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EFFECTS OF DEFECTS ON COMPOSITE STRUCTURES LOAD CARRYING CAPACITY: DELAMINATION AT BI-MATERIAL INTERFACES

VLIV VAD NA ÚNOSNOST KOMPOZITNÍCH KONSTRUKCÍ: DELAMINACE NA ROZHRANNÍ DVOU MATERIÁLŮ

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1 Introduction

Understanding how materials fail is essential for designing safer and more reliable structures. Many failure theories have been developed in the past for homogeneous materials with various level of success. The advances of new composite materials during the last several decades has brought many advantages but also many challenges for the engineers. The non-homogeneous and complex structure of composite materials leads into many more failure modes, both on microscopic and macroscopic scale. The number of constituent materials and their possible arrangements makes it almost impossible to define a unified failure theory.

Manufacturing process of composite components may result in the presence or introduction of unwanted defects such as voids, resin-rich areas, and inclusions. Although many of these so called defects may be difficult to detect, their effects on the overall structural integrity may be very dangerous. Damage and general material degradation can also occur during the in-service operation of composite components. Typical causes of such damage are continuous cyclic loading, rapid changes in local temperature, and impact loading. Often, damage develops over a period of months or years, and is not immediately visible to even the trained eye. However, once the size of defect or stress-raiser reaches a critical value, failure can be catastrophic and consequences severe. Clearly, there is a strong need to identify the various types of damage and defects that occur in composite materials during manufacture and operational service and assess their effects on the performance and safety of the structure.

One of the most commonly observed failure modes in composite materials is delamination and debonding. Fracture mechanics is a useful tool for approaching composite delamination and debonding, due to the crack-like type of discontinuity accompanying these defects. The harmful effects of delamination and debonding have made these defects the subject of particularly extensive research. This includes extension of the fundamental principles of fracture mechanics to include anisotropy typically present in composite materials, development of standard test procedures for delamination resistance testing, and including numerical computational methods into FE codes.

Delamination at bi-material interfaces needs to be investigated with special attention. A stress-singularity is present at the vertex of the bi-material interface due to mismatch in elastic parameters. Also state-of-art of the standardised test methods for delamination resistance doesn't include the effect of crack propagating between two dissimilar materials. In reality the delamination occurrence is highly probable at the interface of two different materials; therefore the analysis and testing methods must be established to include these facts.

This thesis is divided into two main parts. First part, the literature review, gives an overview of typical failure mechanisms in composite materials and describes mathematical theories of failure. Delaminations are described in more detail together with basic fracture mechanics principles and their application in the analysis and experimental testing of composite materials. Next, main type of defects that may occur in a composite structure and the possible effects of defects on the structural performance and material strength are discussed. First part of the thesis is concluded with a summary of composite materials testing methods. Special attention is given to a delamination and fracture toughness testing.

Second part of the thesis describes the author's experimental work on the delamination at bi-material interfaces. The test methods and analysis are adopted from fracture toughness testing of composite materials and extended to account for materials with different moduli in the beam test specimen. New method of measuring crack length by digital image processing is described and alternative method of crack growth initiation proposed. Also, the limitations of using mixed mode delamination criteria are highlighted.

2 Literature review

2.1 Composite materials

In a broad sense, composite material is a material made from two or more constituent materials, which include steel reinforced concrete, ceramic composites, metal and plastic composites. In a more narrow sense, the term composite materials is often used for fibre reinforced plastic materials, as is the case throughout this thesis. In fibre reinforced plastic, usually some sort of reinforcing fibre with high strength and stiffness is combined with plastic matrix, which provides continuous bonding between the fibres.

2.2 Failure of laminated composites

There is no clear definition of what 'failure' in composite laminates actually means. In general, a structure is considered as failed, when it ceases to fulfil its function. For example, someone designing a composite pipe might consider a liquid leaking through the pipe wall as a failure, for others it might be a certain loss of stiffness or even total structural disintegration. So, from this point of view, it is a clearly a matter of purpose how the failure is understood and it is likely to be different for various applications.

Certainly, the failure of composite materials is a complex process, consisting mainly of matrix cracking, interface deboning, fibre breakage and interaction of these. The evolution of the damage depends on many factors such as orientation of the fibres, matrix content, general state of stress in the material and other environmental effects.

2.3 Failure theories

The mechanical behaviour of monolithic materials (metals, ceramics and polymers) had been a fairly mature field when in the early 1960s composite materials such as glass/polyester and carbon/epoxy began emerging as promising materials of the future. It was natural for the scientific community then to apply and extend concepts and analyses developed for the monolithic materials to composites. In the decades that followed, great success was achieved in micromechanics estimates of effective elastic properties, homogenization, laminate plate theory, etc. However, theories for treating failure of composite materials did not succeed to the same extent. In fact after numerous efforts extending over approximately five decades many uncertainties and controversies still remain in predicting composite failure.[1]

2.3.1 Lamina failure

The most common lamina failure theories are developed phenomenologically and are to some extent a generalization from corresponding failure theories of isotropic materials. In general, these theories are directly applied to the stress components of the composite laminae, but in their local (or material) coordinate system. Usually they are defined for a thin orthotropic lamina in a plane stress condition. Lamina failure criteria can be categorized into three main groups:

- Limit criteria - these criteria predict failure only by comparing lamina stresses with corresponding strengths. The interaction between stresses is not considered. Among these criteria belong Maximum stress criterion and Maximum strain criterion.

- Interactive criteria - these criteria predict the failure load by using a single polynomial equation involving all stress (or strain) components. Many such criteria were proposed. The most notable are: Tsai-Hill [2, 3] and Tsai-Wu [4] criterion
- Separate mode criteria - there is a separate failure criterion for different failure modes, with accounting for some interaction between them. Most used criteria from this group are Hashin failure criterion [5] and Puck failure criterion [6]

2.3.2 Delamination

There are three types of loading that crack can experience. Mode I loading, where the principal load is applied normal to the crack plane. Mode II corresponds to in-plane shear loading. Mode III refers to out-of-plane shear. The most usual fracture mode to be considered is the opening mode I which results from stresses normal to crack. In homogeneous isotropic materials, even if other type of loading is present, a propagating crack seeks the path of least resistance and need not be confined to its initial plane, so the crack usually kinks and propagates under mode I conditions. However, this is not a case for material interfaces, where mode II, mode III and their combination with mode I are more important.

The growth of a crack between two solids with different elastic behaviour is a difficult problem to deal with. Using the linear elasticity theory, the obtained results show unusual complex singularities in the neighbourhood of the crack tip. In addition, the three stress intensity factors at the crack tip, K_I,K_{II} and K_{III}, are coupled to each other and achieve complex values. Although the many proposals to avoid the stress singularity at the crack tip, the stress intensity factor is governed by the local crack-tip field and is extremely sensitive. Thus, most of the studies about composite delaminations are based on the critical energy release rate, G_c, instead of the critical stress intensity factor K_c, to predict the onset of interlaminar cracks. [7]

To fully understand this failure mechanism, the total strain energy release rate, G_T, the mode I, G_I, the mode II component, G_{II}, and the mode III component, G_{III}, need to be calculated. In order to accurately predict delamination onset or growth for two dimensional problems, these calculated Gcomponents are compared to interlaminar fracture toughness properties experimentally measured over a range from pure mode I loading to pure mode II loading. [7] There are many forms of delamination onset criteria. The one used by Benzeggagh and Kenanane [8] determines the quasi-static mixed-mode fracture criterion by plotting the interlaminar fracture toughness, G_c , versus the mixed-mode ratio, G_{II}/G_T . Failure is expected when the calculated total energy release rate, G_T, exceeds the interlaminar fracture toughness, G_c. Mathematically, this criterion can be expressed

$$G_{Tc} = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^m \tag{2.1}$$

Another frequently used mixed mode failure criterion is the power law described by Wu [9] and has a form

$$\left(\frac{G_I}{G_{Ic}} \right)^\alpha + \left(\frac{G_{II}}{G_{IIc}} \right)^\beta = 1 \tag{2.2}$$

2.4 Defects in composite materials

2.4.1 Types of defects

Defects in composite materials can be grouped into specific categories according to when they arise during their life, their relative size, their location or origin within the structure:

1. Defect occurrence - defects may occur during different stages of the component life:
   (a) Manufacturing process
      i. Materials processing - the processes of advanced composite manufacture are predisposed to errors, especially human errors, that can lead to the formation of defects in structure. Such material processing defects occur because of improper storage of materials, or inadequate quality control and batch certification procedures. Both can lead to material property variations and in some cases can lower the properties below the design allowables.
      ii. Component Manufacture - component manufacture induced defects occur during either lay-up or cure (component fabrication), or machining and assembly of the components.

