin bond lines under mode I loading and hardly changed under mixed mode loading. It was further concluded that the effect of bond-line thickness was more pronounced at higher crack growth rates. Blanchard et al. [18] studied the monotonic and fatigue shear behaviour of an epoxy adhesive joint using a short overlap thick substrate configuration. They found that the strength of the joint was strongly dependent on the strain rate and the joint thickness.

In composite bonded joints, the fibre orientation of the different plies, especially the ply next to the adhesive/substrate interface, has a significant effect on the fatigue performance of the joints. Meneghetti et al. [19] studied the effect of the orientation of the composite layer at the adhesive/substrate interface on the fatigue behaviour of adhesively bonded composite joints. They applied a damage model to the prediction of fatigue lifetime as the sum of initiation and propagation phases. Ferreira et al. [20] presented a fatigue study of composite adhesive lap joints. They used different stacking sequences for the composite substrates, namely, bidirectional woven E-glass fibres and polypropylene composites and hybrid stacked composites. Opposite to what was expected, they found that the fatigue strength in hybrid stacked joints was lower than that in the original thermoplastic composite joints.

Further studies on the effect of geometric parameters on the fatigue of adhesively bonded joints include a review FEA [21, 22] and guidelines on fatigue and creep testing [23].

*2.2. Effect of Material Parameters.* Modern adhesives exhibit a large amount of plasticity, which affects the fatigue behaviour of adhesive joints. Kumar and Pandey [24] performed computational simulations on adhesively bonded SLJ considering both geometrical and material nonlinearities to predict the fatigue life. They applied the modified Coffin-Manson equation, which is given by

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'\left(2N_f\right)^c, \tag{2}$$

where $\Delta\varepsilon_p/2$ = plastic strain amplitude, $\varepsilon_f'$ = fatigue ductility coefficient defined by the strain intercept at one load reversal, $2N_f$ = total number of reversals to failure, and $c$ = fatigue ductility exponent, which is a material property.

They used elastoplastic material models for both adhesive and substrates. Markolefas and Papathanassiou [25] developed a shear-lag model to evaluate stress redistributions in DLJs under fatigue loading. They assumed that substrate has a linear elastic behaviour, while the adhesive has an elastic-perfectly plastic shear stress-strain relationship. Kumar and Pandey [26] investigated the fatigue behaviour of Al adhesive SLJs by carrying out nonlinear finite element analysis taking into account both material and geometric nonlinearities and modelling adhesive as elastoplastic multilinear material with kinematic hardening, which accounts for cyclic plasticity. They have observed that the peel stress in the interlaminar adhesive layer edge zone grew significantly with fatigue loading to failure initiation.

In order to enhance the fatigue performance, reinforcing the adhesive material used in a joint has been investigated. Datla et al. [27] studied the fatigue behaviour of Al adhesively bonded joints using ADCB and cracked lap shear (CLS) joints (Figure 10), which eliminate the yielding of the substrates. It has been shown that the reinforcing adhesive layer had an insignificant effect on the fatigue behaviour. Lap strap joint (LSJ) has the same configuration as CLS, except that no crack is present. Khalili et al. [28] presented experimental investigations on reinforcing the adhesive material in SLJs subjected to tensile, bending, impact, and fatigue loads. They found that the fatigue lifetime increased by 125% due to reinforcing adhesive layer with unidirectional and chopped glass fibres and microglass powder.

In order to improve their fatigue life, Täljsten et al. [29] have strengthened old steel plates with a centre notch bonded to CFRP laminates using adhesives. From their results, it was shown that there was a significant improvement in fatigue performance when CFRP laminated was used.

*2.3. Effect of Loading Conditions.* Type, level, and multiaxiality of loads have an important effect on the fatigue behaviour of adhesive joints. Nolting et al. [30] examined the fatigue life and failure mode of Al double strap joint (DSJ) (Figure 11). They found that substrate failures occurred at lower stresses, while debonding of the patches occurred at higher stresses. From FEA, they concluded that the stress/strain state at the edge of the patch was altered by changing the patch thickness, patch modulus, or by tapering the edges of the patch. They further found that a power-law relationship existed between fatigue life and either the peak principal strain in the adhesive for adhesive failures

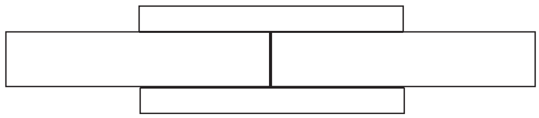


Figure 11: DSJ.

or the nominal axial stress in the substrate for substrate failures.

Ishii et al. [31, 32] carried out a series of fatigue tests on butt, scarf, and thick substrate SLJs in order to investigate the fatigue failure criterion of CFRP/metal adhesively bonded joints under multiaxial stress conditions. They found that the fatigue limits were governed by the maximum principal stress except when negative hydrostatic pressure acts on the adhesive layer. Crocombe [33] predicted the response of adhesively bonded structures to different service loadings, namely, quasistatic, fatigue, creep, and environmental loading. Imanaka and Iwata [34, 35] proposed a method for the estimation of endurance limits for adhesively bonded SLJs and single-step DLJs using the stress multiaxiality in the adhesive layer. They studied the fatigue failure criteria for adhesively bonded joints under combined stress conditions [36]. They tested two types of adhesively bonded joints, namely, scarf joint and butterfly-type butt joint. Imanaka et al. [37, 38] carried out a series of fatigue tests by using adhesively bonded butt joints with unbounded layer at adhesive/substrate interface under the push-pull fatigue load condition of stress ratio −1.0 in order to determine the fatigue strength. Mertiny and Ursinus [39] presented a study on cyclic damage behaviour of adhesively bonded GFRP tubes. From experiments on small-scale and large-scale specimens, it was concluded that damage modes and their severity depended on the applied biaxial pipe stress ratio and the type of loading. Knox et al. [40] carried out an experimental study to investigate the fatigue performance of adhesively bonded composite pipe joints subjected to external mechanical loading. From the results, they found that pure axial fatigue loading was more detrimental to fatigue life than cyclic loading due to internal pressure. Keller and Schollmayer [41] experimentally and numerically investigated the through-thickness performance of pultruded FRP bridge decks and steel girders adhesive joints due to uplift forces caused by load bearing of the bridge deck. They found that no stiffness degradation occurred for fatigue loading up to 10 million cycles.

The effect of bending fatigue loading has been investigated by a few authors. Clark and Romilly [42] presented an experimental and FEA study of a bonded composite repair applied to a metallic aircraft structure. They performed fatigue testing of 2024-T3 Al plates repaired with boron/epoxy composite patches. From the experimental and FEA results, they illustrated the important influence of bending and composite failure modes on the fatigue lifetime and the strength of the repair. Gao and Yue [43] performed a special bending fatigue experiment to investigate the fatigue behaviour of polyethylene methacrylate in adhesive assembly. From experimental data and FEA, they derived a local stress law for predicting bending fatigue lifetime. Using curve fitting of the experimental data, the maximum tensile stress, $\sigma_{\max}$, is expressed in terms of the number of cycles $N$ as [43]

$$\sigma_{\max} = \left(\frac{1.494e^{44}}{N}\right)^{1/23.55}. \quad (3)$$

Prestrain and loading speed has been investigated by Takiguchi and Yoshida [44], who conducted repeated tensile experiments of an Al SLJ bonded with highly ductile acrylic adhesive in order to investigate the fatigue strength. From experimental results, it was found that the prestrain did not affect the fatigue life and that the fatigue strength became higher with increasing loading speed, especially for low cycle fatigue.

The effect of loading frequency and load ratio on the fatigue performance of bonded joints has been studied by a few researchers. Gomatam and Sancaktar [45] studied the effects of stress state and cyclic parameters including frequency and waveform of mechanical and/or thermal loading on the fatigue failure behaviour of adhesively bonded joints. From the results, they found a significant effect of the stress state and cyclic waveform type on the fatigue strength of the joints. They also observed that lowering the cyclic load frequency reduced the fatigue life. They have further presented a fatigue damage life predictive model using experimental data and analytical and modelling techniques [46, 47]. A load number of cycles curves were generated under fatigue conditions using different load ratios. Gladkov and Bar-cohen [48] experimentally determined the dependence of the fatigue life of two packaging epoxy adhesives on temperature, peak cycling stress, and loading frequency using SLJs. Crocombe and Richardson [49] experimentally obtained normalised fatigue load-life data for four different structural configurations of an adhesive/substrate system. They assessed the effect of the mean load and the frequency of the fatigue cycle. They found that the effect of the frequency of the fatigue cycle was relatively negligible, while the mean load had a significant effect on the fatigue performance. From a study of life spent in initiation, they concluded that crack initiation life increased with decreasing levels of fatigue load and varied considerably between different configurations.

*2.4. Effect of Surface Treatment and Curing Conditions.* Curing conditions should be optimised in order to achieve the best mechanical performance of an adhesive joint. Only a few articles have dealt with the effect of curing conditions. Yang et al. [50] studied the effect of curing pressure, curing temperature, and curing time on the fatigue lifetime of CFRP and Al adhesively bonded joints. They were able to obtain the optimal curing scheme within the test range. Furthermore, they determined the fatigue lifetime under the optimal scheme. Shin and Lee [51] studied the effects of thermal residual stresses on failure of co-cured SLJs and DLJs with steel and composite substrates under fatigue loading conditions using experimental and analytical techniques.

Surface preparation plays a very important role in the quality of the interface between adhesive and substrate and consequently has a great effect on the fatigue performance of a joint. da Silva et al. [52] studied the influence of the macroscopic state of the substrate surface on the fatigue strength of adhesive joints. They considered two different patterns on the surface of Al substrates, namely, cleaned with acetone or chemically etched. Comparing the different patterns with specimens without pattern, they concluded that the patterns increased the joint strength of nontreated substrates in the case of brittle adhesive. Sekercioglu and Kovan [53] developed a fatigue life prediction model using artificial neural network (ANN). They used their model to predict the fatigue life of adhesively bonded cylindrical joints for different surface roughness, bonding clearances, and substrate types. Azari et al. [54] investigated the effect of surface roughness on the fatigue and fracture behaviour of a toughened epoxy adhesive system. From mixed mode fatigue tests, a significant dependency on surface roughness was observed. They found that the threshold strain energy release rate increased with roughness, reached a plateau, and then decreased for very rough surfaces. Pereira et al. [55] studied the effect of surface pretreatment and substrates thickness on the fatigue behaviour of Al alloy SLJs. They used an abrasive preparation and sodium dichromate-sulphuric acid etch as surface preparation. They obtained maximum fatigue strength for the sodium dichromate-sulphuric acid etch surface treatment with a 1.0 mm substrate thickness. Kim and Lee [56] used a silane coupling agent, gamma-glycidoxypropyltrimethoxysilane to enhance the adhesion strength of composite/metal joints fabricated by cocure bonding process. They found that the silane interphase formation improved both the adhesion strength and the fatigue life of cocure bonded lap joints by chemical bonding introduced at the interface. Bland et al. [57] investigated the morphology and chemistry of the failure of adhesively bonded phosphoric acid anodising treated Al alloy. They used XPS and transmission electron microscopy/parallel electron energy-loss spectroscopy (TEM/PEELS). They have conducted fatigue tests using tapered DCB joints in water. They observed a failure at the crack tip very close to the oxide/adhesive interface, but in the adhesive phase, by both XPS and energy-filtered TEM (EFTEM). Bermejo et al. [58] analysed the influence of two different surfaces on the fatigue behaviour of epoxy adhesive joints. They showed that chemical compatibility of adhesive and paint improved the adhesion of joints and the mechanical resistance against static and fatigue loads. Gomatam and Sancaktar [59] investigated the effects of various substrate surface treatments on the fatigue and failure behaviours of adhesively bonded joints. They tested SLJs with substrate surfaces modified by employing various chemical and mechanical modification techniques, under a spectrum of fatigue and environmental conditions. They found a significant effect of the substrate surface on the fatigue behaviour of the joint.

## 3. Fatigue Crack Initiation

In general, fatigue lifetime can be divided into two main phases, namely, crack initiation and crack propagation. Many authors have neglected the crack initiation phase and based their lifetime analysis only on the crack propagation phase. The main reason for doing this is that the crack initiation phase is more difficult to deal with due to the difficulties associated with modelling the nucleation of a crack and the ability to monitor and detect the initiation phase. Damage models can be either empirical based on plastic strain, or principal strain, or scientific based on continuum damage mechanics theory. Monitoring and detecting crack initiation has been performed in the literature using back-face strain and video microscopic. Although the research into crack initiation in adhesively bonded joints has been started since 1986, it has not yet been well developed and could be seen as in its early stage. This section is divided into two parts, namely, damage models and the monitoring of crack initiation. In some references, both crack initiation and propagation were studied, and therefore sometimes an overlap between them in Sections 3 and 4 is unavoidable.

*3.1. Damage Models.* Many authors have used empirical damage models based on relating the accumulation of damage to plastic strain through a power law function. Shenoy et al. [60] proposed a unified model to predict the fatigue behaviour of adhesively bonded joints, in which the evolution of fatigue damage in the adhesive material was defined as a power law function of the microplastic strain. Katnam et al. [61] presented a fatigue damage model that included the effect of fatigue mean stresses on the failure behaviour of adhesively bonded joints. They used an effective strain-based approach in order to develop their model, which was implemented on a tapered SLJ. Graner Solana et al. [62] used an elastoplastic damage model to predict the fatigue lifetime, which is given by

$$\frac{\Delta D}{\Delta N} = b \times (\varepsilon_{\max} - \varepsilon_{\text{th}})^z, \tag{4}$$

where $D$ is the damage variable (equal to 0 for virgin material and 1 for fully damaged material), $\Delta D/\Delta N$ is the fatigue damage rate, $b$ and $z$ are material constants, and $\varepsilon_{\max}$ and $\varepsilon_{\text{th}}$ are the adhesive maximum principal strain and threshold strain, respectively, calculated at integration points from FEA. The damage variable is updated after each time increment as follows:

$$D_i = D_{i-1} + \left(\frac{\Delta D}{\Delta N}\right) \times \Delta N, \tag{5}$$

where $i$ refers to the time step and $N$ is the number of cycles. Shenoy et al. [63] measured the strength degradation of adhesively bonded SLJs during fatigue cycling and related them to damage evolution. They found that residual strength decreased nonlinearly with respect to the number of fatigue cycles. They proposed a nonlinear strength wear-out model, which could be used to predict the residual strength of a joint. Kim et al. [64] tested stepped lap composite joints under static and fatigue loading conditions. From the results, they found that crack was initiated at the end of overlap and propagated through the delamination of composite substrate.