   (b) In-Service Use - during service, composite structures are prone to many mechanical and environmental conditions such as impact and handling damage, local overloading, local heating, chemical attack, ultraviolet radiation, battle damage, lightning strikes, acoustic vibration, fatigue or inappropriate repair action.

2. Defect size - the size of a defect has significant bearing on its criticality. Therefore, defects are listed under two sizes:
   (a) Microscopic - these defects occur at the level of micromechanics of composites, i.e. at the level of the individual constituents.
   (b) Macroscopic - macroscopic defects can be found at the level of individual plies or the whole structure.

3. Defect location - defects may be present in isolation, originating from structural features such as cut-outs, ply drops and joints, or a random accumulation resulting from their interaction. However, they tend to concentrate at discontinuities, either geometrical or material.

The most common defects occurring in composite material, either in manufacturing process or during service, are: delamination, disbond, ...

2.4.2 Effects of defects in composites

In general, all types of defects, both manufacturing and in-service, might affect stiffness, strength, stability and fatigue life of the composite structure mainly because they act as the stress concentrators and failure initiation points. Profound understanding of how these defects influence the performance of composites is essential for making the structures safer, more durable, and economic. Because of the wide range of possible defects and many failure mechanisms occurring in composite materials, the studies on effects of defects are usually performed separately for particular defects. The most common types of defects investigated by various researchers include ply waviness, porosity, impact damage and delaminations.

2.5 Composite materials testing and characterization

Composites properties can are very complex and depend on fibres, matrix, layup, volume fraction, environmental conditions, manufacturing methods, cure conditions, etc. Thus, mechanical testing methods and requirements are more demanding than is the case for metals. Mechanical testing is mainly for establishing the design allowables, qualification of materials for certain application and quality control. Many of the testing methods have their origin in testing of metals and other homogeneous isotropic materials. However, when a testing method of isotropic materials is adapted for composites, special attention is needed because of the composites anisotropic nature.

2.5.1 Building block approach

A common approach used in development of aircrafts but also adopted by many other industries is so called 'Building Block Approach'. The Building Block Approach is frequently referred to as the Testing Pyramid. On the first two levels, large number of coupons and structural elements are tested in different loading modes, such as tension, compression, flexure and shear in order to generate material design allowables under static and fatigue conditions. Then, a combination of testing and analysis is used at various levels of complexity through structural elements and details, sub-components, components and finally full scale product. Each level builds on knowledge gained at previous, less complex levels.

The multiplicity of potential failure modes is perhaps the main reason that the Building Block approach is essential in the development of composite structures. The many failure modes in composites are mainly due to the defect, environmental and out-of-plane sensitivities of the materials. It is important to carefully select the correct test specimens that will simulate the desired failure modes. Special attention should be given to matrix sensitive failure modes [10].

2.5.2 Delamination testing

Resistance to interlaminar fracture is a major interest for safe application of composites. This concern is also related to bonded composite joints, as the two phenomena are very closely relate. Several methods for measuring interlaminar fracture toughness have been developed. Davies et al. [11] give a basic overview of the test methods, which have been more recently reviewed by Brunner et al [12]. Several standards exist for mode I, mode II and mixed mode loading scenarios. Some of these methods have been standardised either by ISO [13, 14], or ASTM [15, 16, 17].

Mode I

Double Cantilever Beam (DCB) specimen is the most widely used mode I specimen type. Figure 2.1 illustrates The DCB specimen geometry. The opening load is produced by a test machine cross-head displacement at constant speed.

The load, P, cross-head displacement (i.e. crack opening), δ, and delamination length, a, are recorded continuously during the test. The delamination length is determined as the distance from the loading line to the front of delamination. Delamination lengths are determined visually during the test, the use of a travelling microscope for more accurate delamination length readings is optional, but recommended. Fracture toughness values, G_{Ic}, are then calculated either by using the beam theory or compliance calibration methods.

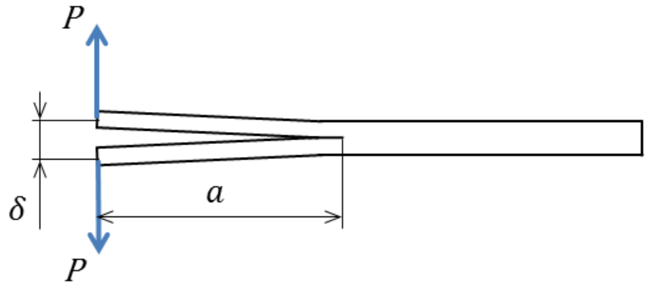

Figure 2.1: Delamination length definition

The basis of all methods of data analysis is equation (2.3) that relates the energy release rate G_C with the change in compliance due to a change in delamination length. The data analysis methods all use different approaches to evaluate dC/da.

$$G_C = \frac{P^2}{2b}\left(\frac{dC}{da}\right) \tag{2.3}$$

One of the methods is 'simple bean theory' which leads to following equation for energy release rate

$$G_{IC} = \frac{3P\delta}{2ba} \tag{2.4}$$

The crack length a must be usually adjusted by a correction factor ?. Fracture toughness calculated by the 'modified beam theory' is then

$$G_{IC} = \frac{3P\delta}{2b\,(a + |\Delta|\,)} \tag{2.5}$$

The 'compliance calibration' method is based on assumption of a certain type of functional dependence of the compliance on the delamination length. For DCB it is assumed that the compliance is proportional to a^n in the form of equation (2.6)

$$C = Ka^n \tag{2.6}$$

After derivation and substitution into equation (2.3), the final equation used in compliance calibration data reduction method is

$$G_{IC} = \frac{nP\delta}{2ba} \tag{2.7}$$

The experimental parameter, n, can be determined as a slope of the line fitted to the $log\,(C) - log\,(a)$.

The definition of when the crack starts to grow is not straightforward and several methods are used to determine initiation values of fracture toughness. The ASTM standard [15] defines three main points of interest: (a) deviation from nonlinearity, (b) visual observation and (c) 5% offset or maximum load.

The lowest most conservative values are obtained by deviation from linearity (NL) point in the load-displacement plot as shown in Figure 2.2. However, in reality it is often very difficult to establish such a point and this definition itself allows for some variability. Additionally, nonlinear behaviour may occur due to other reasons, such as material yielding at the crack tip or local crack growth. Less scatter can be obtained by 5% offset method, where the initiation point is determined as an intersection of the load-displacement curve with a line drawn from origin and offset by a 5% increase in compliance from original linear region of the load-displacement curve. If the intersection occurs after the maximum load point, the maximum load should be used to calculate this value. The visual observation point is the point where the crack is observed visually. However, even this method can lead to large scatter in results because it is very much dependent on the operator's eyesight and judgement.

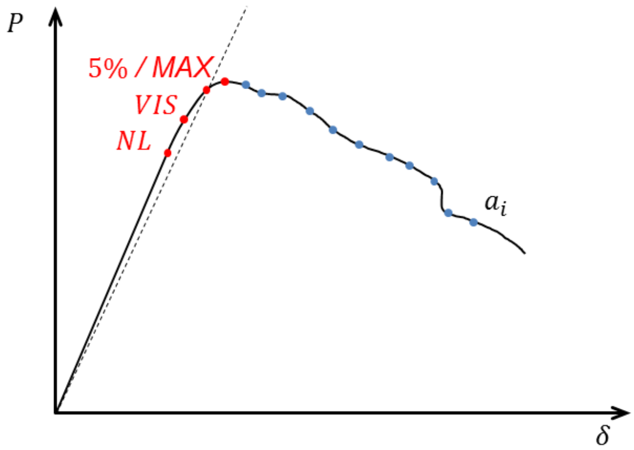

Figure 2.2: Initiation point definition

Mode II

The specimen geometry for testing delamination fracture toughness in mode II is usually the same as in the DCB configuration. There are several loading configuration proposed, three of them can be seen on Figure 2.3. Currently, two standard methods are: ASTM D7905 [17], which uses end notch flexure specimen (ENF); and ISO 15114 [14] which is based on the end load split specimen (ELS). Other methods include stabilized end notched flexure [18] and four point end notch flexure [19].