Scientific-based damage models are normally derived from continuum damage mechanics theory using the principles of thermodynamics [65]. The number of cycles to failure is expressed in terms of the stresses in the adhesive layer, calculated from FEA, and material constants. Abdel Wahab et al. [66] investigated the measurement of fatigue damage in adhesive bonding using bulk adhesive. They have carried out low cycle fatigue tests to determine the damage variable, $D$, as a function of the number of cycles. Damage was evaluated using the decrease in stress range during fatigue lifecycles of a constant displacement amplitude test. The damage variable is given by [65, 66]

$$D = 1 - \left[1 - A(\beta + m + 1)\left(\Delta\sigma_{\mathrm{eq}}\right)^{\beta+m} R_V^{\beta/2} N\right]^{1/(\beta+m+1)}, \tag{6}$$

where $\Delta\sigma_{\mathrm{eq}}$ is the range of von Mises stress, $R_V$ is the triaxiality function, $m$ is the power constant in Ramberg-Osgood equation, and $A$ and $\beta$ are damage parameters to be determined experimentally. Wahab et al. [67] determined the damage parameters for crack initiation in an SLJ by combining continuous damage mechanics, FEA, and experimental fatigue data. They have studied the effect of stress singularity, due to the presence of corners at edges, on the complex state of stress and the variability of the triaxiality function along the adhesive layer. The damage parameters $A$ and $\beta$ determined in [66] for bulk adhesive were extended to take into account the multiaxial stress state in the adhesive layer, as calculated from FEA. Hilmy et al. [68] have shown that scarf joint test specimen could simulate constant triaxiality in the adhesive layer. Several types of adhesive joints have been modelled and analysed using FEA. From FEA, they showed that $R_v$ changed as a function of adhesive bond-line angle of the scarf joint and that its values were constant along adhesive line except at the free edges. Quaresimin and Ricotta [69] presented a model for the prediction of the fatigue life of composite bonded joints. The model was based on the actual mechanics of the fatigue damage evolution and divided the joint lifetime into a crack nucleation phase and a crack propagation phase. They modelled the nucleation phase using a generalised stress intensity factor approach. They have further studied the evolution of the fatigue damage in SLJs and observed that a significant fraction of the fatigue life of the joint was spent in the nucleation of one or more cracks [70]. They found that the duration of nucleation process was from 20% up to 70% of the joint life. Imanaka et al. [71] proposed an estimation method of fatigue strength of adhesively bonded joints with various stress triaxialities using a damage evolution model for high cycle fatigue. Imanaka et al. [72] investigated the damage evolution of adhesively bonded butt joints under cyclic loading. They applied an isotropic continuum damage model coupled with a kinetic law of damage evolution, which was solved using analytical and numerical methods. Wahab et al. [65, 73] presented and programmed a procedure in order to predict the fatigue threshold in composite adhesively bonded joints. They considered two different joint configurations, namely, DLJs and LSJs. Software has been developed to automatically calculate the damage parameters and produce the required load number of cycle to failure curves. Lefebvre and Dillard [74, 75] have shown that the fatigue initiation criterion using stress singularity parameter, a generalized stress intensity factor and the singular eigenvalue lambda (see (1)), is only appropriate for adhesive contact angle smaller than 90° and modulus ratio between adhesive and substrate smaller than 0.1.

*3.2. Monitoring of Crack Initiation.* Back-face strain has extensively been used in the literature to monitor crack initiation in adhesively bonded joints. Khoramishad et al. [76, 77] monitored damage initiation and propagation phases in SLJs using the back-face strain (Figure 12) and in situ video-microscopy techniques. Graner Solana et al. [62] presented experimental fatigue data obtained from SLJ tests at a range of load levels. They used six strain gauges (SGs) placed along the overlap to monitor fatigue initiation and propagation within the adhesive layer. Shenoy et al. [78] used the back-face strain measurement technique to characterise fatigue damage in SLJs subjected to fatigue loading. They found that crack initiation dominated at lower fatigue loads, whereas crack propagation dominated at higher fatigue loads. They used the back-face strain and fatigue life measurement results to propose a simple predictive model, which divided the fatigue lifetime into different regions depending upon the fatigue loads. Solana et al. [79] presented experimental fatigue testes of a selection of adhesive joints. They used multiple strain gauges to record the change in back-face strain during the tests and measure damage in different locations. They found that damage first appeared in the fillet as a change in adhesive colour in a specific area. Deng and Lee [80] presented details of a fatigue test programme of a series of small-scale steel beams bonded with a CFRP plate. They used back-face strain technique to detect crack initiation and monitor crack growth. They found that crack initiated and propagated in mode I earlier than in mode II. Crocombe et al. [81] studied the fatigue damage evolution in adhesively bonded joints using the back-face strain technique. From the results of the fatigue tests, they found that there was an initiation phase of about half the total fatigue life of the joint. They further observed that removing the adhesive fillet eliminated the initiation phase and consequently reduced the fatigue life. Zhang et al. [82] developed a back-face strain technique to detect fatigue crack initiation in SLJs. From experimental measurements, they found that fatigue crack initiation lives at different stresses have greater proportion of the total fatigue life as the stress decreased.

Chirped fibre Bragg grating sensors have been used by Capell et al. [83] and embedded within GFRP substrates to monitor disbond initiation and growth in a GFRP/Al SLJ. It was found that disbond initiation and growth between the substrates during fatigue cycling caused peaks or dips in the reflection spectra from the chirped fibre Bragg grating sensor.

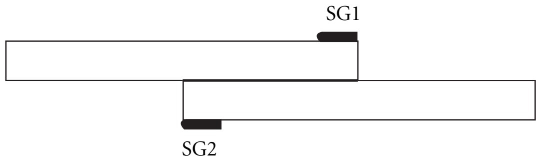



Figure 12: Position of back-face strain gauges in SLJ.

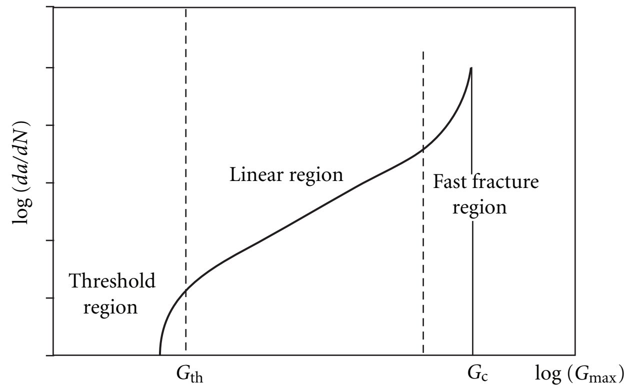



Figure 13: A typical fatigue crack propagation curve.

Dessureault and Spelt [35] investigated fatigue crack initiation and propagation in Al/epoxy adhesive joints, namely, DCB (mode I), CLS (mixed mode I/II), and ENF (mode II). They observed negligible differences in crack initiation lives for mixed mode I/II and mode II specimens. For the adhesive system tested, they recommended that adhesive joint design should be based on threshold values for zero crack growth due to the high scatter in crack propagation rates. Johnson and Mall [84] conducted an experimental study of CLS specimens in order to determine the influence of substrate stacking sequence on debond initiation and damage growth in a composite bonded joint. They found that fatigue damage initiated in the adhesive layer in specimens with 0° and 45° interface plies, whereas damage initiated in the form of ply cracking in the substrate for the specimens with 90° interface plies.

## 4. Fatigue Crack Propagation

This topic has been intensively studied in the literature. Fatigue crack propagation studies are carried out by identifying the relationship between a fracture parameter, such as strain energy release rate ($G$) and the crack growth rate using fracture mechanics tests. A common fatigue crack propagation curve for adhesively bonded joints is a logarithmic plot of crack growth rate ($da/dN$) against the maximum strain energy release rate ($G_{\max}$) over time (Figure 13). The fatigue crack propagation curve, which has a sigmoidal shape, has three different regions: (a) threshold region defined by fatigue threshold $G_{\text{th}}$ below which no crack growth takes place, (b) linear or steady state crack growth region, which can be well described by Paris' law, and (c) fast or unstable crack growth region where catastrophic failure takes place when the fracture toughness $G_c$ is reached. Knowing the relationship between the crack length $a$ and $G_{\max}$, the integration of the fatigue crack propagation curve leads to an estimation of crack propagation lifetime of the joint. In order to monitor crack growth and measuring crack length as a function of time, several techniques have been used in the literature, for example, optical techniques such as video microscopic and magnification lenses, chirped fibre Bragg grating sensors, and ultrasonic technique. This section is divided into two main parts, namely, crack propagation models and fatigue crack growth rate.

*4.1. Crack Propagation Models.* Paris's equation has been extensively used in the literature to relate crack growth rate to a fracture parameter. The fracture parameter that mostly used for adhesively bonded joint is the strain energy release rate. The strain energy release can be calculated from analytical solution or FEA using the measured force, crack length, or the rate of chance in compliance. Fernández et al. [85] experimentally investigated the fatigue behaviour of CFRP composite bonded joints under mode I loading. The fatigue crack growth rates were determined using DCB test specimens. They studied the steady crack propagation region, which leads to a linear trend on Paris's law; that is,

$$\frac{da}{dN} = C_1 \times \left(\frac{\Delta G}{G_c}\right)^m, \tag{7}$$

where $a$ is the crack length, $N$ is the number of cycles, $G$ is the strain energy release rate, and $G_c$ is the fracture toughness. The constants $C_1$ and $m$ can be obtained by curve fitting of (7) to experimental data. The power constant $m$ represents the sensitivity of the crack to its growth and is higher for adhesives than for metals. The mode I strain energy release rate $G_1$ is obtained from the variation of the compliance as a function of crack length ($dC/da$) as

$$G_1 = \frac{P^2 dC}{2Bda}, \tag{8}$$

where $P$ is the applied load and $B$ is the width of the specimen. Wahab et al. [86–88] proposed a generalised technique for the prediction of fatigue crack propagation lifetime in bonded structures using FEA. They applied the technique to CFRP joints bonded with an epoxy adhesive and used an experimentally determined crack growth law from DCB samples. They predicted the load-life response of SLJs and DLJs using a modified crack growth law, which describes the full $da/dN$ versus $G_{\max}$ curve and is given by

$$\frac{da}{dN} = C_1 G_{\max}^n \left(\frac{1 - (G_{\text{th}}/\max)^{n_1}}{1 - (G_{\text{th}}/\max)^{n_2}}\right), \tag{9}$$

where $G_{\text{th}}$ is the fatigue threshold and the constants $n$, $n_1$, and $n_2$ can be obtained by fitting (9) to experimental data.

They further proposed a modified law for mixed mode crack growth, that is,

$$\frac{da}{dN} = C_1 G_I^{n_I} \left( \frac{1 - (G_{\text{th}}/\max)^{n_{1_I}}}{1 - (G_{\text{th}}/\max)^{n_{2_I}}} \right) + C_2 G_{II}^{n_{II}} \left( \frac{1 - (G_{\text{th}}/\max)^{n_{1_{II}}}}{1 - (G_{\text{th}}/\max)^{n_{2_{II}}}} \right), \tag{10}$$

where the subscripts I/II refer to mode I and mode II, respectively.

Another technique, which is recently used in fatigue crack propagation analysis in adhesively bonded joint, is the cohesive zone model. Moroni and Pirondi [89–91] simulated fatigue crack growth in bonded joints and have implemented a cohesive damage model in ABAQUS. They used different Paris-like expressions in terms of strain energy release rate in order to evaluate the crack growth rate. Mode I cohesive zone model is shown in Figure 14.

The crack growth rate was transformed to a variation of damage distribution over the cohesive zone by assuming that the increment of crack length is equivalent to the increment of damage. The rate of growth in the defect area is expressed in terms of the range of strain energy release rate ($\Delta G$) as

$$\frac{dA}{dN} = B \times \Delta G^d, \tag{11}$$

where $A$ is the defect area and the parameters $B$ and $d$ depend on the material and load mixity ratio. The damage growth rate is then given by

$$\frac{dA}{dN} = \frac{B}{A_{\text{CZ}}} \times \Delta G^d, \tag{12}$$

where $A_{\text{CZ}}$ is the cohesive zone area. In order to account for mixed mode I/II, they used a mixed mode cohesive zone mode (Figure 15) and an equivalent opening displacement, $\delta_{\text{eq}}$, which is defined as

$$\delta_{\text{eq}} = \sqrt{\left( \frac{\delta_1 + |\delta_1|}{2} \right)^2 + {\delta_2}^2}, \tag{13}$$

where $\delta_1$ and $\delta_2$ are the opening and sliding displacements, respectively. They further proposed a mixed mode defect growth rate in terms of mode I and mode II range of strain energy release rate, $\Delta G_I$ and $\Delta G_{II}$, respectively, that is,

$$\frac{dA}{dN} = B \times (\Delta G_I + \Delta G_{II})^d. \tag{14}$$

Khoramishad et al. [76, 77] investigated the effect of load ratio on the fatigue behaviour of adhesively bonded joints using both experimental and numerical approaches. Using a cohesive zone approach with a bilinear traction-separation response (Figure 15), they modelled the progressive damage of the adhesive material.

In case of crack propagation with large-scale yielding, Gurson's model is suitable. Gurson's model was used by Ishii [92] to investigate the effect of substrate type, namely, CFRP composite and Al, on the fatigue crack propagation rate using adhesively bonded DCB specimens. They applied FEA and Gurson's model to the adhesive layer in order to determine the growth of voids. In a modified Gurson's model, the yield condition is given by

$$\phi = \frac{\sigma_e^2}{\sigma_y^2} + 2 f q_1 \cosh\left( \frac{q_2 \sigma_m}{2\sigma_y} \right) - \left(1 + q_3 f^2\right) = 0, \quad \text{where } q_3 = {q_1}^2, \tag{15}$$

where $\sigma_e$ is the effective stress, $\sigma_m$ is the hydrostatic pressure, $f$ defines the void volume fraction, and $\sigma_y$ is the material yield stress. The constants $q_1$, $q_2$, and $q_3$ depend on the material and analysis conditions. For instance, $q_1 = 1.5$, $q_2 = 1.0$, and $q_3 = 2.25$ may represent materials subjected to plain strain condition. For $q_1 = q_2 = q_3 = 1.0$, the yield function has the same form as the original Gurson's model. If $f = 0$, (15) becomes identical to von Mises yield criterion. From the experimental results, it was shown that increasing the thickness of the substrate decreased the fatigue threshold and increased the crack growth power parameter. It was also found that the crack growth power parameter for the Al joints was less than that for the CFRP composite joints.

*4.2. Fatigue Crack Growth Rate.* Many studies have been devoted to the effect of mode mixity and the contribution of mode II in the crack growth process. Undoubtedly mixed mode loading has a significant effect on the crack propagation rate. Baek et al. [93] investigated the fatigue characteristics of a composite/metal interface using single leg bending (SLB) specimens (Figure 16) under different mode mixities loading condition. From the results, it was concluded that the crack propagation rate increased with increasing the contribution of mode II loading.

Giannis and Martin [94] studied the debonding of Glare skin-stringer configurations for aerospace applications. Crack growth rate has been experimentally determined as a function of the maximum cyclic strain energy release rate and was used in conjunction with FEA to predict the fatigue lifetime. They studied pure mode I, pure mode II, and mixed mode I/II using DCB test specimen applying different loading conditions. Azari et al. [95] studied the fatigue crack growth behaviour of adhesive joints under mode I and mixed mode loading conditions. They found that increasing mode II loading rate had insignificant effect on the fatigue threshold strain energy release rate and the crack growth rate at low phase angles, but significant effect at higher phase angles. Ashcroft et al. [96] proposed a mechanistically based model for predicting anomalous behaviour for fatigue crack growth in mixed mode fracture. Pirondi and Moroni [97] applied a fracture mechanics-based model in order to predict fatigue failure of adhesive joints. Diab et al. [98] presented an analytical solution for the evolution and distribution of shear stresses along the bond length of FRP/concrete interfaces due to mode II fatigue loading. Marannano et al. [99] investigated the propagation of an interface crack in Al adhesively bonded joints subjected to mixed mode I/II. Using beam theory, they have presented an analytical expression for computing the strain energy release rate for the mixed

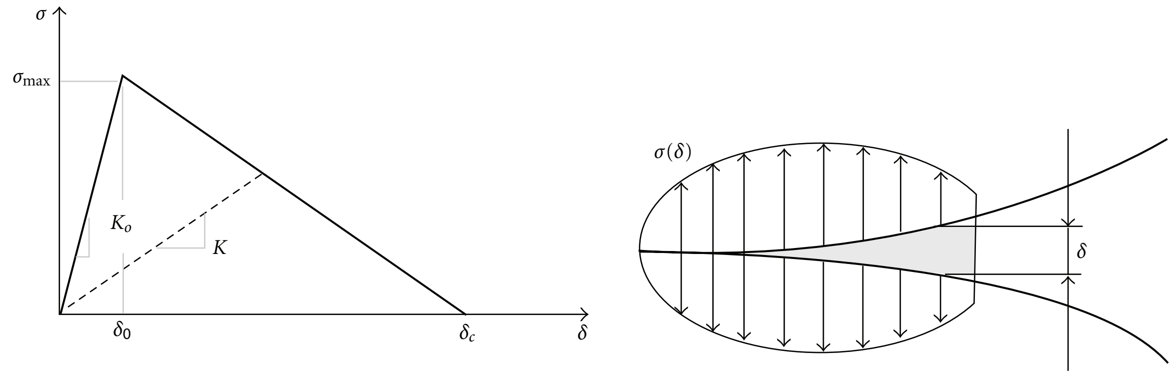



Figure 14: Mode I CZM, adopted from [89].

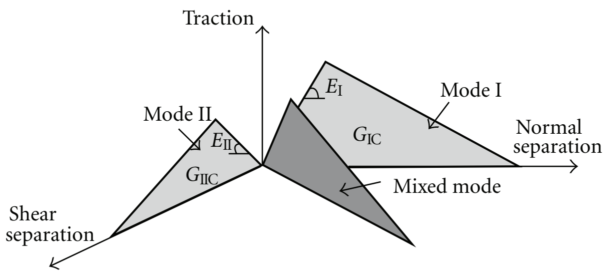



Figure 15: Mixed mode CZM, adopted from [76].

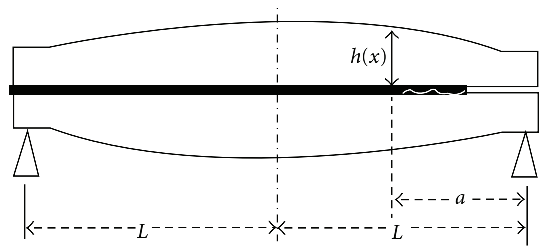



Figure 17: TENF specimen, adopted from [103].

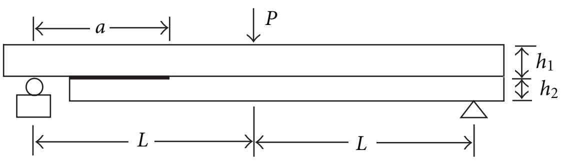



Figure 16: SLB joint.

mode end loaded split (MMELS) test specimen, which is similar to the mixed mode DCB joint (Figure 8). Pirondi and Nicoletto [100] carried out fatigue crack growth tests on adhesively bonded compact tension/shear specimens to assess the behaviour of a structural adhesive under mixed mode I/II conditions. From fractographic analysis, it was observed that energy dissipation mechanisms due to inelastic phenomena-like bulk plastic deformation and crazing were more pronounced in mode I than in mixed mode I/II. Cheuk et al. [101] presented an analytical model for crack propagation in cracked adhesively bonded DLJs subjected to fatigue loading. Xu et al. [102] carried out mixed mode fatigue and quasistatic tests on joints bonded with either a filled or a filled and toughened adhesive. They found that both modes I and II strain energy release rate components contributed to the fatigue and fracture processes as they determined the local stress distributions around the crack tip. They further concluded that in the mixed mode joints subject to fatigue load, the range of mode I strain energy release rate became a controlling factor in determining the fatigue crack growth rates as the ratio between mode I and mode II increased. Edde and Verreman [103] proposed a tapered end-notched flexure (TENF) specimen (Figure 17) in order to study mode II fracture and fatigue of adhesively bonded joints. A linear compliance change with crack propagation was produced resulting in a constant mode II strain energy release rate under linear elastic fracture mechanics conditions. Moutrille et al. [104] studied stress relief and mode II crack propagation in the adhesive during fatigue tests of Al structures bonded with composite patches. Thermoelasticity was used to study the relief in the Al substrate during cyclic loading, that is, stress distribution, global relief, and progressive load transfer zone.

The effect of precrack and fillet on fatigue crack propagation has been studied by a few researchers. Azari et al. [105] studied the fatigue threshold and slow crack growth rate behaviour of a highly toughened epoxy adhesive. They considered different starting conditions, such as fatigue precrack and fillet, testing approaches, and interfacial bond strengths. They found that for cohesive failure the fatigue threshold was very similar when starting from a precracked or uncracked fillet specimen. While for interfacial failure the threshold was lower when cracks grew from a precracked specimen. Kayupov and Dzenis [106] performed a nonlinear FEA to study stress fields in adhesively bonded composite SLJs containing cracks of different lengths. By applying load corresponding to the load amplitude during fatigue tests, they showed that the critical values of the strain energy release rates for fast crack propagation in the final stage of fatigue life were two to three times lower than the critical strain energies for cracks propagating under quasistatic loading.

In order to monitor crack growth rate, different measurement techniques have been proposed, namely, chirped fibre Bragg grating, optical, ultrasonic, and X-radiographs. Guo et al. [107] embedded chirped fibre Bragg grating sensors within the adhesive bond line of CFRP SLJs in order to study the effect of disbond propagation due to fatigue loading on the reflected spectra from the sensors. They found that a peak in the reflected spectra could be seen as the disbond propagated. Cheuk et al. [108] presented experimental and numerical investigations of the fatigue crack initiation and growth mechanism in metal/composite DLJs. They conducted fatigue tests under tension dominated loading and measured crack lengths using optical technique. They concluded that fatigue failure of metal/composite DLJs was mainly driven by tensile mode loading due to the peel stress. Brussat and Chiu [109] presented adhesive bond-line crack growth data from fatigue tests of structural bonded SLJs with initial bond-line flaws. They monitored crack growth using ultrasonic and a compliance techniques. Casas-Rodriguez et al. [110] presented experimental methods for analysing delamination zones at various stages of their evolution in bonded composite joints. They digitalized X-radiographs of delamination zones and performed scaling analyses using fractal and multifractal approaches in order to quantify the morphology and damage distribution in the immediate vicinity of delamination fronts. Ashcroft et al. [111] investigated a number of methods for studying damage and crack propagation in bonded composite lap joints subjected to fatigue loading. They have demonstrated that dye penetrant enhanced X-radiography was capable of distinguishing between cracked, micro-damaged, and undamaged areas of the joints. Moreover it was clearly seen that large damage zones could form ahead of the crack tip. Du et al. [112] developed a new experimental technique for determining fatigue crack growth of the polymer/metal interface in an adhesive system under cyclic loading using piezoelectric actuation. They observed that under alternating electric fields, fatigue crack grew along epoxy/Al interface.

The effect of substrate and bon-line thickness has been investigated by a couple of authors. Ishii et al. [113] conducted fatigue tests on adhesively bonded CFRP/Al DCB specimens to investigate the effect of substrate thickness on the fatigue crack growth rate. They found that the increase in the Al plate thickness lowered the fatigue threshold and steepened the slope in the steady state crack growth region. Abou-Hamda et al. [114] experimentally measured fatigue crack growth rates for DCB adhesive joint containing a cohesive crack. They measure debond growth rates using a compliance method for three different bond-line thicknesses. They found that the larger the bond-line thicknesses, the larger the fatigue crack growth resistanceis.

Depending on adhesive type, loading frequency may have effect on fatigue crack growth in bonded joints. Pirondi and Nicoletto [115] carried out fatigue crack growth tests on DCB bonded specimens under two different loading frequencies and two different loading ratios in order to characterize an adhesive system for structural applications. Xu et al. [116] conducted mode I fatigue crack growth tests on joints bonded with two different adhesive systems and at different loading frequencies. They found that the fatigue crack growth rate in the joints bonded with one adhesive system was relatively independent of frequency while it increased with decreasing frequency for the joints bonded with another adhesive system. Aglan and Abdo [117] presented a technique to characterize the resistance of adhesively bonded joints to fatigue disbond propagation. They used the modified crack layer model to extract parameters characteristic of the adhesive joint resistance to fatigue disbond propagation. These parameters are the specific energy of damage and the dissipative characteristic of the joints. Xu et al. [118, 119] conducted mode I fatigue crack growth tests on DCB joints bonded with two commercial adhesives and studied the effect of loading frequency on the crack growth rate.

Further studies on fatigue crack propagation in composite bonded joints were performed by Zhang et al. [120] using DLJ and stepped lap joint and by Kinloch and Osiyemi [121] using DCB specimen.

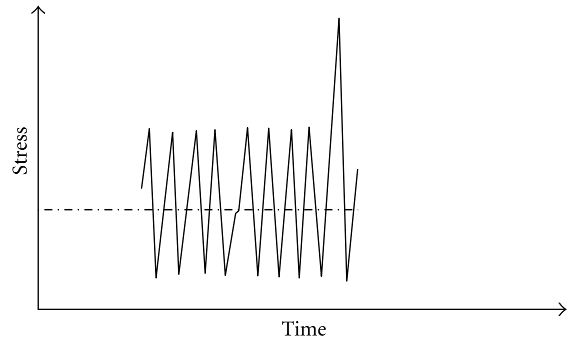



Figure 18: Typical VAF spectrum.

## 5. Variable Fatigue Amplitude

This topic has received significant attention in the literature. The research into variable fatigue amplitude in adhesively bonded joints could be considered as new since the first WoS article was published in 2003. The classical way of analysing fatigue in adhesive joints is to consider constant amplitude loading. However, in real applications variable amplitude fatigue (VAF) takes place and may induce damage acceleration effects in the joints. A typical VAF spectrum consists of a number of constant amplitude cycles followed by an overload as shown in Figure 18. For ductile materials, crack growth retardation after overloads is expected due to the formation of plastic zone ahead of the crack tip. It follows that for brittle materials, crack growth acceleration after overloads is expected.

A cohesive zone model with a bilinear traction separation law has been used by Khoramishad et al. [122] to predict the fatigue response of adhesively bonded joints under VAF loading. They used a damage model that incorporated fatigue load ratio effects to simulate the detrimental influence of VAF loading.

The effect of loading frequency on VAF in adhesively bonded joints has been studied by a couple of authors. Eskandarian and Jennings [123] developed an experimental technique to test DCB under VAF loads. They have investigated the effects of test frequency and applied load history within a range of 4 to 20 Hz for a nominal adhesive thickness of 0.5 mm. They found that the fatigue damage occurred at about 35% of the monotonic fracture load and that the power law constants were influenced by test frequency, but not sensitive to loading order. Al-Ghamdi et al. [124] investigated the effect of frequency on fatigue crack propagation in adhesively bonded CFRP composite and metallic joints. They tested DCB samples in fatigue at different frequencies. They found that the crack growth per cycle increased and the fatigue threshold decreased as the test frequency decreased.

Palmgren-Miner rule has been proposed by a few authors to characterize damage in VAF regime. Shenoy et al. [125] investigated the behaviour of adhesively bonded SLJs subjected to different types of VAF loading and used Palmgren-Miner's damage sum, in which the damage variable of a block is given by

$$D_{\mathrm{PM}} = \sum_{i=1}^{n_b} \frac{n}{N_f}, \qquad (16)$$

where $n$ is the applied number of cycles, $N_f$ is the number of cycles to failure, and $n_b$ is the number of blocks. They found that a small proportion of fatigue cycles at higher fatigue loads could result in a significant reduction in fatigue life. Shenoy et al. [126] presented a study on VAF of adhesively bonded joints. From constant amplitude and VAF fatigue tests, they found that the addition of a small number of overloads to a fatigue spectrum could greatly reduce the fatigue life. They concluded that linear damage accumulation, such as the Palmgren-Miner rule, was appropriate for VAF analysis and tended to over predict fatigue lifetime.

A few studies have concentrated on failure modes in adhesively bonded joints under VAF loading. Nolting et al. [127] investigated the effect of VAF loading on the fatigue life and failure mode of adhesively bonded DSJ (see Figure 11) made from clad and bare 2024-T3 Al. The failure mode was shifted from adhesive or substrate failure at high and low stress levels, respectively, under constant amplitude loading to adhesive failure in the presence of overload cycles for the clad specimens. While bare Al specimens failed only in the adhesive layer. Ashcroft [128] studied and characterised the influence of VAF on the evolution of damage. Erpolat et al. [129] investigated cohesive and interlaminar crack growth in bonded composite joints under constant fatigue and VAF loading using DCB joints. They used numerical crack growth integration to predict the VAF lifetime using constant amplitude data, which underestimated the fatigue crack growth rate for both interlaminar and cohesive cracks.

## 6. Impact Fatigue

This topic has not received enough attention in the literature. Although research into impact fatigue in adhesively bonded joints has been started in 1983, only 13 WoS publications could be found.

Impact fatigue (IF) is defined as cyclic low velocity impacts or repetitive low energy impacts. IF accelerates fatigue crack growth in bonded joints depending on many parameters. Ashcroft et al. [130] proposed a model to predict crack growth in bonded joints subjected to combined standard and impact fatigue. They found that the rate of crack growth in IF was greater than that in standard fatigue (SF) for a given strain energy release rate and that the fatigue crack growth rate in SF increased after a block of IF. Ashcroft et al. [131] presented a study on the behaviour of the toughened epoxy adhesive FM73 under IF. They performed Izod IF tests on FM73 specimens in order to study and characterise the evolution of damage. Tsigkourakos et al. [132] investigated the behaviour of adhesive joints subjected to SF, IF, and a combination of them. They have further analysed the damage evolution in both SF and IF regimes in terms of the deterioration of residual strength of joints after certain loading histories. Silberschmidt et al. [133] presented studies of the effect of IF on reliability and crack growth in adhesively bonded joints. They compared the results of IF with SF in order to assess the severity of IF regime. Casas-Rodriguez et al. [134–137] investigated the behaviour of adhesively bonded CFRP and Al joints subjected to IF and compared them with specimens tested in SF. They found that the accumulated energy associated with damage in IF is significantly lower than that associated with a similar damage in SF. Furthermore, they found that the mechanisms of failure were very different for the two loading regimes. They proposed different parameters in order to characterise damage in IF and SF, for example, crack velocity, accumulated absorbed energy, and normalised maximum force. Ashcroft et al. [138] studied mixed mode crack growth in epoxy bonded CFRP joints in SF and IF regimes. They showed that the back-face strain technique could be used to monitor cracking in LSJs and piezo strain gauges could be used to measure the strain response. Silberschmidt et al. [139] studied IF in adhesive joints using two types of typical substrates, namely, an Al alloy and a CFRP composite.

The effect of overlap length on fatigue strength of an SLJ bonded with an epoxy-polyamide adhesive under IF and non-IF conditions has been investigated by Imanaka et al. [140]. They concluded that the longer the overlap lengthis, the lower the non-IF strengthis. They observed that IF strength showed more rapid lowering trend with increasing number of stress cycles than the non-IF strength. They have further conducted a series of IF tests on butt joint specimens bonded with epoxy-polyamide adhesive [141]. They concluded that the IF strength was higher than the ordinary fatigue strength in a relatively low stress cycles range but it decreased rapidly at a certain transitional number of stress cycles.

In order to test a filament wound carbon fibre tube with bonded steel end fittings, Barber and Radford [142] designed an IF testing machine, in which the generated impact pulses closely resembled to those of a conventional drop weight impact test machine. The machine was also capable of completing high cycle IF tests ($10^6$ impacts) within a relatively short period of time by operating in excess of 10 impacts per second.

## 7. Thermal Fatigue

This topic has also not received enough attention in the literature. Similar to impact fatigue, thermal fatigue in adhesively bonded joints has not attracted many researchers. Although the first WoS publication on thermal fatigue was in 1995; only 3 articles have been found.

Gao et al. [143] conducted experimental and theoretical studies to determine the fatigue lifetime of anisotropic conductive adhesive film under different testing conditions including hygrothermal aging and thermal cycling. They found that the fatigue lifetime decreased when increasing hygrothermal aging time. When increasing the number of thermal cycles, after an initial increase, the fatigue lifetime decreased. Chan et al. [144] investigated the effectiveness of using edge bond adhesive for the enhancement of solder joint thermal fatigue reliability. They used accelerated temperature cycling test and simulation. They concluded that in order to enhance the thermal fatigue reliability of solder joints, edge bond with large elastic modulus and coefficient of thermal expansion close to that of the solder joints should be used. Yu et al. [145] developed an FEA of nonsteady thermal stress analysis in order to analyze metal/FRP bonded joints. They have studied the thermal fatigue strength of Al/CFRP bonded joints through a series of thermal fatigue tests. They found that the thermal fatigue strength of the joints could be described by the maximum equivalent stress at the adhesive layer, which can be calculated from FEA.

## 8. Fatigue Durability

This topic has been extensively investigated in the literature. Fatigue durability of adhesively bonded joints has gained lots of attention in the literature, which can be seen from the considerable amount of WoS publications. This is because an adhesive joint loses its strength and fatigue resistance when exposed to hostile environmental conditions, that is, high humidity and/or high temperature. Since hostile environmental conditions degrade the interface between adhesive and substrate, the surface treatment of the substrate prior to bonding plays an important role in enhancing the durability of bonded joints. The literature review carried out in this section is divided into three main parts, namely, the effect of humidity, effect of temperature, and the role of surface treatment.