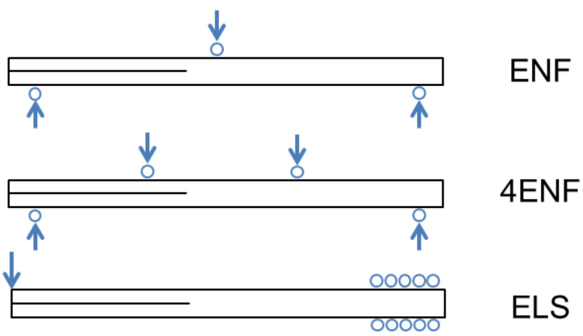

Figure 2.3: Mode II specimens

In ELS configuration, the specimen is clamped at one end and load is applied at the other end by loading blocks or piano hinge, similarly to the DCB test. This method offers more stable crack growth compared to the ENF and also the friction effects appear to be less significant [14]. The crack lengths can be calculated experimentally without complicated and not very reliable optical measurements. The methods for determining the fracture toughness are: simple beam theory, experimental compliance calibration and corrected beam theory.

Mixed mode

Mixed loading conditions can be achieved by unequal tensile loading of the upper and lower portions of the specimen. Common configurations are MMB (mixed mode bending), MMF (mixed mode flexure), CLS (crack lap shear) and ADCB (asymmetric DCB). Figure 2.4 shows schematically these configurations.

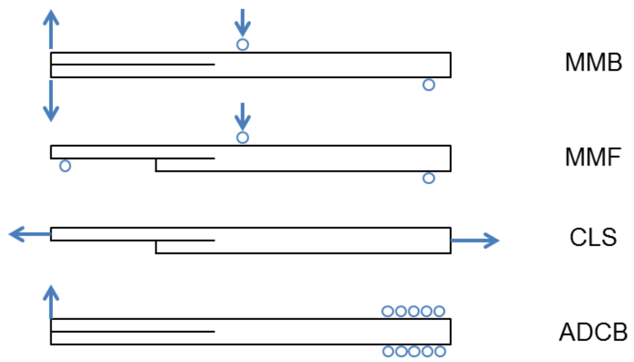

Figure 2.4: Mixed mode loading configurations

Mixed mode bending (MMB) configuration allows for many different mode ratios to be tested and has been widely used and ASTM standard exists [16].One of the rare criticisms of the MMB test has been the cost of relatively complicated fixture. On the other hand, a great advantage of this method is that the length of the lever arm can be changed and wide range of mixed mode ratios tested with one specimen configuration.

Fixed ratio mixed mode ADCB has only limited mixed mode ratio of 4:3 of mode I to mode II component, but the same fixture as for mode II ELS configuration can be used. The test procedure and data analysis are essentially similar ELS, except that the load is applied in the opposite direction, where one arm of the cantilever beam is lifted up at the free edge, which causes crack to propagate in combination of opening and shearing mode.

2.6 FEA methods for delamination analysis

The virtual crack closure technique [20] is widely used for computing energy release rates based on results from continuum two-dimensional and solid three-dimensional finite element analyses. Another method for analysing delaminations by finite element method is cohesive zone approach, which is based on a traction-separation description of the interface element or a contact formulation.

2.7 Summary

Defects in composite materials can have a significant effect on the structural strength and load-carrying capacity. Moreover, the composite materials have very complex failure behaviour and the presence of defects certainly makes the analysis of failure even more complicated. The material testing is an essential tool in understanding the failure mechanisms and in developing material allowables to be used in analytical calculations and design methods.

The composite material failure theories have been reviewed together with the defects types that can occur in composite material either during the manufacture or during the service life. The review of the testing methods has focused on the fracture toughness testing of delaminations which is one of the most commonly discussed types of defects in composite materials and which has attracted a huge attention within the scientific community in recent years.

3 Thesis aims and objectives

3.1 Delmination at a bi-material interface

Very few studies were done so far, which would include the effect of delamination between two dissimilar materials. In real life constructions made of composite materials, for example small aircrafts, the combination of glass and carbon reinforced plastics is a common design practice. This enables the utilization of carbon composite materials superior mechanical properties and glass composites lower cost. This approach is very effective; however the interface between two materials may cause the delamination initiation. Fatigue and static experiments of small aircraft wing root section conducted in the past at the Institute of Aerospace Engineering, Brno University of Technology, confirms this dangerous effect.

Methods for analysing delamination in composites are well established and widely used as described in Chapter 2.3.2. However, delaminations at bi-material interface needs to be investigated with special attention because of a stress singularity due to mismatch in elastic parameters. Also state-of-art of the standardised test methods for delamination resistance doesn't include the effect of crack propagating between two dissimilar materials. In reality the delamination occurrence is highly probable at the interface of two different materials; therefore the analysis and testing methods must be established to include these facts.

Test methods presented in 2.5.2 were developed and used extensively to measure fracture toughness in unidirectional fibre composites and the data reduction methods and beam theory equations are only based on single material elastic modulus. If these methods are to be applied to specimens with different elastic moduli in cantilever specimen arms, fracture toughness calculation methods need to be reviewed and modified to account for different elastic moduli.

A common problem in composite materials fracture testing is the accurate crack length measurement. The crack length is needed to calculate propagation values and R-curve, but can also be used for calculating initiation values by compliance calibration methods. Current standard procedures recommend optical measurements with optional use of travelling microscope, which is a test operator dependent method prone to a human error. With modern high resolution digital cameras and computer programming this method can be automated.

3.2 Research aims

With respect to the previous findings, the thesis has following aims:

1. Investigate the influence of different material characteristics on delamination fracture toughness

2. Examine the analytical methods used to calculating fracture toughness in different mixed mode conditions

3. Develop a mixed mode failure criteria that can be used for delaminations at bi-material interface.

4. Automate crack length measurement methods.

3.3 Objectives

Objectives to achieve the aims above can be split into two main categories:

1. Experimental investigation

   (a) Perform a series of fracture toughness measurements at a bi-material interface of a glass-carbon composite in DCB, ADCB and ELS test configuration as shown in Figure 3.1
   (b) Record each test with a high resolution digital camera
   (c) Create a computer program to process the acquired images and automate the crack length measurement

2. Analytical investigation

   (a) Modify the analytical methods used to calculate fracture toughness from experimentally measured data (data reduction methods) in order to account for two different material in the specimen arms and non-centrally positioned crack
   (b) Calculate a ratio of mode I and mode II in each configuration tested in the experimental investigation
   (c) Apply new equations to the data obtained in experimental investigation and construct a mixed mode delamination failure envelope

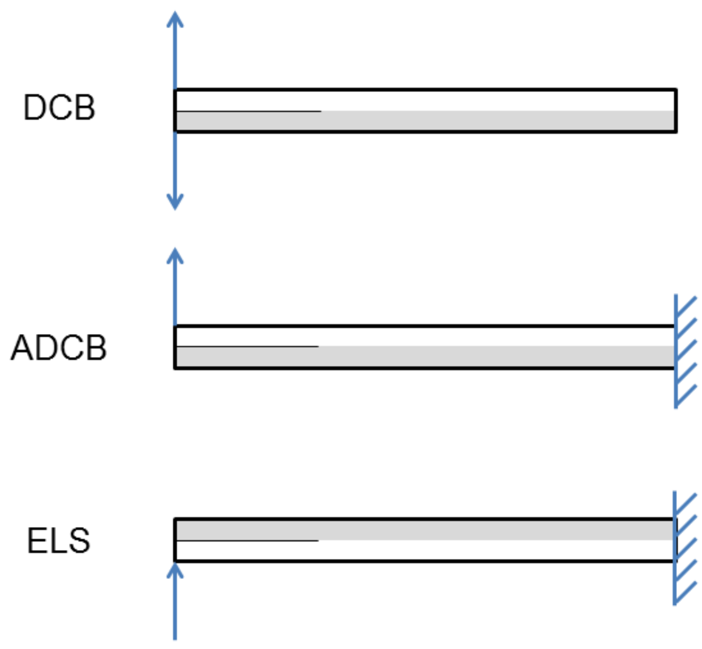

Figure 3.1: Test configurations

4 Experimental investigation

4.1 Specimen description and test setup

The same specimen base geometry and manufacturing method were used for the three delamination test configuration; DCB, ADCB and ELS. The specimen geometry is shown in Figure 4.1. During the manufacture, several already cured CFRP stripes were placed on a wet layup sheet of glass fabric impregnated by epoxy resin. Then, both components were cured under vacuum. The excess amount of GFRP was cut out after the curing. This manufacturing process was chosen to simulate a technique of manufacturing a wing root section with CFRP flange and GFRP web, where epoxy impregnated wet glass fabric is wrapped around already cured unidirectional carbon flange.