*8.1. Effect of Humidity.* The effect of humidity on the fatigue strength of adhesively bonded joints has attracted many researchers. Joints are exposed to moisture through aging in humidity chamber or in distilled water and then tested under fatigue loading regime. Datla et al. [146] studied the effects of test humidity and temperature on the fatigue threshold and crack growth behaviour of P2-etched and commercial coil-coated Al adhesive joints under mixed mode loading condition. They used Al ADCB specimens and found that in dry conditions, increasing the temperature up to 80°C had no significant effect on the fatigue threshold, but it caused an increase in the crack growth rates. At test temperature of 40°C, for high crack growth rates the fatigue behaviour was insensitive to moisture, while for low crack growth rates close to the threshold it became more sensitive. It was also concluded that at higher crack growth rates the fatigue performance was degraded due to only the effect of temperature, while at low crack growth rates it was degraded due to the effect of moisture. Gomatam and Sancaktar [147, 148] studied the effect of elevated humidity on the fatigue behaviour of electronically conductive adhesives. They tested stainless-steel joints under monotonic and fatigue loading conditions, at two humidity levels, namely, 20% RH and 90% RH at 28°C. They found that the modes of failure were interfacial and joint conductivity was significantly decreased. Kinloch et al. [149] investigated the fatigue behaviour of an aerospace grade epoxy Al alloy adhesive joints. They conducted the test in a dry environment (23 ± 1°C and 55% RH) and a wet environment of immersion in distilled water at 28 ± 1°C. They have further investigated the effect of using various surface pretreatments for the Al alloy substrates. Abdo and Aglan [150] investigated the effect of thermal aging on the static and fatigue behaviour of adhesively bonded aircraft joints. They aged Al SLJs at high and low cyclic temperatures at different levels of humidity. They found that the greatest loss of fatigue resistance was encountered after the first two thermal aging cycles and that the fatigue crack propagation data showed a considerable loss in resistance due to aging. Valentin et al. [151] performed a multifaceted study to investigate the durability of a boron-epoxy doubler (patch) adhesively bonded to an Al substrate. They tested DCB specimens in order to determine the fracture toughness and fatigue characteristics of the adhesive bond line. Kinloch and co-workers [152–154] used a fracture mechanics approach to examine the fatigue behaviour of adhesively bonded joints, which consisted of Al alloy or electrogalvanised steel substrates bonded using toughened epoxy structural paste adhesives. They conducted the fatigue tests in a relatively dry environment (23°C and 55% RH) and in a wet environment (immersion in distilled water at 28°C). They further considered the mechanisms of failure due to environmental attack. They found that for electrogalvanised steel joints the failure path is associated with corrosion in a wet environment. Fernando et al. [155] used a fracture mechanics approach to investigate the fatigue behaviour of Al alloy adhesively bonded joints. They conducted the fatigue tests in a relatively dry environment (23°C and 55% RH), which caused crack propagation at lower rates of maximum strain energy release rate compared to the fracture toughness. In a wet environment (immersion in distilled water at 26°C), a dramatic effect on the fatigue performance of the adhesive joints was observed. Lachmann [156] conducted fatigue tests on steel and Al alloys SLJs in unaged and aged conditions in order to estimate their long term behaviour. So et al. [157]

tested Polymethyl methacrylate/epoxy (PMMA/epoxy) and Al/epoxy joints immersed in distilled water and in saline water at different temperatures and subjected to different sinusoidal tensile loads. They found that PMMA joints had better fatigue performance both in distilled water and sodium chloride solution than in air, whereas Al joints had better fatigue performance in air.

Zhang et al. [158] studied the fatigue response of adhesively bonded pultruded GFRP DLJ under different environmental conditions. They found that the dominant mode of failure was a fibre tear in the GFRP laminates. The mode of failure was shifted from cohesive to interfacial (adhesive/composite interface) in the presence of high humidity. The fatigue lifetime and fracture behaviour of the joints was affected by test temperature and was aggravated by humidity. Neser and Altunsaray [159] experimentally studied the combined effects of material direction, thickness, and seawater environment on the fatigue behaviour of adhesively bonded and bolted joints used in GRP boat building. Tests were carried out under atmospheric and marine conditions, for which seawater environment ageing has been realized using 3.5% of NaCl solution. In general, they found that the fatigue performance obtained by testing the material in synthetic seawater was much lower than those obtained from testing under atmospheric conditions. Ashcroft et al. [160] investigated the effects of environment and fatigue loading on the performance of bonded composite joints. They found that adhesively bonded composite joints can be significantly affected by the service environment depending on the joint type and materials used. Reis et al. [161] studied the fatigue of polypropylene/glass fibre composites adhesive lap joints and investigated the effect of water in the fatigue behaviour. They immersed the specimens in water of different temperatures during periods of one day to 90 days.

Charalambides et al. [162] investigated the performance of carbon fibre/epoxy repair joints bonded using an epoxy film adhesive under static and fatigue loading. They immersed the repair joints in distilled water at 50°C for periods of up to 16 months and evaluated the effect of the hot/wet environment on the static and fatigue strengths. They found that the fatigue behaviour of the repair joints was significantly inferior to that of the parent material. Butkus et al. [163] applied fracture mechanics to assess bonded joint durability including resistance to fatigue and to environmental exposure. Crasto and Kim [164] evaluated the durability of a composite joint under a simulated outdoor environmental exposure using a DLJ subjected to various combinations of moisture, thermal cycling, and fatigue. Gilmore and Shaw [165] studied the effect of temperature and humidity on the fatigue behaviour of composite bonded joints. Okuda et al. [166] investigated the tensile fatigue behaviour of an adhesive bonded joint of a fibre reinforced plastic FRP under low cycle repeated stress and the effect of water environment on fatigue strength. Miyairi et al. [167] carried out fatigue tests under constant stress amplitude with tension-shear loads and examined the fatigue strength and the stress-strain hysteresis loops for GFRP adhesive joints. They found that damage in adhesive joints was not detected for 3000 hours in the static and the fatigue tests; however, with exposure time over 3000 hours, the static and fatigue strengths suddenly decreased.

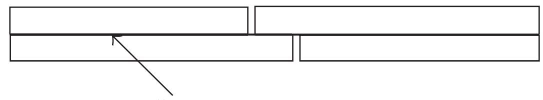



Figure 19: TAST specimen.

Many studies have been devoted to the prediction and design of fatigue of adhesively bonded joints exposed to moisture. Curley et al. [168] used a fracture mechanics approach to predict the fatigue performance of the adhesively bonded SLJ and adhesively bonded top-hat box-beam joint. They tested the joints under fatigue loading in dry and wet environments. Johnson and Butkus [169] presented a design approach that uses fracture mechanics and accounts for environmental effects. From the results, they found that mode I fracture toughness and fatigue crack growth threshold were significantly reduced upon exposure to a high temperature, high humidity aircraft service environment. Ashcroft et al. [170] presented a method to predict failure in bonded composite joints subjected to combined mechanical loading and environmental degradation based on a coupled mechanical-diffusion FEA. The method was evaluated by predicting the fatigue thresholds of epoxy-CFRP LSJs preconditioned and tested in dry and wet environments. Abdel Wahab et al. [171] analyzed the diffusion of moisture in adhesively bonded composite joints using experimental, analytical, and numerical techniques. They used fatigue test data for LSJs aged and tested in different environments to establish a relationship between fatigue threshold and water concentration at the position of failure initiation. Wahab et al. [172] analysed the fatigue strength of aged adhesively bonded composites joints using stress analysis and fracture mechanics. They performed nonlinear stress and fracture analyses in order to predict the strength of the joints in different hostile environmental conditions. They found that criterion based on the principal stress provided good threshold prediction for small plastic deformation.

*8.2. Effect of Temperature.* The effect of temperature on the fatigue performance of bonded joints has been studied by many authors. Banea and da Silva [173, 174] studied the mechanical properties of room temperature vulcanising silicone adhesives for aerospace applications. They used the standard Thick Substrate Shear Test (TAST), Figure 19, in order to measure the shear properties of the adhesives and to assess the adhesive performance in a joint. They investigated the influence of temperature on the joint strength and found that the shear strength decreased when increasing the temperature.

Hattori [175] developed evaluation methods for the fatigue strength and fatigue lifetime of FRP/metal adhesive joints under low temperatures. He used two stress singularity parameters to determine the fatigue strength and delamination propagation rates. He measured the delamination propagation rates of DLJs under fatigue loadings at room temperature. Hwang and Lee [176] experimentally studied the effect of temperature on the static and fatigue characteristics of adhesively bonded tubular SLJs. Liechti et al. [177] investigated the fatigue crack growth characteristics of adhesively bonded joints at several temperatures in air and in salt water. They used modified cracked LSJs under four-point bending loading conditions. They found that in air both high and low temperatures increased crack growth rates and reduced thresholds relative to room temperature. Ashcroft and Shaw [178] investigated the effect of temperature on fatigue crack propagation in bonded joints and compared the results to quasistatic loading and fatigue failure in uncracked lap joints. They conducted the fatigue tests on epoxy bonded CFRP joints at −50°C, 22°C, and 90°C. They pointed out that temperature had a significant effect on the locus of failure. Ashcroft et al. [179, 180] studied the effects of fatigue loading, test environment, and preconditioning on bonded composite joints. They tested CFRP/epoxy DLJs and LSJs in quasistatic and fatigue across the temperature range experienced by a jet aircraft. They found that as temperature increased the fatigue resistance decreased. They pointed out that at high temperatures strength is controlled by creep, which is determined by the minimum stresses in the joint. They showed that the fatigue resistance of LSJs did not vary significantly until the glass transition temperature was approached. They also noted that absorbed moisture resulted in a significant reduction in the glass transition temperature of the adhesive. They observed that the locus of failure of the joints was highly temperature dependent, that is, failure in the composite substrate at low temperatures and failure in the adhesive at elevated temperatures. Aglan et al. [181] evaluated the durability of composite repairs of aircraft skin grade Al with simulated flaws using mechanical fatigue and thermal cyclic aging. They found that thermal cyclic aging reduced the fatigue lifetime of the repaired structures due to the deterioration of the interface. Harris and Fay [182] tested SLJs to determine the fatigue behaviour of two automotive adhesive systems. From the experimental results over a wide range of temperatures, they found that fatigue life was dominated by a crack initiation phase associated with the buildup of creep deformation in the adhesive layer. They further found that thinner adhesive layers resulted in stronger and more fatigue resistant joints. They concluded that for load bearing applications the adhesive glass transmission temperature should be above the maximum temperature expected in service.

*8.3. The Role of Surface Treatment.* Surface treatment plays a vital role in the fatigue behaviour of bonded joints and its effect has been studied by many researchers. Improving surface preparation will enhance the mechanical joint performance in general and the fatigue performance in particular. Underhill et al. [183] investigated the effect of warm water treatment on the fatigue life of 2024 T3 Al alloy adhesively bonded joints. They concluded that the fatigue life depended on the surface preparation of the bonds and the specimens in wet conditions led to a slightly shorter life than under dry conditions. They showed that warm water treatment of Al leaded to an improvement in fatigue lifetime and properties. Abel et al. [184] studied the durability of organosilane pretreated joints, which were adhesively bonded using a hot cured epoxy film adhesive. They investigated the use of gamma-glycidoxypropyltrimethoxysilane as silane primer. The fatigue tests were conducted in a dry environment with a relative humidity of 55 ± 5% and a wet environment by fully immersing the joints in distilled water at 28°C ± 2°C. They found that the use of the gamma-glycidoxypropyltrimethoxysilane pretreatment has enhanced the joint durability, compared with a simple grit-blast and degrease treatment and provided comparable results to the use a chromic-acid etch as a pretreatment. Underhill and Duquesnay [185] investigated the effect of surface preparation using a silane pretreatment on the fatigue life of epoxy bonded SLJs under dry and wet conditions. They found that even in dry condition, the fatigue life of unsilaned joints was reduced by about an order of magnitude from silaned joints. Rushforth et al. [186] tested adhesively bonded Al SLJs under fatigue loading in order to determine the effects of a silicon-based surface pretreatment on joints durability. Tests were performed in a chamber that generated 96% RH. They found that the fatigue performance of pretreated and untreated joints was similar when tested in air, but the performance of the untreated joints was greatly reduced when tested in 96% RH. They also found that pretreated joints failed cohesively in the adhesive layer, while untreated joints failed interfacially at the adhesive/Al interface. Hadavinia et al. [187, 188] investigated the performance of adhesively bonded joints under monotonic and fatigue loading using experimental and analytical FEA. They used Al alloy substrates bonded with an epoxy film adhesive and tested in a dry environment (55% RH at 23°C) and a wet environment by immersing the joints in distilled water at 28°C. They further studied the influence of employing different surface pretreatments for the Al alloy substrates. Mays and Vardy [189] carried out an experimental programme to study the fatigue performance of steel and Al SLJs. They studied the effect of surface preparation techniques, curing temperatures up to 80°C, accelerated temperature cycling, and prolonged immersion in water.

## 9. Torsional Fatigue

This topic has not received enough attention in the literature. Research in torsional fatigue in adhesively bonded joints is dated back to 1995, but it has not attracted many researchers as only 5 WoS articles have been published. This kind of loading is important when joining tubes using adhesive bonding; however, it takes place in a few specific applications.

Portillo et al. [190] studied the fatigue behaviour of adhesively joined Al tubular connections subjected to torsional cyclic loading. Tomioka and Kakiage [191] performed torsional fatigue tests of the adhesively bonded box section beams in order to investigate the applicability of the structural adhesive to the automobile body. Kwon and

Lee [192] investigated the effect of surface roughness on the fatigue life of adhesively bonded tubular SLJs using a fatigue torsion test. They found that the optimum surface roughness of the substrates for the fatigue strength of tubular SLJs depended on the bond-line thickness and applied load. Nayeb-Hashemi et al. [193] analyzed the shear stress distribution in the tubular joints under axial and torsional loadings. They found that under axial load for tubes with equal cross-sectional area, the shear stress distribution along the bonded area was almost symmetric. They showed that the shear stress in the bonded area depends on the polar moments of inertia of the tubes. Prakash et al. [194] presented a torsional fatigue test for adhesively bonded butt joints. They used an apparatus for the test, which is a modification the standard fixture outlined in the ASTM E 229 test for determining the shear strength of adhesive joints subjected to torsion.

## 10. Fatigue in Hybrid Adhesive Joints

In the last several years, hybrid joints, which combine a traditional mechanical joint and a layer of adhesive, are gradually attracting the attention of many industrial sectors such as automotive and transportation. This is due to their better performance compared to just mechanical joints or just bonded joints. The literature review presented in this section on fatigue in hybrid adhesive joints is divided into three parts, namely, bolted/bonded, welded/bonded, and other hybrid types.

*10.1. Bolted/Bonded.* Adding adhesive bonding to bolted joints improves their fatigue strength and prolongs their lifetime. However, the benefit of adding bolts to an adhesively bonded joint is not evident. Hurme et al. [195] experimentally and analytically studied hybrid joints that combine mechanical fastening and adhesive bonding to determine the static and cyclic mode II shear strength of epoxy bonded steel interfaces subjected to static mode I prestress. They observed a shear stress amplitude threshold equal to about 50% of the fracture shear stress. Hoang-Ngoc and Paroissien [196] studied adhesively bonded and bolted/bonded SLJs using FEA. Two-dimensional and three-dimensional analyses have been carried out taking into account geometrical and material nonlinearities. Adhesives were modelled a hyperelastic material using Mooney-Rivlin model. From their numerical analyses, they concluded that hybrid bolted/bonded joints have a longer fatigue life than bolted joints. Kelly [197] investigated the strength and fatigue life of hybrid bonded/bolted joints with CFRP substrates. They experimentally determined the effect of adhesive material properties and laminate stacking sequence on the joint structural performance and modes of failure. They found that hybrid joints had greater strength, stiffness, and fatigue life when compared to adhesively bonded joints for adhesives with lower elastic modulus. However, hybrid joints for adhesives with high elastic modulus showed no significant improvement in strength, but an increase in fatigue life.