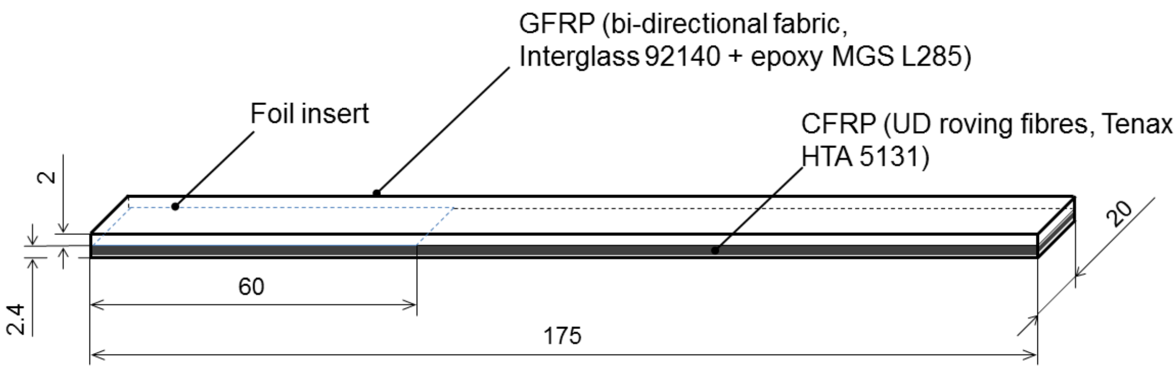

Figure 4.1: Specimen dimensions

Then piano hinges for load application were bonded to the specimens' ends on the side of the foil insert. One hinge was applied to the GFRP side for ADCB and ELS tests. For DCB configuration, hinges were applied both on GFRP and CFRP sides. Because of the bonding area of the hinges, the load application point is moved by approximately 26 mm from the specimen edge. And after considering also the slightly variable alignment of the bond, the resulting length of the starting delamination defect is between 33 and 36 mm.

For DCB test, only universal testing machine with constant displacement load rate is needed. Specimen arms are pulled apart through the hinges that are connected directly to the machine crosshead attachments. ELS test requires a special fixture which allows sliding in horizontal direction.

4.2 Automated crack length measurement

Delamination lengths are usually determined visually with the aid of travelling optical microscope during the test. Major drawback of this method is the dependence on alertness and experience of the operator. Alternative approach is to record the test procedure on a high resolution camera and analyse the taken pictures by the means of automated image processing after the test. This method is very similar to the conventional measurement by optical travelling microscope, but takes of the work load from test operator and also eliminates human error. Possible advantage can also be an application not only for quasi-static testing but also for fatigue crack length measurement or high-rate delamination testing.

A new method for automated crack length measurement by image processing has been developed by the author and applied for the DCB and ADCB test of bi-material interface. Despite the very specific application here, the method is general and can be easily applied in mode I and mixed mode testing of single unidirectional composite materials. Image processing for mode II ELS test didn't prove to be practical and no satisfactory results were obtained, because of the lack of clear opening between the specimen arms. However, accurate crack length measurements in ELS test are not so important, because other preferred methods of calculating the energy release rate are available, such as corrected beam theory with effective crack length [14].

4.2.1 Image acquisition

Image acquisition is the essential step preceding any further processing and analysis. Electromagnetic, X-ray or ultrasonic sensing devices have a wide field of application; however the most used and available are light sensing devices. CCD camera with a resolution 4096x3072 from system for digital image correlation Aramis 12M, made by GOM mbH, was used for the image acquisition. Digital image correlation (DIC) is a common method in experimental mechanics for measuring surface displacements. A typical DIC system is shown in Figure 4.2.

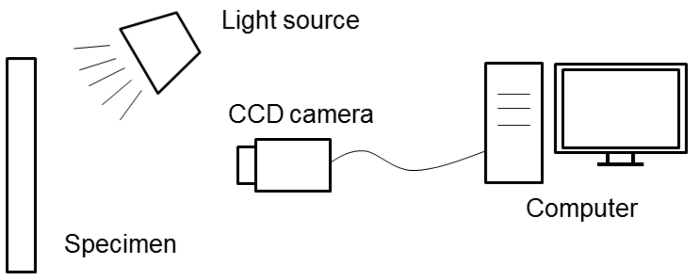

Figure 4.2: DIC system setup

In this method, a sequence of images of a studied object is compared to detect displacements by searching a matched point from one image to another. In order to perform this process, the surface of the object must have a feature that allows matching the subset. If no feature is observed on the surface of the object, an artificial random pattern must be applied. The spray pattern is very important in the typical DIC system, where measuring displacements on the surface is the main goal. On the other hand, when accurate tracking of a crack tip position is the objective, the dark spray pattern can be disadvantageous because there is no clear distinction whether the dark pixel represents a crack or a spray drop. Clear white contrast paint has proved to be more useful for the purpose of measuring the delamination length. Better contrast and also image quality is assured by high intensity lighting. Usually, more light sources are required to get consistent light reflection over the observed area with minimum shadows.

4.2.2 Image processing

In digital grayscale images, each pixel's light intensity is stored as a number ranging between 0, meaning complete black, and a certain maximum value for complete white. Traditionally, when 8 bits per pixel are used the maximum number for complete white is 255. Another digital image representation is binary, when each pixel has only two possible values, i.e. 0 for black and 1 for white. One method of converting a grayscale image into binary image is called thresholding, where each pixel having a lower intensity than a specified limit is replaced by black pixel and each pixel having higher intensity is replaced by white pixel. A simple example of this process is illustrated in Figure 4.3.

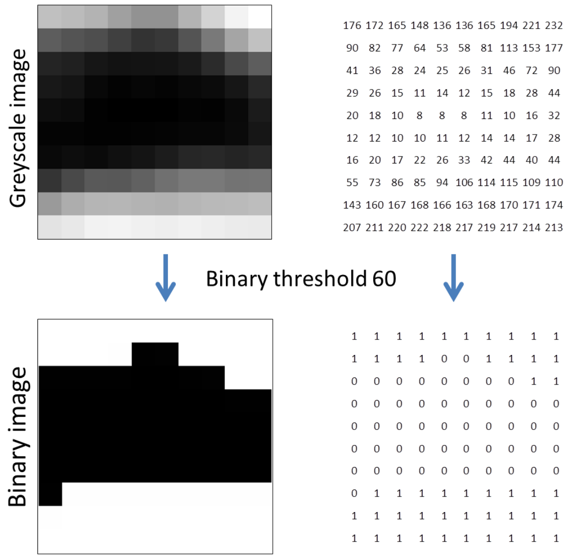

Figure 4.3: Binary thresholding of grayscale image

Binary thresholding is an effective method for analysing images of the crack propagation, because of the clear distinction between dark background and very light specimen front. However, some of the information in the image is lost during the process and care must be taken when selecting the threshold value. Figure **??** shows the effect of different threshold values. In general, lower threshold value leads effectively in shorter cracks being detected and higher threshold values give more accurate representation of the crack geometry. The disadvantage of higher threshold values is that some dark pixels which don't represent the crack geometry are kept in the image and cause a noise, which might lead to false results, when the crack tip searching algorithm is used. Noise can be effectively removed by morphological operations, such as dilation, erosion, opening and closing.

4.2.3 Algorithm to find a crack tip

After the recorded grayscale image of a cracked specimen was processed in the way described above, i.e. binary thresholding and noise reduction by mathematical morphology, only black and white pixels remain with a clear geometry describing the crack tip. Finding a crack tip pixel location presented here is based on moving a probe pixel inside the crack, which consists of black pixels, from left to right. Crack tip is found, when there are no more black pixels in the vicinity of the probe.

The finding of a crack tip position is achieved by moving the pixel probe within an area specified by a tolerance distance in X and Y directions. The probe is moved into a new position if black pixel is found. This tolerance enables the probe to jump over small areas of white pixels, which are usually present around the crack tip due to fibre bridging or crack propagating out of plane.