*10.2. Welded/Bonded.* Combining welding and bonding to enhance fatigue of welded joints has attracted many researchers. However, adding welds to an adhesively bonded joint is not beneficial. Sam and Shome [198] examined the tensile shear and fatigue behaviour of SLJs of dual phase steel sheets prepared by adhesive bonding, spot welding, and weld-bonding processes. It was concluded that the endurance limit of welded/bonded joint was much higher than that of spot welded joint but smaller than that of adhesively bonded joints. Gonçalves and Martins [199] evaluated the influence of adhesives and applied load characteristics on the static and fatigue performance of welded/bonded structural metal joints. Ghosh and co-workers [200, 201] studied the fatigue behaviour of steel SLJs joined by adhesive bonding, conventional spot welding, and weld-bonding processes. They found that the welded/bonded joints prepared at optimum process parameters had superior mechanical properties than those of the conventional spot welds, especially under fatigue loading conditions. Chang et al. [202] investigated the construction and hardness distribution of welded/bonded lap joints using a computational model. They carried out fatigue tests on welded/bonded, spot welded and adhesively bonded joints to study their fatigue behaviour and fracture characteristics. They found that the application of adhesives in spot welding greatly improved the joint fatigue performance, while the presence of weld spots in an adhesive joint had a negative effect on the joint fatigue performance. Ring-Groth et al. [203] investigated the fatigue life of a welded/bonded stainless-steel epoxy adhesive joint. The results revealed that the welded/bonded specimens had better fatigue properties than spot welded specimens. Hejcman et al. [204] studied the monotonic fracture and fatigue behaviour of a wide range of joining methods for Al alloys including spot welding, metal inert gas welding, laser welding, and adhesive bonding for 6000 series (Al-Mg-Si) Al alloys tested at room temperature. Wang et al. [205] investigated the fatigue behaviour of welded/bonded Al joints. From the results, they found that the welded/bonded joints had a slightly lower fatigue resistance than the Al adhesively bonded joints, but a much higher fatigue resistance than Al and steel spot welds. Gilchrist and Smith [206–208] used two-dimensional and three-dimensional FEA to predict the stresses within adhesively bonded and welded/bonded T-peel joints. They predicted the likely region of fatigue crack initiation using the knowledge of the critical tensile stresses. Wentz and Wolfe [209] developed predictive methods to determine the sonic fatigue life of various welded/bonded and adhesively bonded aircraft structures, when exposed to high intensity acoustic excitation.

Effect of corrosion and durability on fatigue performance of welded/bonded joints has been studied by a few researchers. Somervuori et al. [210] investigated the corrosion fatigue and fatigue properties of welded/bonded and spot welded austenitic stainless steels. They simulated corrosion using corrosive environment of 3.5% NaCl solution at +50°C. They found that the fatigue strengths of the welded/bonded single spot SLJs were significantly higher than those of the spot welded specimens, while in the corrosive environment the difference was reduced.

Furthermore, they pointed out that the failure mode of the welded/bonded specimens was adhesive in the corrosive environment and cohesive in air. Wang et al. [211] have further performed experiments to joints subjected to 100% RH at 38°C. They found that the presence of water vapour at elevated temperature decreased the fatigue strength of welded/bonded joints by about 33% at $5 \times 10^6$ cycles.

*10.3. Other Hybrid Types.* Similar to bolted/bonded and welded/bonded, combining rivets and adhesives would enhance the fatigue behaviour of riveted joints. di Franco et al. [212] investigated the fatigue behaviour of an SLJ self-piercing riveted and bonded using experimental fatigue tests. They used two rivets placed longitudinally and an epoxy resin adhesive. Moroni et al. [213] evaluated the benefits of using hybrid welded/bonded, riveted/bonded, or clinch-bonded joints in comparison with simple adhesive, spot welded, riveted, or clinched joints. Kwakernaak and Hofsiede [214] showed that combining mechanical fastening and a structural adhesive improved the fatigue strength of the riveted joint. They have further shown that by adding high strength fibres to the adhesive the fatigue and damage tolerance properties would be significantly improved. Imanaka et al. [215] investigated the fatigue behaviour of riveted/bonded SLJs with different lap widths and adhesive and rivet strengths. They pointed out that fatigue cracks propagated more gradually in combined joints than in adhesive joints after crack initiation.

Combining adhesive with press-fitted or drive-fitted joints improves their fatigue performance. A few researchers have investigated the effect of this combination. Croccolo et al. [216] performed experimental fatigue tests on steel/Al components mixed hybrid joints, press-fitted and adhesively bonded using anaerobically cured single component adhesive. They concluded that the use of the adhesive increased the press-fitted joint performances, with respect to its release force. Croccolo et al. [217] studied the static and fatigue performance of hybrid joints, namely, press-fitted connections supplemented with anaerobic adhesive. They demonstrated that the addition of the adhesive always improves the performance of the joint. Croccolo et al. [218] evaluated the anaerobic adhesive residual strength in drive-fit and adhesively bonded cylindrical joints under fatigue loading. They tested shaft hub cylindrical joints made of different materials. The hubs were always made of steel alloy whereas the shafts were made either of steel alloy or of Al alloy. Dragoni [219] compared the static and fatigue strength of axially loaded taper press fits, either dry or bonded, with an anaerobic adhesive. They observed a general increase of both static and fatigue strength with the contact pressure.

## 11. Nanoadhesives

The use of nanoadhesive to enhance fatigue performance of bonded joints is a quite new topic as the first WoS publication is dated to 2009 and 4 articles have been found.

Liu and Ho Bae [220] proposed a new nanoadhesive in order to improve the conventional automobile epoxy resin. They have used a mixer to mix multiwalled carbon nanotubes (1% to 3% by weight) with epoxy resin. Both the static tensile strength and fatigue strength have dramatically increased at a carbon nanotube weight of 2%. Dorigato and Pegoretti [221] dispersed different percentages of both untreated and calcined fumed alumina nanoparticles into an epoxy adhesive. They found that fatigue lifetime of Al SLJs was improved by using the untreated alumina nanoparticles. Alumina nanoparticles had positively affected the mechanical performance of epoxy structural adhesives by enhancing both their mechanical properties and interfacial wettability for an Al substrate. Ho Yoon and Gil Lee [222] mixed epoxy adhesive with quartz nanoparticles, which have much higher piezoelectric properties than adhesives, in order to enhance the sensitivity of damage monitoring through the change in piezoelectric signal during damage progress. From experiments, it was concluded that quartz nanoparticles not only increased the sensitivity of damage monitoring, but also enhanced the static and fatigue joint strengths. Bhowmik et al. [223] investigated the fabrication of polybenzimidazole by high-performance nanoadhesive and studied its performance under space environments. From thermogravimetric analysis, it was shown that the cohesive properties of nanoadhesive were more stable when heated up to 350°C. They found an increase in the adhesive joint strength of surface modified polybenzimidazole and a further significant increase in joint strength when it is prepared by nanosilicate epoxy adhesive.

## 12. Conclusions

Fatigue in adhesively bonded joints has been reviewed by analysing 222 articles published in WoS in the period between 1975 to 2011. The topics covered were fatigue strength and lifetime analysis, fatigue crack initiation, fatigue crack propagation, fatigue durability, variable fatigue amplitude, impact fatigue, thermal fatigue, torsional fatigue, fatigue in hybrid adhesive joints, and nanoadhesives. Conclusions for each topic are given below.

Fatigue strength and lifetime analysis has attracted lots of researchers. Several studies have been published in the literature in order to study the effect of many parameters with the intention to optimise these parameters and maximize the fatigue strength and lifetime. These parameters were identified as geometric parameters, material parameters, loading conditions, and surface treatment and curing conditions.

Fatigue crack initiation is a very important topic, but it is difficult to deal with due to the difficulties associated with modelling the nucleation of a crack and the ability to monitor and detect the initiation phase. The accuracy and reliability of using back-face strain and optical techniques to monitor and detect crack initiation is questionable. The research into crack initiation in adhesively bonded joints has not yet been well developed and could be regarded as in its early stage.

Fatigue crack propagation has attracted lots of researchers and can be considered as a well-established research area. Improvement in this area can be achieved by enhancing the experimental measurement and numerical modelling crack propagation techniques of mixed mode I/II and pure mode II.

Variable fatigue amplitude has attracted considerable amount of researchers. The research could be considered as new since the first WoS article was published in 2003. As in real applications variable amplitude fatigue takes place, this analysis is closer to reality than classical analysis assuming constant amplitude fatigue.

Impact fatigue has not attracted many researchers. Although research into this topic has been started in 1983, only 13 WoS publications could be found.

Thermal fatigue has not attracted researchers. Although the first WoS publication on thermal fatigue was in 1995, only 3 articles have been found.

Fatigue durability is a very important topic and has gained lots of attention in the literature. An adhesive joint loses its strength and fatigue resistance when exposed to hostile environmental conditions. Enhancing fatigue durability remains a challenge and techniques that improve fatigue performance for joints exposed to moisture and temperature should be further investigated and developed.

Torsional fatigue in adhesively bonded joints is dated back to 1995, but it has not attracted many researchers as only 5 WoS articles has been published.

Fatigue in hybrid adhesive joints has attracted a considerable amount of researchers. The main aim of the research into fatigue of hybrid joints is to enhance the fatigue performance of joints compared to just mechanical joints. However, the benefit to the fatigue performance of an adhesively bonded joint by additional bolting, riveting, or welding is questionable.

The use of nanoadhesives is a new field of application to adhesively bonded joints and has a potential to enhance their fatigue performance. The first WoS publication related to this topic is dated to 2009 and further research is expected in this direction.

## References


[1] Y.-M. Jen, "Fatigue life evaluation of adhesively bonded scarf joints," *International Journal of Fatigue*, vol. 36, no. 1, pp. 30–39, 2012.

[2] G. Altan, M. Topçu, and H. Çallioğlu, "The effects of the butterfly joints on failure loads and fatigue performance of composite structures," *Science and Engineering of Composite Materials*, vol. 17, no. 3, pp. 199–212, 2010.

[3] G. Fessel, J. G. Broughton, N. A. Fellows, J. F. Durodola, and A. R. Hutchinson, "Fatigue performance of metallic reverse-bent joints," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 32, no. 9, pp. 704–712, 2009.

[4] P. R. Underhill, A. N. Rider, and P. Livingstone, "Fatigue behaviour of aluminum bonded joints as a function of wedge test performance," *Journal of Adhesion Science and Technology*, vol. 23, no. 4, pp. 555–566, 2009.

[5] 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*, vol. 30, no. 10-11, pp. 1813–1820, 2008.

[6] R. T. Tenchev and B. G. Falzon, "An experimental and numerical study of the static and fatigue performance of a composite adhesive repair," *Key Engineering Materials*, vol. 383, pp. 25–34, 2008.

[7] V. Marcadon, Y. Nadot, A. Roy, and J. L. Gacougnolle, "Fatigue behaviour of T-joints for marine applications," *International Journal of Adhesion and Adhesives*, vol. 26, no. 7, pp. 481–489, 2006.

[8] A. Zhou and T. Keller, "Fatigue behavior of adhesively bonded joints composed of pultruded GFRP adherends for civil infrastructure applications," *Composites A*, vol. 37, no. 8, pp. 1119–1130, 2006.

[9] Q. Zeng and C. T. Sun, "Fatigue performance of a bonded wavy composite lap joint," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 27, no. 5, pp. 413–422, 2004.

[10] M. Imanaka, K. Ishii, and H. Nakayama, "Evaluation of fatigue strength of adhesively bonded single and single step double lap joints based on stress singularity parameters," *Engineering Fracture Mechanics*, vol. 62, no. 4-5, pp. 409–424, 1999.

[11] H. S. da Costa Mattos, A. H. Monteiro, and R. Palazzetti, "Failure analysis of adhesively bonded joints in composite materials," *Materials & Design*, vol. 33, pp. 242–247, 2012.

[12] Y.-M. Jen and C.-W. Ko, "Evaluation of fatigue life of adhesively bonded aluminum single-lap joints using interfacial parameters," *International Journal of Fatigue*, vol. 32, no. 2, pp. 330–340, 2010.

[13] A. Bernasconi, S. Beretta, F. Moroni, and A. Pirondi, "Local stress analysis of the fatigue behaviour of adhesively bonded thick composite laminates," *The Journal of Adhesion*, vol. 86, no. 5-6, pp. 480–500, 2010.

[14] A. Melander, J. Linder, H. Stensiö, M. Larsson, A. Gustavsson, and G. Björkman, "How defects in an adhesive layer influence the fatigue strength of bonded steel-sheet specimens," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 22, no. 5, pp. 421–426, 1999.

[15] S. K. Mazumdar and P. K. Mallick, "Static and fatigue behavior of adhesive joints in SMC-SMC composites," *Polymer Composites*, vol. 19, no. 2, pp. 139–146, 1998.

[16] S. Azari, M. Papini, and J. K. Spelt, "Effect of adhesive thickness on fatigue and fracture of toughened epoxy joints—part I: experiments," *Engineering Fracture Mechanics*, vol. 78, no. 1, pp. 153–162, 2011.

[17] S. Azari, M. Papini, and J. K. Spelt, "Effect of adhesive thickness on fatigue and fracture of toughened epoxy joints—part II: analysis and finite element modeling," *Engineering Fracture Mechanics*, vol. 78, no. 1, pp. 138–152, 2011.

[18] C. Blanchard, A. Chateauminois, and L. Vincent, "A new testing methodology for the assessment of fatigue properties of structural adhesives," *International Journal of Adhesion and Adhesives*, vol. 16, no. 4, pp. 289–299, 1996.

[19] G. Meneghetti, M. Quaresimin, and M. Ricotta, "Influence of the interface ply orientation on the fatigue behaviour of bonded joints in composite materials," *International Journal of Fatigue*, vol. 32, no. 1, pp. 82–93, 2010.

[20] J. M. Ferreira, H. Silva, J. D. Costa, and M. Richardson, "Stress analysis of lap joints involving natural fibre reinforced interface layers," *Composites B*, vol. 36, no. 1, pp. 1–7, 2005.

[21] X. He, "A review of finite element analysis of adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 31, no. 4, pp. 248–264, 2011.

[22] X. He, "FEA of fatigue behaviour of adhesively bonded joints," *Advanced Materials Research*, vol. 148-149, pp. 753–757, 2011.

[23] W. R. Broughton and G. D. Dean, Measurement Good Practice Guide No. 104: Fatigue and Creep Testing of Adhesives and Thermoplastic Joined Systems, 2007.

[24] S. Kumar and P. C. Pandey, "Fatigue life prediction of adhesively bonded single lap joints," *International Journal of Adhesion and Adhesives*, vol. 31, no. 1, pp. 43–47, 2011.

[25] S. I. Markolefas and T. K. Papathanassiou, "Stress redistributions in adhesively bonded double-lap joints, with elastic-perfectly plastic adhesive behavior, subjected to axial lap-shear cyclic loading," *International Journal of Adhesion and Adhesives*, vol. 29, no. 7, pp. 737–744, 2009.

[26] S. Kumar and P. C. Pandey, "Cyclic-fatigue performance of adhesively bonded lap joint," in *Computational Methods*, part 1, 2, pp. 541–546, 2006.

[27] N. V. Datla, M. Papini, J. A. Schroeder, and J. K. Spelt, "Modified DCB and CLS specimens for mixed-mode fatigue testing of adhesively bonded thin sheets," *International Journal of Adhesion and Adhesives*, vol. 30, no. 6, pp. 439–447, 2010.

[28] S. M. R. Khalili, A. Shokuhfar, S. D. Hoseini, M. Bidkhori, S. Khalili, and R. K. Mittal, "Experimental study of the influence of adhesive reinforcement in lap joints for composite structures subjected to mechanical loads," *International Journal of Adhesion and Adhesives*, vol. 28, no. 8, pp. 436–444, 2008.

[29] B. Täljsten, C. S. Hansen, and J. W. Schmidt, "Strengthening of old metallic structures in fatigue with prestressed and non-prestressed CFRP laminates," *Construction and Building Materials*, vol. 23, no. 4, pp. 1665–1677, 2009.

[30] A. E. Nolting, P. R. Underhill, and S. W. Dean, "Fatigue behavior of adhesively bonded aluminium double strap joints," *Journal of ASTM International*, vol. 5, no. 5, p. 101559, 2008.

[31] K. Ishii, M. Imanaka, H. Nakayama, and H. Kodama, "Evaluation of the fatigue strength of adhesively bonded CFRP/metal single and single-step double-lap joints," *Composites Science and Technology*, vol. 59, no. 11, pp. 1675–1683, 1999.

[32] K. Ishii, M. Imanaka, H. Nakayama, and H. Kodama, "Fatigue failure criterion of adhesively bonded CFRP/metal joints under multiaxial stress conditions," *Composites A*, vol. 29, no. 4, pp. 415–422, 1998.

[33] A. D. Crocombe, "Predicting the response of adhesively bonded structures under a range of service load conditions using finite element methods," *International Journal of Materials and Product Technology*, vol. 14, no. 5-6, pp. 411–429, 1999.

[34] M. Imanaka and T. Iwata, "Estimation of fatigue strength for adhesively-bonded lap joints based on fatigue failure criterion under multiaxial stress conditions," *The Journal of Adhesion*, vol. 65, no. 1–4, pp. 7–24, 1998.

[35] M. Dessureault and J. K. Spelt, "Observations of fatigue crack initiation and propagation in an epoxy adhesive," *International Journal of Adhesion and Adhesives*, vol. 17, no. 3, pp. 183–195, 1997.

[36] M. Imanaka and T. Iwata, "Fatigue failure criterion of adhesively-bonded joints under combined stress conditions," *The Journal of Adhesion*, vol. 59, no. 1–4, pp. 111–126, 1996.

[37] M. Imanaka, W. Kishimoto, K. Okita, and H. Nakayama, "Estimation of fatigue life of adhesive joints and reliability assessment," *Journal of the Society of Materials Science, Japan*, vol. 39, no. 439, pp. 412–418, 1990.

[38] M. Imanaka, W. Kishimoto, K. Okita, and H. Nakayama, "Study on fatigue behavior of adhesive-bonded butt joint (effect of unbonded defects at adhesive/adherend interface on fatigue strength)," *Journal of the Society of Materials Science, Japan*, vol. 34, no. 377, pp. 134–137, 1985.

[39] P. Mertiny and K. Ursinus, "Damage behavior of joined fiber-reinforced polymer pipe under monotonic and cyclic loading," in *Proceedings of the ASME Pressure Vessels and Piping Conference (PVP '07)*, vol. 3, pp. 499–504, San Antonio, Tex, USA, July 2007.

[40] E. M. Knox, M. J. Cowling, and S. A. Hashim, "Fatigue performance of adhesively bonded connections in GRE pipes," *International Journal of Fatigue*, vol. 22, no. 6, pp. 513–519, 2000.

[41] T. Keller and M. Schollmayer, "Through-thickness performance of adhesive joints between FRP bridge decks and steel girders," *Composite Structures*, vol. 87, no. 3, pp. 232–241, 2009.

[42] R. J. Clark and D. P. Romilly, "Bending of bonded composite repairs for aluminum aircraft structures: a design study," *Journal of Aircraft*, vol. 44, no. 6, pp. 2012–2025, 2007.

[43] Z. Z. Gao and Z. F. Yue, "Fatigue failure of polyethylene methacrylate in adhesive assembly under unsymmetrical bending," *Theoretical and Applied Fracture Mechanics*, vol. 48, no. 1, pp. 89–96, 2007.

[44] M. Takiguchi and F. Yoshida, "Effects of loading speed and shear prestrain on adhesive fatigue strength in single-lap joint," *Key Engineering Materials*, vol. 340-341, pp. 1479–1484, 2007.

[45] R. R. Gomatam and E. Sancaktar, "The effects of stress state, loading frequency and cyclic waveforms on the fatigue behavior of silver-filled electronically-conductive adhesive joints," *Journal of Adhesion Science and Technology*, vol. 20, no. 1, pp. 53–68, 2006.

[46] R. R. Gomatam and E. Sancaktar, "A novel cumulative fatigue damage model for electronically-conductive adhesive joints under variable loading," *Journal of Adhesion Science and Technology*, vol. 20, no. 1, pp. 69–86, 2006.

[47] R. R. Gomatam and E. Sancaktar, "A comprehensive fatigue life predictive model for electronically conductive adhesive joints under constant-cycle loading," *Journal of Adhesion Science and Technology*, vol. 20, no. 1, pp. 87–104, 2006.

[48] A. Gladkov and A. Bar-Cohen, "Parametric dependence of fatigue of electronic adhesives," *IEEE Transactions on Components and Packaging Technologies*, vol. 22, no. 2, pp. 200–208, 1999.

[49] 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*, vol. 19, no. 1, pp. 19–27, 1999.

[50] Z. Yang, K. Zhang, Y. Ma, and Y. Li, "Orthogonal test research on the effect of curing technology on the fatigue life of adhesive bonding of CFRP and aluminum alloy," *Advanced Materials Research*, vol. 181-182, pp. 534–539, 2011.

[51] K. C. Shin and J. J. Lee, "Effects of thermal residual stresses on failure of co-cured lap joints with steel and carbon fiber-epoxy composite adherends under static and fatigue tensile loads," *Composites A*, vol. 37, no. 3, pp. 476–487, 2006.

[52] L. F. M. da Silva, N. M. A. J. Ferreira, V. Richter-Trummer, and E. A. S. Marques, "Effect of grooves on the strength of adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 30, no. 8, pp. 735–743, 2010.

[53] T. Sekercioglu and V. Kovan, "Prediction of static shear force and fatigue life of adhesive joints by artificial neural network," *Kovove Materialy*, vol. 46, no. 1, pp. 51–57, 2008.

[54] S. Azari, M. Papini, and J. K. Spelt, "Effect of surface roughness on the performance of adhesive joints under static and cyclic loading," *The Journal of Adhesion*, vol. 86, no. 7, pp. 742–764, 2010.

[55] A. M. Pereira, J. M. Ferreira, F. V. Antunes, and P. J. Bártolo, "Study on the fatigue strength of AA 6082-T6 adhesive lap joints," *International Journal of Adhesion and Adhesives*, vol. 29, no. 6, pp. 633–638, 2009.

[56] W.-S. Kim and J.-J. Lee, "Adhesion strength and fatigue life improvement of co-cured composite/metal lap joints by silane-based interphase formation," *Journal of Adhesion Science and Technology*, vol. 21, no. 2, pp. 125–140, 2007.

[57] D. J. Bland, A. J. Kinloch, V. Stolojan, and J. F. Watts, "Failure mechanisms in adhesively bonded aluminium: an XPS and PEELS study," *Surface and Interface Analysis*, vol. 40, no. 3-4, pp. 128–131, 2008.

[58] R. Bermejo, J. Oñoro, and R. García-Ledesma, "Fatigue behaviour of single overlap joints on steel and pre-painting steel with epoxy adhesive," *Revista de Metalurgia*, vol. 44, no. 4, pp. 310–316, 2008.

[59] R. R. Gomatam and E. Sancaktar, "Effects of various adherend surface treatments on fatigue behavior of joints bonded with a silver-filled electronically conductive adhesive," *Journal of Adhesion Science and Technology*, vol. 19, no. 8, pp. 659–678, 2005.

[60] V. Shenoy, I. A. Ashcroft, G. W. Critchlow, and A. D. Crocombe, "Unified methodology for the prediction of the fatigue behaviour of adhesively bonded joints," *International Journal of Fatigue*, vol. 32, no. 8, pp. 1278–1288, 2010.

[61] K. B. Katnam, A. D. Crocombe, H. Khoramishad, and I. A. Ashcroft, "Load ratio effect on the fatigue behaviour of adhesively bonded joints: an enhanced damage model," *The Journal of Adhesion*, vol. 86, no. 3, pp. 257–272, 2010.

[62] A. Graner Solana, A. D. Crocombe, and I. A. Ashcroft, "Fatigue life and backface strain predictions in adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 30, no. 1, pp. 36–42, 2010.

[63] V. Shenoy, I. A. Ashcroft, G. W. Critchlow, A. D. Crocombe, and M. M. Abdel Wahab, "Strength wearout of adhesively bonded joints under constant amplitude fatigue," *International Journal of Fatigue*, vol. 31, no. 5, pp. 820–830, 2009.

[64] J. H. Kim, B. J. Park, and Y. W. Han, "Evaluation of fatigue characteristics for adhesively-bonded composite stepped lap joint," *Composite Structures*, vol. 66, no. 1–4, pp. 69–75, 2004.

[65] M. M. A. Wahab, I. A. Ashcroft, A. D. Crocombe et al., "Prediction of fatigue thresholds in adhesively bonded joints using damage mechanics and fracture mechanics," *Journal of Adhesion Science and Technology*, vol. 15, no. 7, pp. 763–781, 2001.

[66] M. M. Abdel Wahab, I. Hilmy, I. A. Ashcroft, and A. D. Crocombe, "Evaluation of fatigue damage in adhesive bonding: part 1: bulk adhesive," *Journal of Adhesion Science and Technology*, vol. 24, no. 2, pp. 305–324, 2010.

[67] M. M. Abdel Wahab, I. Hilmy, I. A. Ashcroft, and A. D. Crocombe, "Evaluation of fatigue damage in adhesive bonding: part 2: single lap joint," *Journal of Adhesion Science and Technology*, vol. 24, no. 2, pp. 325–345, 2010.

[68] I. Hilmy, M. M. Abdel Wahab, I. A. Ashcroft, and A. D. Crocombe, "A finite element analysis of scarf joint for controlling the triaxiality function in adhesive bonding," *Key Engineering Materials*, vol. 385–387, pp. 17–20, 2008.

[69] M. Quaresimin and M. Ricotta, "Life prediction of bonded joints in composite materials," *International Journal of Fatigue*, vol. 28, no. 10, pp. 1166–1176, 2006.

[70] M. Quaresimin and M. Ricotta, "Fatigue behaviour and damage evolution of single lap bonded joints in composite material," *Composites Science and Technology*, vol. 66, no. 2, pp. 176–187, 2006.

[71] M. Imanaka, M. Taniguchi, T. Hamano, and M. Kimoto, "Fatigue life estimation of adhesively bonded scarf joints based on a continuum damage mechanics model," *Polymers and Polymer Composites*, vol. 13, no. 4, pp. 359–370, 2005.

[72] M. Imanaka, T. Hamano, A. Morimoto, R. Ashino, and M. Kimoto, "Fatigue damage evaluation of adhesively bonded butt joints with a rubber-modified epoxy adhesive," *Journal of Adhesion Science and Technology*, vol. 17, no. 7, pp. 981–994, 2003.

[73] M. M. A. Wahab, I. A. Ashcroft, A. D. Crocombe, and L. Joussot, "Lifetime prediction for fatigue damage in bonded joints," *Key Engineering Materials*, vol. 245-246, pp. 43–50, 2003.

[74] D. R. Lefebvre and D. A. Dillard, "A stress singularity approach for the prediction of fatigue crack initiation in adhesive bonds. Part 1: theory," *The Journal of Adhesion*, vol. 70, no. 1-2, pp. 119–138, 1999.

[75] D. R. Lefebvre, D. A. Dillard, and J. G. Dillard, "A stress singularity approach for the prediction of fatigue crack initiation in adhesive bonds. Part 2: experimental," *The Journal of Adhesion*, vol. 70, no. 1-2, pp. 139–154, 1999.

[76] H. Khoramishad, A. D. Crocombe, K. B. Katnam, and I. A. Ashcroft, "A generalised damage model for constant amplitude fatigue loading of adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 30, no. 6, pp. 513–521, 2010.

[77] H. Khoramishad, A. D. Crocombe, K. B. Katnam, and I. A. Ashcroft, "Predicting fatigue damage in adhesively bonded joints using a cohesive zone model," *International Journal of Fatigue*, vol. 32, no. 7, pp. 1146–1158, 2010.

[78] V. Shenoy, I. A. Ashcroft, G. W. Critchlow, A. D. 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*, vol. 29, no. 4, pp. 361–371, 2009.

[79] A. G. Solana, A. D. Crocombe, M. M. Abdel Wahab, and I. A. Ashcroft, "Fatigue initiation in adhesively-bonded single-lap joints," *Journal of Adhesion Science and Technology*, vol. 21, no. 14, pp. 1343–1357, 2007.

[80] J. Deng and M. M. K. Lee, "Fatigue performance of metallic beam strengthened with a bonded CFRP plate," *Composite Structures*, vol. 78, no. 2, pp. 222–231, 2007.

[81] A. D. Crocombe, C. Y. Ong, C. M. Chan, M. M. A. Wahab, and I. A. Ashcroft, "Investigating fatigue damage evolution in adhesively bonded structures using backface strain measurement," *The Journal of Adhesion*, vol. 78, no. 9, pp. 745–776, 2002.

[82] Z. H. Zhang, J. K. Shang, and F. V. Lawrence, "A backface strain technique for detecting fatigue-crack initiation in adhesive joints," *The Journal of Adhesion* , vol. 49, no. 1-2, pp. 23–36, 1995.

[83] T. F. Capell, J. Palaniappan, S. L. Ogin et al., "The use of an embedded chirped fibre Bragg grating sensor to monitor disbond initiation and growth in adhesively bonded composite/metal single lap joints," *Journal of Optics A*, vol. 9, no. 6, article S07, pp. S40–S44, 2007.

[84] W. S. Johnson and S. Mall, "Influence of interface ply orientation on fatigue damage of adhesively bonded composite joints," *Journal of Composites Technology and Research*, vol. 8, no. 1, pp. 3–7, 1986.

[85] M. V. Fernández, M. F. S. F. de Moura, L. F. M. da Silva, and A. T. Marques, "Composite bonded joints under mode I fatigue loading," *International Journal of Adhesion and Adhesives*, vol. 31, no. 5, pp. 280–285, 2011.

[86] M. M. A. Wahab, I. A. Ashcroft, A. D. Crocombe, and P. A. Smith, "Finite element prediction of fatigue crack propagation lifetime in composite bonded joints," *Composites A*, vol. 35, no. 2, pp. 213–222, 2004.

[87] M. M. A. Wahab, I. A. Ashcroft, A. D. Crocombe, and P. A. Smith, "Fatigue crack propagation in adhesively bonded joints," *Key Engineering Materials*, vol. 251-252, pp. 229–233, 2003.

[88] M. M. A. Wahab, I. A. Ashcroft, A. D. Crocombe, and P. A. Smith, "Numerical prediction of fatigue crack propagation lifetime in adhesively bonded structures," *International Journal of Fatigue*, vol. 24, no. 6, pp. 705–709, 2002.

[89] F. Moroni and A. Pirondi, "A procedure for the simulation of fatigue crack growth in adhesively bonded joints based on the cohesive zone model and different mixed-mode propagation criteria," *Engineering Fracture Mechanics*, vol. 78, no. 8, pp. 1808–1816, 2011.

[90] A. Pirondi and F. Moroni, "Simulation of mixed mode I/II fatigue crack propagation in adhesive joints with a modified cohesive zone model," *Journal of Adhesion Science and Technology*, vol. 25, no. 18, pp. 2483–2499, 2011.

[91] A. Pirondi and F. Moroni, "A progressive damage model for the prediction of fatigue crack growth in bonded joints," *The Journal of Adhesion*, vol. 86, no. 5-6, pp. 501–521, 2010.

[92] K. Ishii, "Effect of substrate material on fatigue crack propagation rate of adhesively bonded DCB joints," *Journal of Adhesion Science and Technology*, vol. 25, no. 20, pp. 2775–2787, 2011.

[93] S.-H. Baek, W.-S. Kim, C.-J. Jang, and J.-J. Lee, "Mixed mode fatigue characteristics of composite/metal interfaces," *Key Engineering Materials*, vol. 452-453, pp. 437–440, 2011.

[94] S. Giannis and R. H. Martin, "Predicting fatigue life of Glare skin-stringer configurations in aerospace panels," *Plastics, Rubber and Composites*, vol. 39, no. 3–5, pp. 171–179, 2010.

[95] S. Azari, M. Papini, J. A. Schroeder, and J. K. Spelt, "The effect of mode ratio and bond interface on the fatigue behavior of a highly-toughened epoxy," *Engineering Fracture Mechanics*, vol. 77, no. 3, pp. 395–414, 2010.