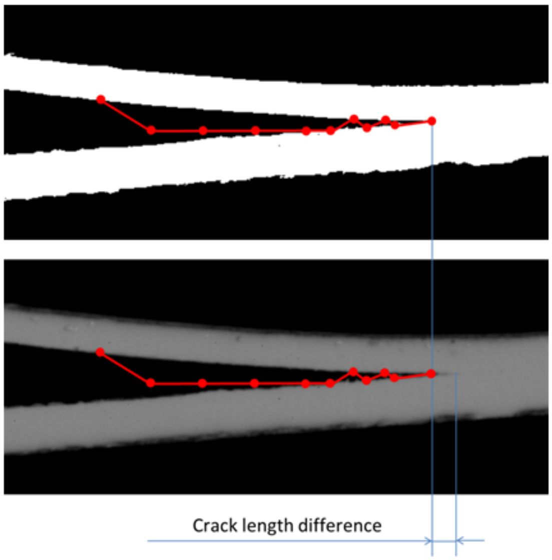

Figure 4.4: Probe path visualisation

The probe path can be visualised by plotting the X and Y coordinates of the probe position superimposed over the image. Figure 4.4 shows this path and comparison between binary thresholded image and original grayscale image. From this comparison it is apparent that the crack length measurements based on binary black and white images can be shorter then in reality and the level of thresholding and subsequent morphology operations can have effect on the scale of this difference. However, when modified beam theory is used as a test data reduction method, this difference is actually accounted for by a crack length correction factor Δ as described in Section 2.5.2 and Equation (2.5). The corrected crack length compares well with the crack length calculated by a simple beam theory for all measured specimens. Figure 4.5 shows results from mode I specimen.

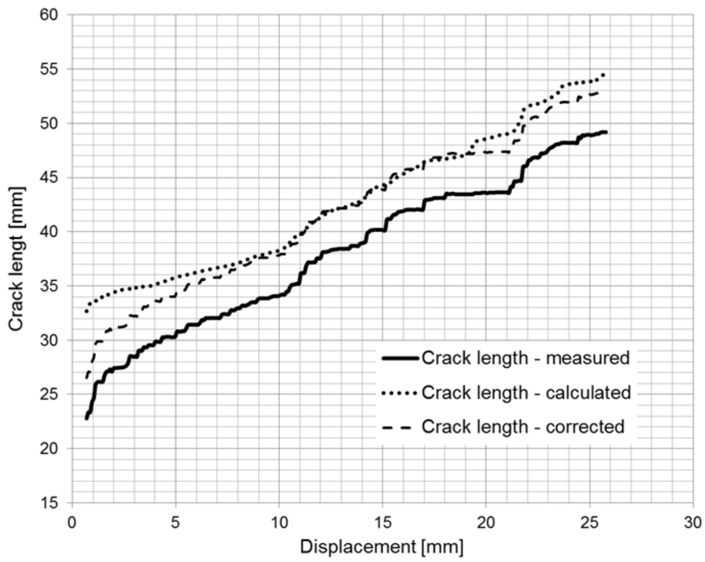

Figure 4.5: Crack length measurements results

5 Analytical investigation

5.1 Beam theory

A general method for calculating the energy release rate G from the local values of bending moments in cracked laminate by Williams [21] can be extended to include different moduli in the two sections. Total energy release rate for the crack growth is

$$G = \frac{1}{2b}\left(\frac{M_1^2}{E_1 I_1} + \frac{M_2^2}{E_2 I_2} - \frac{(M_1 + M_2)^2}{EI}\right) \tag{5.1}$$

DCB

For a DCB specimen with an off-centre delamination and materials with different elastic moduli in upper and lower arms, as shown in Figure 5.1, the moments at the delamination front are

$$M_1 = -Pa \tag{5.2a}$$

$$M_2 = Pa \tag{5.2b}$$

The total energy release rate of the DCB specimen is

$$G_C = \frac{6P^2a^2}{b^2}\left(\frac{1}{h_1^3 E_1} + \frac{1}{h_2^3 E_2}\right) \tag{5.3}$$

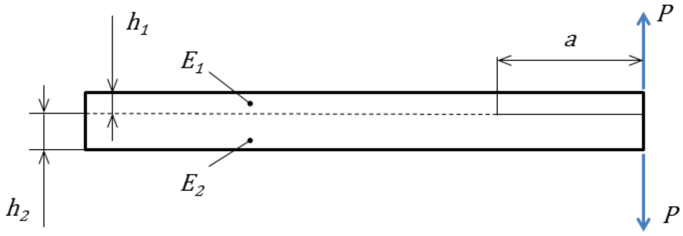

Figure 5.1: DCB specimen

ELS

For an ELS specimen, as shown in Figure 5.2, the total moment, $M = Pa$, will be divided between upper and lower arms in the ratio of their bending stiffness. If we denote the bending stiffness ratio as

$$\psi = \frac{E_2 I_2}{E_1 I_1} = \frac{E_2 h_2^3}{E_1 h_1^3} \tag{5.4}$$

Then the particular moments at the delamination front will be

$$M_1 = \frac{Pa}{1 + \psi} \tag{5.5a}$$

$$M_2 = \frac{\psi Pa}{1 + \psi} \tag{5.5b}$$

After substituting equations (5.5) in (5.1), the energy release rate for ELS specimen is defined as

$$G_C = \frac{18P^2a^2}{b^2}\left[\frac{h_1h_2(h_1+h_2)^2E_1E_2}{(h_2^3E_2+h_1^3E_1)(h_2^4E_2^2+4h_1h_2^3E_1E_2+ \\ +6h_1^2h_2^2E_1E_2+4h_1^3h_2E_1E_2+h_1^4E_1^2)}\right] \tag{5.6}$$

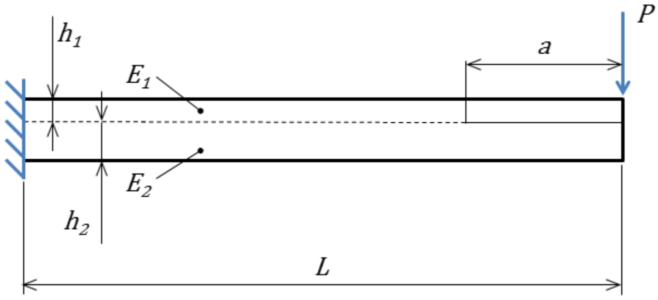

Figure 5.2: ELS specimen

ADCB

In and ADCB specimen (Figure 5.3), the loading force is acting only on one arm. Therefore, the moments at delamination front are

$$M_1 = -Pa \tag{5.7a}$$

$$M_2 = 0 \tag{5.7b}$$

And resulting energy release rate is

$$G_C = \frac{6P^2a^2}{b^2}\left[\frac{h_2E_2(3h_1^3E_1+6h_1^2h_2E_1+4h_1h_2^2E_1+h_2^3E_2)}{h_1^3E_1(h_2^4E_2^2+4h_1h_2^3E_1E_2+ \\ +6h_1^2h_2^2E_1E_2+4h_1^3h_2E_1E_2+h_1^4E_1^2)}\right] \tag{5.8}$$