[96] I. A. Ashcroft, J. P. Casas-Rodriguez, and V. V. Silberschmidt, "A model to predict the anomalous fatigue crack growth behaviour seen in mixed mechanism fracture," *The Journal of Adhesion*, vol. 86, no. 5-6, pp. 522–538, 2010.

[97] A. Pirondi and F. Moroni, "An investigation of fatigue failure prediction of adhesively bonded metal/metal joints," *International Journal of Adhesion and Adhesives*, vol. 29, no. 8, pp. 796–805, 2009.

[98] H. M. Diab, Z. Wu, and K. Iwashita, "Theoretical solution for fatigue debonding growth and fatigue life prediction of FRP-concrete interfaces," *Advances in Structural Engineering*, vol. 12, no. 6, pp. 781–792, 2009.

[99] G. V. Marannano, L. Mistretta, A. Cirello, and S. Pasta, "Crack growth analysis at adhesive-adherent interface in bonded joints under mixed mode I/II," *Engineering Fracture Mechanics*, vol. 75, no. 18, pp. 5122–5133, 2008.

[100] A. Pirondi and G. Nicoletto, "Mixed mode I/II fatigue crack growth in adhesive joints," *Engineering Fracture Mechanics*, vol. 73, no. 16, pp. 2557–2568, 2006.

[101] P. T. Cheuk, L. Tong, A. N. Rider, and J. Wang, "Analysis of energy release rate for fatigue cracked metal-to-metal double-lap shear joints," *International Journal of Adhesion and Adhesives*, vol. 25, no. 2, pp. 181–191, 2005.

[102] X. X. Xu, A. D. Crocombe, and P. A. Smith, "Mixed-mode fatigue and fracture behaviour of joints bonded with either filled or filled and toughened adhesive," *International Journal of Fatigue*, vol. 17, no. 4, pp. 279–286, 1995.

[103] F. C. Edde and Y. Verreman, "Nominally Constant strain-energy release rate specimen for the study of mode II fracture and fatigue in adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 15, no. 1, pp. 29–32, 1995.

[104] M.-P. Moutrille, X. Balandraud, M. Grédiac, K. Derrien, and D. Baptiste, "Applying thermoelasticity to study stress relief and crack propagation in aluminium specimens patched with composite material," *Journal of Strain Analysis for Engineering Design*, vol. 43, no. 6, pp. 423–433, 2008.

[105] S. Azari, M. Papini, J. A. Schroeder, and J. K. Spelt, "Fatigue threshold behavior of adhesive joints," *International Journal of Adhesion and Adhesives*, vol. 30, no. 3, pp. 145–159, 2010.

[106] M. Kayupov and Y. A. Dzenis, "Stress concentrations caused by bond cracks in single-lap adhesive composite joints," *Composite Structures*, vol. 54, no. 2-3, pp. 215–220, 2001.

[107] Y. Guo, S. L. Ogin, T. F. Capell et al., "Effect of disbond propagation on the reflected spectra of CFBG sensors embedded within the bond-line of composite bonded joints," *Advanced Materials Research*, vol. 79–82, pp. 2067–2070, 2009.

[108] P. T. Cheuk, L. Tong, C. H. Wang, A. Baker, and P. Chalkley, "Fatigue crack growth in adhesively bonded composite-metal double-lap joints," *Composite Structures*, vol. 57, no. 1–4, pp. 109–115, 2002.

[109] T. R. Brussat and S. T. Chiu, "Fatigue crack growth of bondline cracks in structural bonded joints," *Journal of Engineering Materials and Technology*, vol. 100, no. 1, pp. 39–45, 1978.

[110] J. P. Casas-Rodriguez, I. A. Ashcroft, and V. V. Silberschmidt, "Propagation of delamination zones in bonded joints," *Proceedings of the Estonian Academy of Sciences*, vol. 56, no. 2, pp. 170–176, 2007.

[111] I. A. Ashcroft, S. Erpolat, and J. Tyrer, "Damage assessment in bonded composite joints," *Key Engineering Materials*, vol. 245-246, pp. 501–508, 2003.

[112] T. Du, M. Liu, S. Seghi, K. J. Hsia, J. Economy, and J. K. Shang, "Piezoelectric actuation of fatigue crack growth along polymer/metal interface," in *Long Term Durability of Structural Materials: Durability 2000*, pp. 187–192, 2001.

[113] K. Ishii, M. Imanaka, and H. Nakayama, "Fatigue crack propagation behavior of adhesively-bonded CFRP/aluminum joints," *Journal of Adhesion Science and Technology*, vol. 21, no. 2, pp. 153–167, 2007.

[114] M. M. Abou-Hamda, M. M. Megahed, and M. M. I. Hammouda, "Fatigue crack growth in double cantilever beam specimen with an adhesive layer," *Engineering Fracture Mechanics*, vol. 60, no. 5-6, pp. 605–614, 1998.

[115] A. Pirondi and G. Nicoletto, "Fatigue crack growth in bonded DCB specimens," *Engineering Fracture Mechanics*, vol. 71, no. 4–6, pp. 859–871, 2004.

[116] X. X. Xu, A. D. Crocombe, and P. A. Smith, "Fatigue crack growth rates in adhesive joints tested at different frequencies," *The Journal of Adhesion*, vol. 58, no. 3-4, pp. 191–204, 1996.

[117] H. Aglan and Z. Abdo, "An innovative approach to fatigue disbond propagation in adhesive joints," *Journal of Adhesion Science and Technology*, vol. 10, no. 3, pp. 183–198, 1996.

[118] X. X. Xu, A. D. Crocrombe, and P. A. Smith, "Fatigue behaviour of joints bonded with either filled, or filled and toughened, adhesive," *International Journal of Fatigue*, vol. 16, no. 7, pp. 469–477, 1994.

[119] X. X. Xu, A. D. Crocombe, and P. A. Smith, "Frequency effect on fatigue-crack growth-rate in joints bonded with either filled or filled and toughened adhesive," *Vide Science Technique et Applications*, vol. 272, pp. 232–236, 1994.

[120] Y. Zhang, A. P. Vassilopoulos, and T. Keller, "Fracture of adhesively-bonded pultruded GFRP joints under constant amplitude fatigue loading," *International Journal of Fatigue*, vol. 32, no. 7, pp. 979–987, 2010.

[121] A. J. Kinloch and S. O. Osiyemi, "Predicting the fatigue life of adhesively-bonded joints," *The Journal of Adhesion*, vol. 43, no. 1-2, pp. 79–90, 1993.

[122] H. Khoramishad, A. D. Crocombe, K. B. Katnam, and I. A. Ashcroft, "Fatigue damage modelling of adhesively bonded joints under variable amplitude loading using a cohesive zone model," *Engineering Fracture Mechanics*, vol. 78, no. 18, pp. 3212–3225, 2011.

[123] M. Eskandarian and R. M. Jennings, "A new test methodology for simultaneous assessment of monotonic and fatigue behaviors of adhesive joints," *Journal of Adhesion Science and Technology*, vol. 25, no. 18, pp. 2501–2520, 2011.

[124] A. H. Al-Ghamdi, I. A. Ashcroft, A. D. Crocombe, and M. M. Abdel-Wahab, "Crack growth in adhesively bonded joints subjected to variable frequency fatigue loading," *The Journal of Adhesion*, vol. 79, no. 12, pp. 1161–1182, 2003.

[125] V. Shenoy, I. A. Ashcroft, G. W. Critchlow, and A. D. Crocombe, "Fracture mechanics and damage mechanics based fatigue lifetime prediction of adhesively bonded joints subjected to variable amplitude fatigue," *Engineering Fracture Mechanics*, vol. 77, no. 7, pp. 1073–1090, 2010.

[126] V. Shenoy, I. A. Ashcroft, G. W. Critchlow, A. D. Crocombe, and M. M. Abdel Wahab, "An evaluation of strength wearout models for the lifetime prediction of adhesive joints subjected to variable amplitude fatigue," *International Journal of Adhesion and Adhesives*, vol. 29, no. 6, pp. 639–649, 2009.

[127] A. E. Nolting, P. R. Underhill, and D. L. DuQuesnay, "Variable amplitude fatigue of bonded aluminum joints," *International Journal of Fatigue*, vol. 30, no. 1, pp. 178–187, 2008.

[128] I. A. Ashcroft, "A simple model to predict crack growth in bonded joints and laminates under variable-amplitude fatigue," *Journal of Strain Analysis for Engineering Design*, vol. 39, no. 6, pp. 707–716, 2004.

[129] S. Erpolat, I. A. Ashcroft, A. D. Crocombe, and M. M. Abdel-Wahab, "Fatigue crack growth acceleration due to intermittent overstressing in adhesively bonded CFRP joints," *Composites A*, vol. 35, no. 10, pp. 1175–1183, 2004.

[130] I. A. Ashcroft, J. P. Casas-Rodriguez, and V. V. Silberschmidt, "Fatigue crack growth in adhesively bonded joints with intermittent impacts," *Key Engineering Materials*, vol. 452-453, pp. 5–8, 2011.

[131] I. A. Ashcroft, V. V. Silberschmidt, B. Echard, and J. Pablo Casas Rodriguez, "Crack propagation in a toughened epoxy adhesive under repeated impacts," *Shock and Vibration*, vol. 18, no. 1-2, pp. 157–170, 2011.

[132] G. Tsigkourakos, J. P. Casas-Rodriguez, and V. V. Silberschmidt, "Analysis of damage propagation in single lap joints in impact fatigue," *Vibro-Impact Dynamics of Ocean Systems and Related Problems*, vol. 44, pp. 247–257, 2009.

[133] V. V. Silberschmidt, J. P. Casas-Rodriguez, and I. A. Ashcroft, "Impact fatigue of adhesive joints," *Key Engineering Materials*, vol. 399, pp. 71–78, 2009.

[134] J. P. Casas-Rodriguez, I. A. Ashcroft, and V. V. Silberschmidt, "Damage in adhesively bonded CFRP joints: sinusoidal and impact-fatigue," *Composites Science and Technology*, vol. 68, no. 13, pp. 2663–2670, 2008.

[135] J. P. Casas-Rodriguez, I. A. Ashcroft, and V. V. Silberschmidt, "Delamination in adhesively bonded CFRP joints: standard fatigue, impact-fatigue and intermittent impact," *Composites Science and Technology*, vol. 68, no. 12, pp. 2401–2409, 2008.

[136] J. P. Casas-Rodriguez, I. A. Ashcroft, and V. V. Silberschmidt, "Damage evolution in adhesive joints subjected to impact fatigue," *Journal of Sound and Vibration*, vol. 308, no. 3-5, pp. 467–478, 2007.

[137] J. P. Casas-Rodriguez, I. A. Ashcroft, and V. V. Silberschmidt, "Effect of impact-fatigue on damage in adhesive joints," *Key Engineering Materials*, vol. 347, pp. 653–658, 2007.

[138] I. A. Ashcroft, J. P. Casas-Rodriguez, and V. V. Silberschmidt, "Mixed-mode crack growth in bonded composite joints under standard and impact-fatigue loading," *Journal of Materials Science*, vol. 43, no. 20, pp. 6704–6713, 2008.

[139] V. V. Silberschmidt, J. P. Casas-Rodriguez, and I. A. Ashcroft, "Impact fatigue in adhesive joints," *Proceedings of the Institution of Mechanical Engineers C*, vol. 222, no. 10, pp. 1981–1994, 2008.

[140] M. Imanaka, W. Kishimoto, K. Okita, H. Nakayama, and M. Shirato, "On the impact fatigue strength of adhesive-bonded lap joint," *Journal of the Society of Materials Science, Japan*, vol. 34, no. 386, pp. 1296–1300, 1985.

[141] M. Imanaka, W. Kishimoto, K. Okita, and H. Nakayama, "On the impact fatigue behavior of adhesive-bonded butt joint," *Journal of the Society of Materials Science, Japan*, vol. 32, no. 358, pp. 796–801, 1983.

[142] B. W. Barber and D. W. Radford, "Impact-fatigue behavior of composite tube/metal end fitting bonded joints," *Composites Engineering*, vol. 5, no. 8, pp. 995–1009, 1995.

[143] L.-L. Gao, L. Wang, H. Gao, G. Chen, and X. Chen, "Fatigue life evaluation of anisotropic conductive adhesive film joints under mechanical and hygrothermal loads," *Microelectronics Reliability*, vol. 51, no. 8, pp. 1393–1397, 2011.

[144] Y. S. Chan, F. Song, and S. W. R. Lee, "Investigation on lead-free solder joint reliability of edge-bonded CBGA under temperature cycling," in *Proceedings of the 12th International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP '11)*, pp. 1–6, August 2011.

[145] Q. Yu, M. Shiratori, and T. Mori, "Nonsteady thermal stress analysis and thermal fatigue strength of metal-CFRP bonded joints," *JSME International Journal A*, vol. 36, no. 1, pp. 43–49, 1993.

[146] N. V. Datla, M. Papini, J. Ulicny, B. Carlson, and J. K. Spelt, "The effects of test temperature and humidity on the mixed-mode fatigue behavior of a toughened adhesive aluminum joint," *Engineering Fracture Mechanics*, vol. 78, no. 6, pp. 1125–1139, 2011.

[147] R. R. Gomatam and E. Sancaktar, "Fatigue and failure behaviors of silver-filled electronically-conductive adhesive joints subjected to elevated humidity," *Journal of Adhesion Science and Technology*, vol. 18, no. 15-16, pp. 1833–1848, 2004.

[148] R. R. Gomatam and E. Sancaktar, "Modeling fatigue behavior of electronically conductive adhesive joints under elevated temperature and humidity conditions," in *Proceedings of the*

4th IEEE International Conference on Polymers and Adhesives in Microelectronics and Photonics*, pp. 14–26, September 2004.

[149] A. J. Kinloch, M. S. G. Little, and J. F. Watts, "The role of the interphase in the environmental failure of adhesive joints," *Acta Materialia*, vol. 48, no. 18-19, pp. 4543–4553, 2000.

[150] Z. Abdo and H. Aglan, "Analysis of aircraft adhesive joints under combined thermal and mechanical cyclic loadings," *Journal of Adhesion Science and Technology*, vol. 11, no. 7, pp. 941–956, 1997.

[151] R. V. Valentin, L. M. Butkus, and W. S. Johnson, "A finite element and experimental evaluation of boron-epoxy doublers bonded to an aluminum substrate," *Journal of Composites Technology and Research*, vol. 20, no. 2, pp. 108–119, 1998.

[152] R. A. Dickie, L. P. Haack, J. K. Jethwa, A. J. Kinloch, and J. F. Watts, "The fatigue and durability behaviour of automotive adhesives. Part II: failure mechanisms," *The Journal of Adhesion*, vol. 66, no. 1–4, pp. 1–37, 1998.

[153] A. J. Curley, J. K. Jethwa, A. J. Kinloch, and A. C. Taylor, "The fatigue and durability behaviour of automotive adhesives. Part III: predicting the service life," *The Journal of Adhesion*, vol. 66, no. 1–4, pp. 39–59, 1998.

[154] J. K. Jethwa and A. J. Kinloch, "The fatigue and durability behaviour of automotive adhesives. Part I: fracture mechanics tests," *The Journal of Adhesion*, vol. 61, no. 1–4, pp. 71–95, 1997.

[155] M. Fernando, W. W. Harjoprayitno, and A. J. Kinloch, "A fracture mechanics study of the influence of moisture on the fatigue behaviour of adhesively bonded aluminium-alloy joints," *International Journal of Adhesion and Adhesives*, vol. 16, no. 2, pp. 113–119, 1996.

[156] E. Lachmann, "Durability of bonded metal joints in motor-vehicle construction," *Vide Science Technique et Applications*, vol. 272, pp. 277–283, 1994.

[157] H. W. So, N. N. S. Chen, and P. I. F. Niem, "Fatigue performance of adhesive joints immersed in different solutions," *The Journal of Adhesion*, vol. 44, no. 4, pp. 245–256, 1994.

[158] Y. Zhang, A. P. Vassilopoulos, and T. Keller, "Environmental effects on fatigue behavior of adhesively-bonded pultruded structural joints," *Composites Science and Technology*, vol. 69, no. 7-8, pp. 1022–1028, 2009.