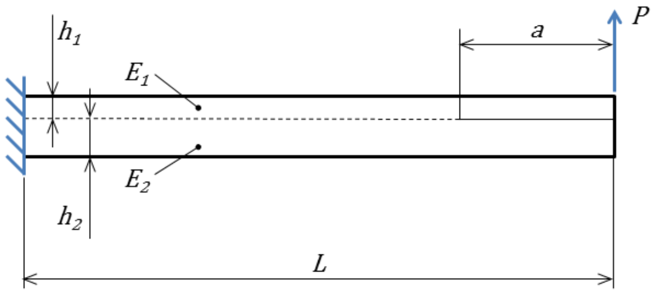

Figure 5.3: ADCB specimen

5.2 Mode Partitioning

Following the analysis by Williams [21], we can separate the total crack energy into mode I and mode II components by splitting the moments into

$$M_1 = M_{II} - M_I \tag{5.9a}$$
$$M_2 = \psi M_{II} + M_I \tag{5.9b}$$

Equations (5.9) needs to be modified in order to correctly account for the different moduli in the two sections. The simple statement, given previously in [21], that the opening mode only requires moments in opposite senses so we have $-M_I$ on the upper arm and M_I on the lower arm, is only valid for symmetrical DCB specimen. For other configuration, the pure opening mode will be obtained only when the curvature of the two arms will be exactly opposite, i.e. $-M_I$ on the upper arm and ψM_I on the lower arm. Equations (5.9) will then have a form

$$M_1 = M_{II} - M_I \tag{5.10a}$$
$$M_2 = \psi M_{II} + \psi M_I \tag{5.10b}$$

After substituting (eq:partitioningM-b) into (5.1) the energy release rate is

$$G = \frac{1}{2b}\left[\frac{E_1 I_1 EI + E_1^2 I_1^2 + E_2 I_2 EI - 2E_1 E_2 I_1 I_2 + E_2^2 I_2^2}{E_1^2 I_1^2 EI} M_I^2 + \right. \\ \frac{(E_1 I_1 + E_2 I_2)(E_1 I_1 + E_2 I_2 + EI)}{E_1^2 I_1^2 EI} M_{II}^2 + \\ \left. \frac{(E_2 I_2 - E_1 I_1)(E_1 I_1 + E_2 I_2 + EI)}{E_1^2 I_1^2 EI} M_I M_{II}\right] \tag{5.11}$$

and because of the cross term on the third line, the mode I and mode II cannot be separated analytically, in contrast to the results derived in [21].

VCCT

Several investigators over the past three decades showed that when numerical methods, such as the finite element method, are used to evaluate the total and individual mode strain energy release rates, the individual modes do not show convergence as the mesh size is refined near the crack tip. The methods to overcome the oscillatory singularity problem and non-convergence have been reviewed by Krueger et al. [22]. They concluded that practical solutions can be obtained only by few methods: the resin interlayer method, the method that chooses the crack tip element size greater than the oscillation zone, the crack tip element method that is based on plate theory and the crack surface displacement extrapolation method.

The method based on choice of Δ larger than the oscillatory zone is explored here as a simple approach that can be easily used with current commercially available finite element analysis software. A set of models were created in Abaqus/Standard™, where the interface crack problem was represented by the DCB specimen geometry. Results in Figure 5.4 confirm the dependence of the mode I and mode II components on the element length near the crack tip. This dependence might be considered small for interfaces where bending stiffness of the two arms is not very different. In this case, the method of choosing large element length might have some applicability. However, for interfaces where bending stiffness between the two components is larger, the convergence cannot be achieved. In fact, it is misleading to talk about convergence, as the mode mixity at material interfaces is a function of the distance from the crack tip and the energy release rate cannot be partitioned into mode components in principle.

These results show that the decomposition of strain energy release rate at the interface of two materials doesn't have any physical meaning, as the results will be dependent on the distance from the crack tip. The larger is the difference in bending stiffness the larger is the oscillatory zone and the methods suggested by many authors as shown in [22] might only be used for limited cases, where the difference in stiffness is not very large.

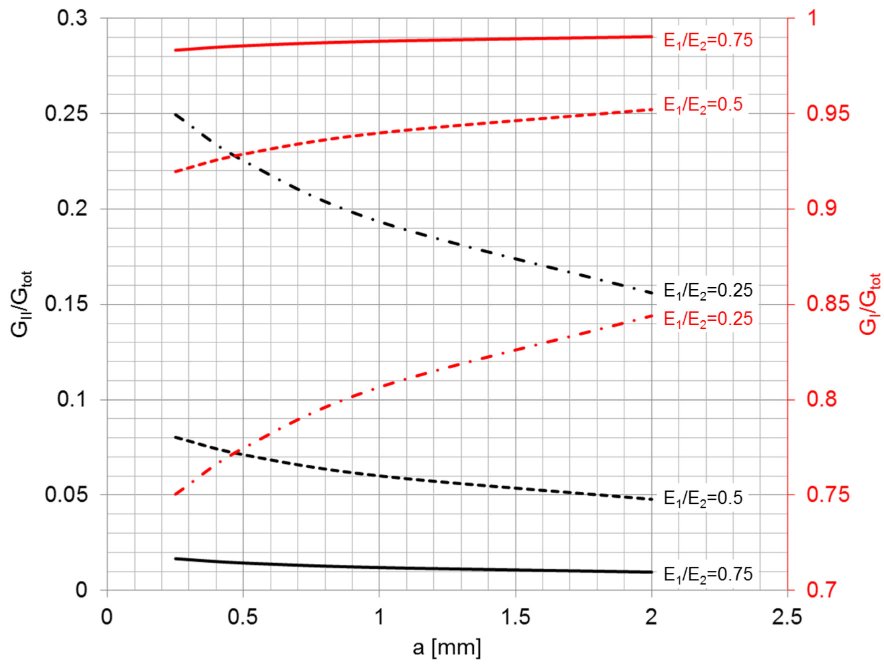

Figure 5.4: Energy release rate components vs. element size (based on different Young's modulus in specimen arms)

5.3 Compliance and effective crack length

When using a classical beam, the applied load and the crack length are the main parameters used to calculate strain energy release rate. However, by measuring the displacements, the strain energy release rate can be equivalently calculated from the compliance as suggested by well-known equation

$$G = \frac{P^2}{2b}\frac{dC}{da} \tag{5.12}$$

This also enables to calculate the theoretical value of crack length, a, which then might be used to check on the measured values of crack length, especially when the crack length measurements includes some inherent uncertainties such as operator dependence. From equation (5.12) the compliance might be expressed as

$$C = \int^a \frac{2bG}{P^2} da + C_0 \tag{5.13}$$

where C_0 is the compliance with no crack present.

DCB
The crack length can be calculated from displacement and applied load as

$$a = \sqrt[3]{\frac{\delta b}{4P\left(\frac{1}{h_1^3 E_1} + \frac{1}{h_2^3 E_2}\right)}} \tag{5.14}$$

ELS
if Ω_{ELS} is defined as

$$\Omega_{ELS} = \frac{h_1 h_2 (h_1 + h_2)^2 E_1 E_2}{(h_2^3 E_2 + h_1^3 E_1)(h_2^4 E_2^2 + 4h_1 h_2^3 E_1 E_2 + 6h_1^2 h_2^2 E_1 E_2 + 4h_1^3 h_2 E_1 E_2 + h_1^4 E_1^2)} \tag{5.15}$$

The crack length can be then calculated as

$$a = -\sqrt[3]{\frac{b\left(P(L + \Delta_{clamp})^3 - 3dEI\right)}{36P\Omega_{ELS}EI}} \tag{5.16}$$

ADCB

$$\Omega_{ADCB} = \frac{h_2 E_2 (3h_1^3 E_1 + 6h_1^2 h_2 E_1 + 4h_1 h_2^2 E_1 + h_2^3 E_2)}{h_1^3 E_1 (h_2^4 E_2^2 + 4h_1 h_2^3 E_1 E_2 + 6h_1^2 h_2^2 E_1 E_2 + 4h_1^3 h_2 E_1 E_2 + h_1^4 E_1^2)} \tag{5.17}$$

Assuming the same specimen length correction factor as in the ELS specimen, Δ_{clamp}, the crack length can be calculated as

$$a = -\sqrt[3]{\frac{b\left(P(L + \Delta_{clamp})^3 - 3dEI\right)}{12P\Omega_{ADCB}EI}} \tag{5.18}$$

6 Results

In total, seventeen bi-material glass-carbon composite specimens were tested in DCB, ELS and ADCB configurations as described in Chapter 4.1.

6.1 DCB

A typical image of DCB specimen during the test is shown in Figure 6.1. Here we can see that significant amount of local bending and large displacement is involved even before the initial crack starts to propagate. This is also the reason for nonlinearity in force-displacement curve recorded during the test, as shown in Figure 6.2. The relatively small thickness of GRFP component in combination with its low elastic modulus is the main cause for this nonlinearity. This fact makes the definition of delamination onset very ambiguous and the fracture toughness values obtained by different delamination onset criteria as defined in Figure 2.2 can be as low as 200 J/m^2 (NL definition of onset) or as high as 1600 J/m^2 (5% definition of onset) with a very high scatter between specimens. It is clear the NL definition of the onset is not the real fracture toughness value, because the force-displacement curve nonlinearity is caused by other factors rather than the delamination growth. The visual definition of delamination growth is also difficult and it is still a subject to an operator judgement, despite the fact that the images of the test were recorded and available for detailed inspection after the test. The 5% definition is commonly used in fracture toughness value, although the value of 5% is arbitrary and might not be enough for specimens with high overall compliance and vice versa.

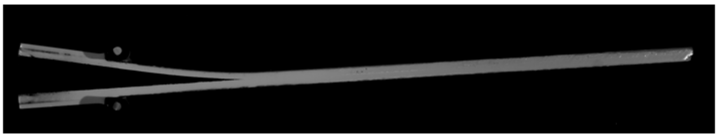

Figure 6.1: DCB specimen opening before crack growth

Finding the NL initiation points is easier when the deviation from linearity is plotted in a separate graph where the displacement is on horizontal axis and the deviation from linearity, i.e. $d_{lin} - d$ in Figure 6.2, is on vertical axis. This graph is shown in Figure 6.3. Here we can also notice that the part of the plot where we are certain that the crack is growing, let's say more than 12 mm displacement for this particular specimen, follows a linear trend. This can be used to define new initiation criteria which have not been considered previously, the "deviation from linearity tangent (DLT)". This new initiation criterion is defined as a point, where a linear fit to the linear part of deviation from linearity plot intersects the horizontal axis.

DLT initiation criterion gives more consistent fracture toughness results with less scatter than both NL and 5% definitions for the 8 specimens tested in DCB configuration. This new initiation criterion has better connection with the actual specimen physical behaviour as it is based on its actual compliance rather than the arbitrarily chosen value of 5% increase in compliance. It has been developed here for the delamination test for bi-material interface, but the author believes that it can have some utility in general composite material fracture toughness testing, where it can help to reduce the scatter in results that is common with the other definitions of initiation points.

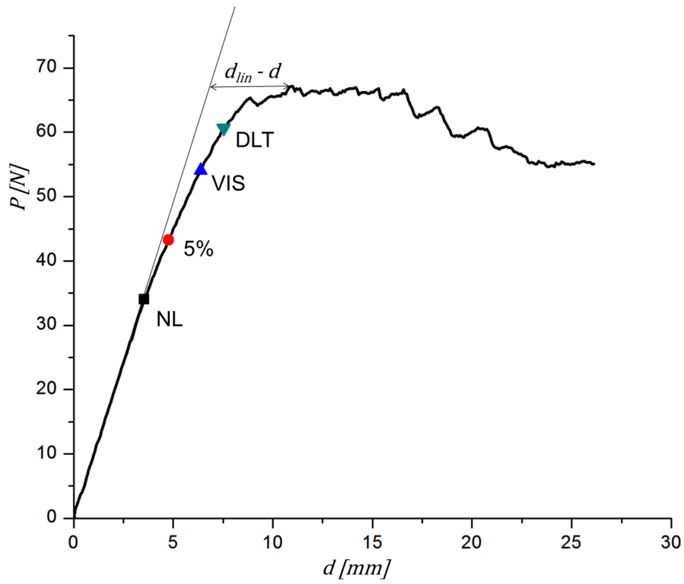

Figure 6.2: DCB specimen opening before crack growth

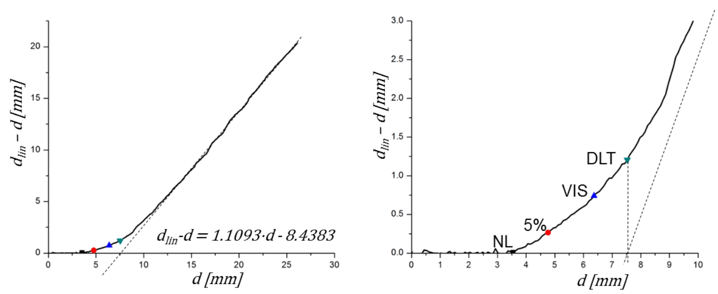

Figure 6.3: Deviation from linearity tangent (DLT) initiation point definition

6.2 ADCB

ADCB specimens showed the same type of nonlinearity as seen previously in DCB specimen and thus the conventional delamination initiation definition (NL, 5%) is not necessarily connected with the crack propagation. An example of force-displacement data, together with a typical specimen opening before the delamination onset is shown in Figure 6.4.

6.3 ELS

Testing in ELS configuration was accompanied by unstable crack propagation as illustrated in Figure 6.5 with an instantaneous decrease in loading force as shown in Figure 6.6. Because of this fact, no propagation data were recorded and it was not possible to use the experimental compliance calibration method as in DCB and ADCB test configurations, where the crack propagation was stable. Also the image processing for measuring the crack length didn't prove to be sufficiently accurate and without a stable crack propagation also unnecessary. There was a very little nonlinear behaviour before the crack started to propagate, and therefore the NL initiation point is very close to the VIS and 5%/MAX initiation points, which coincide for some specimens. Because of the lack of propagation values, the newly proposed DLT initiation

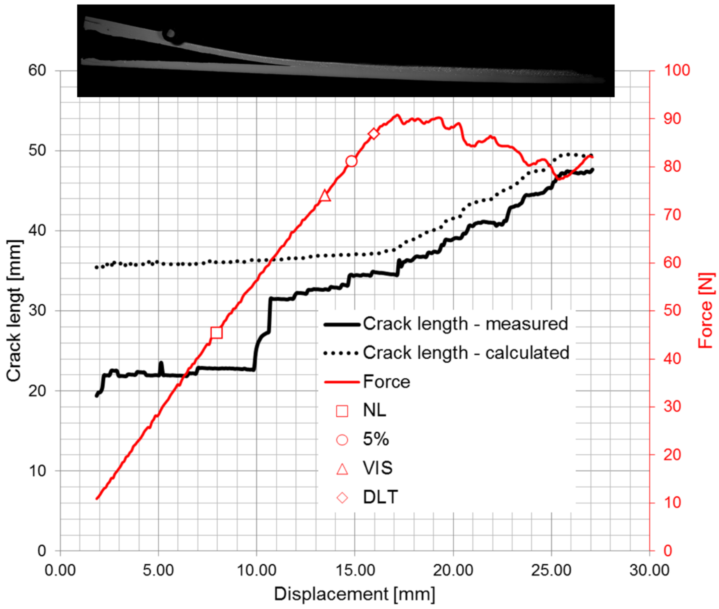

Figure 6.4: ADCB force-displacement data with initiation points and crack length measurements

definition could not be used.

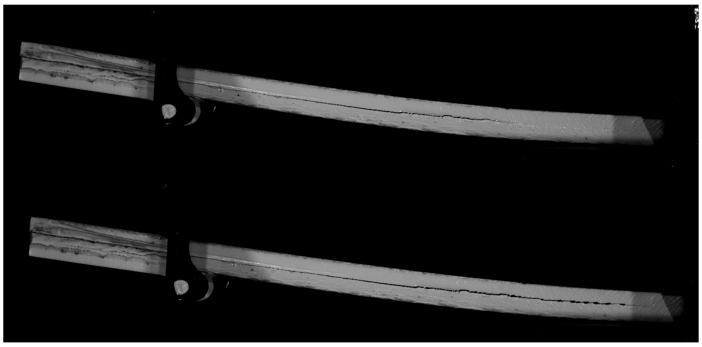

Figure 6.5: ELS specimen unstable crack propagation

6.4 Summary

Figure 6.7 shows a comparison of fracture toughness results from all three tested configurations. Results obtained by modified beam theory and beam theory with calculated crack length are plotted for DCB and ADCB tests rather than a simple beam theory results, because they are believed to be more accurate. Also result from compliance calibration method are plotted for both, DCB and ADCB for comparison. Only method used to calculate fracture toughness in ELS configuration was the corrected beam theory with effective crack length.