[159] G. Neser and E. Altunsaray, "The effcts of seawater environment, material direction and thickness on the fatigue performance of adhesively bonded and bolted joints of non-crimp GRP structures," *Advanced Composites Letters*, vol. 15, no. 4, pp. 127–137, 2006.

[160] I. A. Ashcroft, D. J. Hughes, and S. J. Shaw, "Adhesive bonding of fibre reinforced polymer composite materials," *Assembly Automation*, vol. 20, no. 2, pp. 150–161, 2000.

[161] P. N. Reis, J. A. M. Ferreira, J. D. M. Costa, and M. O. W. Richardson, "Fatigue of thermoplastic composites adhesive lap joints," in *Advances in Mechanical Behaviour, Plasticity and Damage: Proceedings of Euromat 2000*, vol. 1-2, pp. 237–242, 2000.

[162] M. N. Charalambides, R. Hardouin, A. J. Kinloch, and F. L. Matthews, "Adhesively-bonded repairs to fibre-composite materials I: experimental," *Composites A*, vol. 29, no. 11, pp. 1371–1381, 1998.

[163] L. M. Butkus, R. V. Valentin, and W. S. Johnson, "Durability issues in bonded joint design," in *Proceedings of the 19th Symposium of the International Committee on Aeronautical Fatigue (ICAF '97)*, vol. 2, pp. 843–854, Edinburgh, Scotland, June 1997.

[164] A. S. Crasto and R. Y. Kim, "Environmental durability of a composite-to-composite adhesive bond in infrastructure applications," in *Proceedings of the 28th International SAMPE Technical Conference*, pp. 837–849, November 1996.

[165] R. B. Gilmore and S. J. Shaw, "The effect of temperature and humidity on the fatigue behaviour of composite bonded joints," Composites Bonding, American Society for Testing and Materials Special Technical Publication, 1227, pp. 82–95, 1994.

[166] S. Okuda, S. Nishina, and T. Watanabe, "Tensile fatigue behavior of adhesive bonded joint of FRP in water," *Journal of the Society of Materials Science, Japan*, vol. 34, no. 376, pp. 87–92, 1985.

[167] H. Miyairi, A. Muramatsu, and H. Fukuda, "Fatigue strength and endurance of adhesive-bonded joints," *Journal of the Society of Materials Science, Japan*, vol. 24, no. 266, pp. 1051–1056, 1975.

[168] A. J. Curley, H. Hadavinia, A. J. Kinloch, and A. C. Taylor, "Predicting the service-life of adhesively-bonded joints," *International Journal of Fracture*, vol. 103, no. 1, pp. 41–69, 2000.

[169] W. S. Johnson and L. M. Butkus, "Considering environmental conditions in the design of bonded structures: a fracture mechanics approach," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 21, no. 4, pp. 465–478, 1998.

[170] I. A. Ashcroft, M. M. A. Wahab, and A. D. Crocombe, "Predicting degradation in bonded composite joints using a semi-coupled finite-element method," *Mechanics of Advanced Materials and Structures*, vol. 10, no. 3, pp. 227–248, 2003.

[171] M. M. Abdel Wahab, I. A. Ashcroft, A. D. Crocombe, and S. J. Shaw, "Diffusion of moisture in adhesively bonded joints," *The Journal of Adhesion*, vol. 77, no. 1, pp. 43–80, 2001.

[172] M. M. A. Wahab, I. A. Ashcroft, A. D. Crocombe, D. J. Hughes, and S. J. Shaw, "The effect of environment on the fatigue of bonded composite joints. Part 2: fatigue threshold prediction," *Composites A*, vol. 32, no. 1, pp. 59–69, 2001.

[173] M. D. Banea and L. F. M. da Silva, "Static and fatigue behaviour of room temperature vulcanising silicone adhesives for high temperature aerospace applications," *Materialwissenschaft und Werkstofftechnik*, vol. 41, no. 5, pp. 325–335, 2010.

[174] M. D. Banea and L. F. M. da Silva, "Mechanical characterization of flexible adhesives," *The Journal of Adhesion*, vol. 85, no. 4-5, pp. 261–285, 2009.

[175] T. Hattori, "Fatigue strength of FRP/metal adhesive joints under low temperature," in *Proceedings of the 4th International Conference on High Performance Structures and Materials*, May 2008.

[176] H. Y. Hwang and D. G. Lee, "Temperature effects on the torsional fatigue characteristics of adhesively bonded tubular single-lap joints," *Journal of Adhesion Science and Technology*, vol. 18, no. 4, pp. 413–425, 2004.

[177] K. M. Liechti, G. A. Arzoumanidis, and S. J. Park, "Fatigue fracture of fully saturated bonded joints," *The Journal of Adhesion*, vol. 78, no. 5, pp. 383–411, 2002.

[178] I. A. Ashcroft and S. J. Shaw, "Mode I fracture of epoxy bonded composite joints 2. Fatigue loading," *International Journal of Adhesion and Adhesives*, vol. 22, no. 2, pp. 151–167, 2002.

[179] I. A. Ashcroft, D. J. Hughes, S. J. Shaw, M. A. Wahab, and A. Crocombe, "Effect of temperature on the quasi-static strength and fatigue resistance of bonded composite double lap joints," *The Journal of Adhesion*, vol. 75, no. 1, pp. 61–88, 2001.

[180] I. A. Ashcroft, M. M. A. Wahab, A. D. Crocombe, D. J. Hughes, and S. J. Shaw, "The effect of environment on the fatigue of bonded composite joints. Part 1: testing and fractography," *Composites A*, vol. 32, no. 1, pp. 45–58, 2001.

[181] H. Aglan, T. Rowell, T. Ahmed, and R. Thomas, "Durability assessment of composite repairs bonded to aircraft structures," *Journal of Adhesion Science and Technology*, vol. 13, no. 1, pp. 127–148, 1999.

[182] J. A. Harris and P. A. Fay, "Fatigue life evaluation of structural adhesives for automative applications," *International Journal of Adhesion and Adhesives*, vol. 12, no. 1, pp. 9–18, 1992.

[183] P. R. Underhill, A. N. Rider, and D. L. Duquesnay, "The effect of warm water surface treatments on the fatigue life in shear of aluminum joints," *International Journal of Adhesion and Adhesives*, vol. 26, no. 4, pp. 199–205, 2006.

[184] M. L. Abel, A. N. N. Adams, A. J. Kinloch, S. J. Shaw, and J. F. Watts, "The effects of surface pretreatment on the cyclic-fatigue characteristics of bonded aluminium-alloy joints," *International Journal of Adhesion and Adhesives*, vol. 26, no. 1-2, pp. 50–61, 2006.

[185] P. R. Underhill and D. L. Duquesnay, "The dependence of the fatigue life of adhesive joints on surface preparation," *International Journal of Adhesion and Adhesives*, vol. 26, no. 1-2, pp. 62–66, 2006.

[186] M. W. Rushforth, P. Bowen, E. McAlpine, X. Zhou, and G. E. Thompson, "The effect of surface pretreatment and moisture on the fatigue performance of adhesively-bonded aluminium," *Journal of Materials Processing Technology*, vol. 153-154, no. 1–3, pp. 359–365, 2004.

[187] H. Hadavinia, A. J. Kinloch, M. S. G. Little, and A. C. Taylor, "The prediction of crack growth in bonded joints under cyclic-fatigue loading I. Experimental studies," *International Journal of Adhesion and Adhesives*, vol. 23, no. 6, pp. 449–461, 2003.

[188] H. Hadavinia, A. J. Kinloch, M. S. G. Little, and A. C. Taylor, "The prediction of crack growth in bonded joints under cyclic-fatigue loading II. Analytical and finite element studies," *International Journal of Adhesion and Adhesives*, vol. 23, no. 6, pp. 463–471, 2003.

[189] G. C. Mays and A. E. Vardy, "Fatigue performance and durability of epoxy resin bonded metal lap joints," in *Proceedings of the International Conference on Fatigue in Polymers*, London, UK, June 1983.

[190] P. Portillo, J. Kreiner, and T. Lancey, "Torsional fatigue behavior of adhesively joined tubes," *Journal of Materials Processing Technology*, vol. 191, no. 1–3, pp. 339–341, 2007.

[191] N. Tomioka and M. Kakiage, "Evaluation of fatigue strength of adhesive bonded box section beams," in *Advances in Fracture Research*, vol. 1–6, pp. 1717–1724, 1997.

[192] J. W. Kwon and D. G. Lee, "The effects of surface roughness and bond thickness on the fatigue life of adhesively bonded tubular single lap joints," *Journal of Adhesion Science and Technology*, vol. 14, no. 8, pp. 1085–1102, 2000.

[193] H. Nayeb-Hashemi, J. N. Rossettos, and A. P. Melo, "Multiaxial fatigue life evaluation of tubular adhesively bonded joints," *International Journal of Adhesion and Adhesives*, vol. 17, no. 1, pp. 55–63, 1997.

[194] V. Prakash, C. M. Chen, A. Engelhard, and G. Powell, "Torsional fatigue test for adhesive bonded butt joints," *Journal of Testing and Evaluation*, vol. 23, no. 3, pp. 228–230, 1995.

[195] S. Hurme, A. Oinonen, and G. Marquis, "Fatigue of bonded steel interfaces under cyclic shear loading and static normal stress," *Engineering Fracture Mechanics*, vol. 78, no. 8, pp. 1644–1656, 2011.

[196] C.-T. Hoang-Ngoc and E. Paroissien, "Simulation of single-lap bonded and hybrid (bolted/bonded) joints with flexible adhesive," *International Journal of Adhesion and Adhesives*, vol. 30, no. 3, pp. 117–129, 2010.

[197] G. Kelly, "Quasi-static strength and fatigue life of hybrid (bonded/bolted) composite single-lap joints," *Composite Structures*, vol. 72, no. 1, pp. 119–129, 2006.

[198] S. Sam and M. Shome, "Static and fatigue performance of weld bonded dual phase steel sheets," *Science and Technology of Welding & Joining*, vol. 15, no. 3, pp. 242–247, 2010.

[199] V. M. Gonçalves and P. A. F. Martins, "Static and fatigue performance of weld-bonded stainless steel joints," *Materials and Manufacturing Processes*, vol. 21, no. 8, pp. 774–778, 2006.

[200] P. K. Ghosh and M. Balaram, "Improvement in spot weld properties of steel sheet by weldbonding using particulate composite adhesive," *Transactions of the Indian Institute of Metals*, vol. 58, no. 1, pp. 115–131, 2005.

[201] P. K. Ghosh and Vivek, "Weldbonding of stainless steel," *ISIJ International*, vol. 43, no. 1, pp. 85–94, 2003.

[202] B. H. Chang, Y. W. Shi, and L. Q. Lu, "Studies on the stress distribution and fatigue behavior of weld-bonded lap shear joints," *Journal of Materials Processing Technology*, vol. 108, no. 3, pp. 307–313, 2001.

[203] M. Ring-Groth, C. Magnusson, and J. Powell, "The fatigue properties of weldbonded stainless steel joints," *Journal of Advanced Materials*, vol. 32, no. 1, pp. 21–27, 2000.

[204] D. Hejcman, J. F. Knott, P. Bowen, and C. L. Davis, "Fatigue of welded and adhesively bonded aluminium alloys for use in automotive applications," in *Proceedings of the 11th Biennial European Conference on Fracture—Mechanisms and Mechanics of Damage and Failure (ECF '11)*, vol. 3, pp. 1665–1670, September 1996.

[205] P. C. Wang, S. K. Chisholm, G. Banas, and F. V. Lawrence, "The role of failure mode, resistance spot weld and adhesive on the fatigue behavior of weld/bonded aluminum," *Welding Journal*, vol. 74, no. 2, pp. S41–S47, 1995.

[206] M. D. Gilchrist and R. A. Smith, "Fatigue and fracture of adhesively bonded and welded/bonded T-peel joints," Fracture Mechanics: 25Th Volume, American Society for Testing and Materials Special Technical Publication, 1220, pp. 222–238, 1995.

[207] M. D. Gilchrist and R. A. Smith, "Fatigue growth of cohesive defects in T-peel joints," *The Journal of Adhesion*, vol. 42, no. 3, pp. 179–190, 1993.

[208] M. D. Gilchrist and R. A. Smith, "Development of cohesive fatigue cracks in T-peel joints," *International Journal of Adhesion and Adhesives*, vol. 13, no. 1, pp. 53–57, 1993.

[209] K. R. Wentz and H. F. Wolfe, "Development of random fatigue data for adhesively bonded and weld/bonded structures subjected to dynamic excitation," *Journal of Engineering Materials and Technology*, vol. 100, no. 1, pp. 70–76, 1978.

[210] M. E. Somervuori, M. T. Alenius, T. Kosonen, R. Karppi, and H. E. Hänninen, "Corrosion fatigue of weld-bonded austenitic stainless steels in 3.5% NaCl solution," *Materials and Corrosion*, vol. 57, no. 7, pp. 562–567, 2006.

[211] P. C. Wang, P. Mabery, and C. K. Chisholm, "Degradation of fatigue properties of welded/bonded aluminum exposed to moisture and elevated-temperature," *The Journal of Adhesion* , vol. 43, no. 1-2, pp. 121–137, 1993.

[212] G. di Franco, L. Fratini, and A. Pasta, "Fatigue strength of a single lap joint SPR-bonded," in *Proceedings of the 14th*

*International ESAFORM Conference on Material Forming (ESAFORM '11)*, vol. 1353 of *AIP Conference Proceedings*, pp. 1265–1271, May 2011.

[213] F. Moroni, A. Pirondi, and F. Kleiner, "Experimental analysis and comparison of the strength of simple and hybrid structural joints," *International Journal of Adhesion and Adhesives*, vol. 30, no. 5, pp. 367–379, 2010.

[214] A. Kwakernaak and J. C. J. Hofsiede, "Adhesive bonding: providing improved fatigue resistance and damage tolerance at lower costs," *SAMPE Journal*, vol. 44, no. 5, pp. 6–15, 2008.

[215] M. Imanaka, K. Haraga, and T. Nishikawa, "Fatigue-strength of adhesive rivet combined lap joints," *The Journal of Adhesion* , vol. 49, no. 3-4, pp. 197–209, 1995.

[216] D. Croccolo, M. de Agostinis, and N. Vincenzi, "Experimental analysis of static and fatigue strength properties in press-fitted and adhesively bonded steel-aluminium components," *Journal of Adhesion Science and Technology*, vol. 25, no. 18, pp. 2521–2538, 2011.

[217] D. Croccolo, M. de Agostinis, and N. Vincenzi, "How to improve static and fatigue strength in press-fitted joints using anaerobic adhesive," *Proceedings of the Institution of Mechanical Engineers C*, vol. 225, no. 12, pp. 2792–2803, 2011.

[218] D. Croccolo, M. de Agostinis, and N. Vincenzi, "Static and dynamic strength evaluation of interference fit and adhesively bonded cylindrical joints," *International Journal of Adhesion and Adhesives*, vol. 30, no. 5, pp. 359–366, 2010.

[219] E. Dragoni, "Fatigue testing of taper press fits bonded with anaerobic adhesives," *The Journal of Adhesion*, vol. 79, no. 8-9, pp. 729–747, 2003.

[220] Z. Liu and D. Ho Bae, "A study on joining technology of aluminum alloy sheet using nano-adhesives," *International Journal of Modern Physics B*, vol. 25, no. 31, pp. 4265–4268, 2011.

[221] A. Dorigato and A. Pegoretti, "The role of alumina nanoparticles in epoxy adhesives," *Journal of Nanoparticle Research*, vol. 13, no. 6, pp. 2429–2441, 2011.

[222] S. Ho Yoon and D. Gil Lee, "In situ crack propagation monitoring in tubular adhesive joints containing quartz nano-particles," *Journal of Adhesion Science and Technology*, vol. 25, no. 16, pp. 1973–1985, 2011.

[223] S. Bhowmik, R. Benedictus, J. A. Poulis, H. W. Bonin, and V. T. Bui, "High-performance nanoadhesive bonding of space-durable polymer and its performance under space environments," *Journal of Spacecraft and Rockets*, vol. 46, no. 1, pp. 218–224, 2009.