According to expectation, the deviation from non-linearity (NL) initiation point definition yields the lowest fracture toughness results for all tested configurations and data reduction methods. However, these are only included here for completeness, as they do not represent the real fracture toughness because other factors contribute to the non-linear behaviour of the

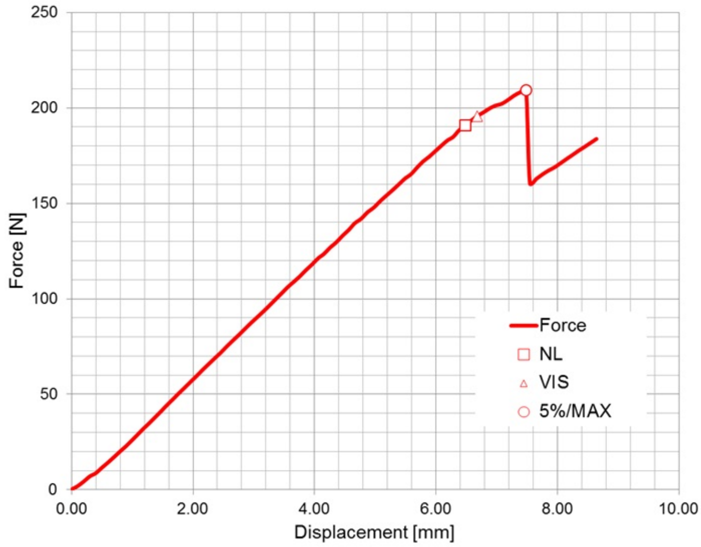

Figure 6.6: ELS Force-Displacement curve

specimen before the crack starts to propagate. This is very significant for DCB and ADCB specimen. In ELS, where local bending of specimen arms before the crack propagation is smaller, the results from deviation from non-linearity are closer to other initiation definitions.

Interesting comparison can be made between the visual onset definition (VIS) and the 5% increase in compliance definition (5%). Visually determined values are higher for DCB and lower for ADCB. This can be explained by generally higher compliance of ADCB, which is affecting the 5% offset definition results. Also, it is difficult to rely on a judgement and eyesight of a test operator and thus the visual onset values remain only hypothetical.

The new initiation definition, deviation from linearity tangent (DLT), gives the highest fracture toughness results, however with less variability.

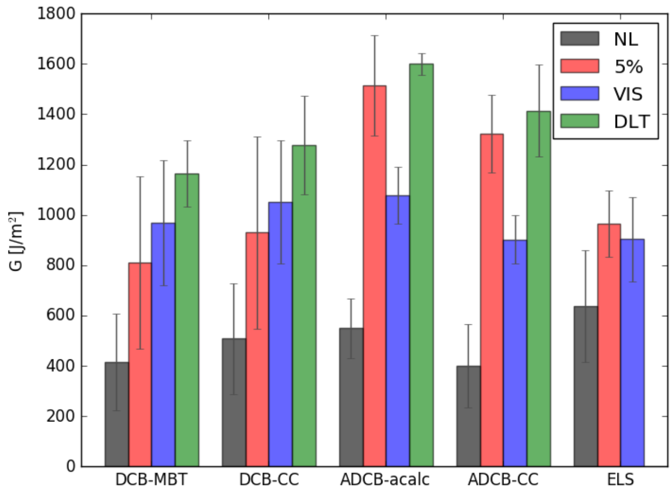

Figure 6.7: Results summary

7 Discussion

Defects in composite structures need to be considered as an important factor that can affect their strength and load-carrying capacity. Economic aspects of composite materials manufacture, quality control and product maintenance require some level of defects to be present, however the safety is the primary concern and the structural integrity needs to be assured throughout the component life. One of the main defects with potential harmful consequences to the structural strength of a product made of composite materials is the delamination. Composite laminates are very prone to this type of defect that usually starts from stress concentration area, such as straight edges, corners or an interface between two components with different elastic properties.

This doctoral thesis focuses on experimental testing methods of delaminations at a bi-material interface. The beam specimens made of combination of glass and carbon composites were tested in several configurations, which are commonly used for testing delamination fracture toughness of composite materials. The analytical equations for test data reduction were modified in order to account for the two different materials in specimen.

One of the issues with the composite delamination testing is the measurement of the crack length. Often, this measurement is done optically with a travelling microscope and the results can be affected by the operator's eyesight and judgement. New method of crack length measurement by digital image processing was developed here and proved to be very accurate with the combination of corrected beam theory data reduction method. This new method can be applied in any test configuration with a clear opening between the specimen arms and not only to a bi-material interface as presented here. This method can reduce the workload of the test operator and it assures consistent results between different specimens within the batch. Python programming language was used for the image processing, because of its simple syntax and easily available open-source libraries for scientific computing. One of the downsides of the current method is the slow speed of image processing. This can be improved by implementing the method in a faster programming language.

Another problem with composite delamination testing is the definition of the delamination onset. The onset criteria used currently are deviation from linearity, visual observation and 5% increase in compliance, but sometimes these criteria can produce significantly different results with a large scatter, especially for specimens with low stiffness and nonlinear behaviour occurrence before the crack starts to propagate. A new initiation point definition was proposed in this thesis; the deviation from linearity tangent. This new initiation point definition is based on the specimen physical behaviour during the crack propagation and yields less scatter than any of the other initiation criteria.

Mode mixity is an essential parameter used in delamination fracture criteria. However, it has been shown here that this parameter has no physical meaning for the bi-material interface, as the mode I and mode II contribution to the energy release rate will always be a function of the distance from the crack tip. An approximation of the mode mixity can be made for the interfaces where the difference in bending stiffness is small, but the uncertainty about the contribution of each mode grows with the larger mismatch between material properties. The use of the fracture criteria based on the mode mix parameter thus have significant limitation and perhaps the conservative fracture criteria, $G = G_{Ic}$, can be used instead.

8 Conclusion

The aims set in Section 3.2 were met only partially. The analytical investigation presented in Section 5 showed that the fracture toughness at a bi-material interface cannot be divided into mode I and mode II contribution and that the mode mix ratio varies with distance from the crack tip. For this reason, it is impossible to develop a failure criterion based on a mixed mode ratio. Automatic crack length measurement method was successfully developed and validated as described in 4.2.

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Abstract

Composite materials exhibit a complex failure behaviour, which may be further affected by various defects that arise either during the manufacturing process or during the service life of the component. A detailed understanding of the failure behaviour, and the factors affecting it, is essential for designing composite structures that are safer, more durable and economical.

First part of this thesis gives an overview of typical failure mechanisms in composite materials and describes mathematical theories, currently being used in analysing and predicting the failure. Different types of defects are reviewed and their effects on composite materials performance briefly discussed. Delaminations are described in more detail together with basic fracture mechanics principles and their application in the analysis and experimental testing of composite materials.

The second part focuses on delamination at an interface of two different materials. An experimental measurement of fracture toughness was performed under three types of loading conditions in order to determine a delamination failure criterion based on a ratio of mode I and mode II. As a part of the experiment, a novel method of measuring the crack length based on digital image processing was developed and also a new type of delamination initiation point definition proposed. Analytical equations for calculating the energy release rate from experimentally measured data were reviewed and extended to account for different elastic moduli of the two materials at the interface. Analytical and finite element investigation revealed that the mode I and mode II contributions are dependent on the distance from the crack tip and therefore a failure criterion based on the mixed mode ratio cannot be used.

Abstrakt

Kompozitní materiály se projevují komplexním způsobem porušování, které může být dále ovlivněno přítomností různých poruch plynoucích z výrobních processů nebo se vyskytujících v průběhu života součásti. Důkladné porozmění procesů porušování a jejich okolností je nezbytné pro navrhování kompozitních konstrukcí, jenž budou bezpečnější, trvanlivější a ekonomičtější.

V první části disertační práce jsou popsány způsoby porušování kompozitů a uvedeny současné matematické metody pro analýzu a výpočet únosnosti. Dále jsou zde vyjmenovány hlavní druhy vad a stručně diskutován jejich vliv na vlastnosti kompozitních materiálů. Zvláštní důraz je kladen na delaminace, společně se základními principy lomové mechaniky a jejich uplatnění při výpočtech a zkoušení kompozitů.

Druhá část je zaměřena na delaminace na rozhranní dvou různých materialů. Lomová houževnatost byla experimantálně měřena ve třech typech zatížení za účelem stanovení poruchového kritéria založeného na podílu módu I a módu II. Během tohoto experimentu byla vyvinuta nová metoda měření délky trhliny pomocí digitáního zpracování obrazu a rovněž byla navržena nová definice počátku šíření trhliny. Analytické vztahy pro výpočet míry uvolnění deformační energie z naměřených dat byly rozšířeny o vliv rozdílných elastické parametrů materiálů na rozhranní. Podrobnější prozkoumání analytických vztahů a výpočet metodou konečných prvků odhalil, že podíl módu I a módu II je závislý na vzdálenosti od čela trhliny a poruchové kritérium založené na podílu smíšenosti tak nemůže být použito.