

Report

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Project ACLAIM (Advanced
Composite Life Assessment and
Integrity Management):
Measurement of Mode I and II
Fracture Toughness for Mixed
Material Systems Used in
ACLAIM Case Studies

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Project ACLAIM (Advanced Composite Life Assessment and Integrity Management): Measurement of Mode I and II Fracture Toughness for Mixed Material Systems Used in ACLAIM Case Studies

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ABSTRACT

A range of processing, machining and in-service defects typically found within advanced composite structures have previously been reviewed within the ACLAIM project [1]. Due to the large number of defects that can occur, and the fact that not all defects represent a serious threat to loss of structural integrity, the focus of definitions for failure modes has been on the “crack-like” defects, such as delamination and matrix micro-cracking, that give real cause for concern over remnant performance.

This report details experimental work that has been carried out to measure the Mode I and II fracture toughness values, G_{IC} and G_{IIC} respectively, for three case studies undertaken within ACLAIM that are concerned with delamination or interfacial de-bonding. The measurement of Mode I and II fracture toughness data for these material systems is not an easy task, with Mode II data being particularly difficult to measure. Existing test standards or protocols for measuring fracture toughness properties for composites and adhesives have been developed for configurations where the material on each side of the delamination tip is the same and in the case of composites is continuous and unidirectional in format. The material systems tested in this study consisted of bi-material interfaces, of various formats and where in some instances a degree of curvature in the specimens existed due to differences in coefficients of thermal expansion. Hence the stress state at the delamination tip is more complicated than for the ideal cases catered for in the test methods used. Data have been produced although it is emphasised that all values, and in particular the Mode II values, should be treated as approximate.

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1 INTRODUCTION

Key to reductions in the level of structural or operational performance throughout service life, is the initiation and propagation of defects within the structure and/or parent materials. In order to develop effective structural health monitoring (SHM) systems for structures fabricated from advanced composite materials, it is important to have a detailed understanding of the salient design driver(s), service life conditions (e.g. mechanical/thermal stress field, environment etc.) and the defects that are most likely to occur and their typical location(s).

A range of defects typically found within advanced composite structures have been described in a previous report [1] prepared within the ACLAIM project. Due to the large number of defects that can occur, and the fact that not all defects represent a serious threat to loss of structural integrity, the focus of definitions for failure modes within ACLAIM has been on the “crack-like” defects, such as delamination and matrix micro-cracking, that give real cause for concern over remnant performance. Establishing the criticality of these defect types may involve one or a combination of: (i) reference to appropriate standards, (ii) predictive modelling [2-4] and (iii) experimental determination.

This report details experimental work that has been carried out to measure the Mode I and II fracture toughness values, G_{IC} and G_{IIC} respectively, for three case studies undertaken within ACLAIM that are concerned with delamination or interfacial de-bonding. **It is noted here that for these case studies the predominant mode of delamination or de-bonding is Mode I. Therefore the Mode I fracture toughness data is of most importance. In addition, the case studies have only looked at delamination or de-bonding initiation and therefore the fracture toughness initiation values are of most importance.**

This report consists of 6 sections including the introduction. Section 2 of the report briefly describes the case studies and material combinations studied, whilst Section 3 provides details as to the causes and nature of delaminations/de-bonds and the application of fracture mechanics in modelling approaches. Section 4 details the Mode I and II test methods used and how they were applied to bi-material interfaces, whilst in Section 5 the experimental procedures and results are detailed. Discussion and conclusions are covered in Section 6.

2. CASE STUDY MATERIAL COMBINATIONS

The five case studies chosen for the development and validation of effective structural health monitoring systems within the ACLAIM project were:

1. Wind turbine blade sub-component
2. Bridge strengthening using bonded carbon fibre-reinforced plastic (CFRP) plates
3. Pressure containment within glass fibre-reinforced plastic (GFRP) pipes
4. SHM analysis protocol e.g. data recording, fusion and analysis
5. CFRP/GFRP pipe repairs

The following sub-sections provide brief details for those case studies (1, 2 and 5) where interfacial de-bonding is the major defect type and Mode I and II fracture toughness data are required. Each of these case studies is detailed fully in it's own report [5-7].

Table 1: Material Combinations in Case Studies Concerned With Interfacial De-Bonding

Case study		Material interfaces/combinations
N°	Application	
1	Wind turbine blade sub-component	• Biaxial GFRP - SP340 structural adhesive - biaxial GFRP
2	Bridge strengthening	• Unidirectional CFRP - Sikadur 31 adhesive - mild steel
5	Oil and gas pipe repairs	• Quadraxial CFRP - mild steel • Quadraxial CFRP - biaxial woven GRP - mild steel

2.1 CASE STUDY 1 - WIND TURBINE BLADE COMPONENT

The component of interest in this case study is a web T-peel coupon section from a “mini-beam” sub-structure which is used for investigating various design concepts and material combinations in wind turbine blades. The component is a representative, but not scaled version of the main load bearing component within a blade structure. It consists of a ~3.5 mm thick 90° GFRP shear web flange, secondarily bonded to the main axial load bearing spar comprising of pultruded CFRP sections (running the length of the blade) sandwiched between birch ply wood. The adhesive used in the secondary bond is ~10 mm thick and is a structural adhesive system produced by Gurit. Of particular interest is the secondary bonded interface between adhesive and GFRP laminates. The coupons are used to measure the pull-off strength of the joint.

In this case study, theoretical and finite element analyses (FEA) have been used to model the behaviour of the joint so that an investigation of defect criticality can be performed. The Mode I and II G_C values were needed for input into the FEA and theoretical models.

2.2 CASE STUDY 2 - BRIDGE STRENGTHENING USING BONDED CFRP PLATES

The design of CFRP strengthened systems is generally based on the ultimate limit state of strength, although other limit states designed may include serviceability, durability etc. The key components of a strengthened system are the substrate to which the reinforcement is to be bonded (in this case, a bridge), the adhesive and the reinforcement plate itself. Efficient and successful design of CFRP plates for structural strengthening or repair depends on an accurate knowledge of material properties and, in particular, the tensile properties (i.e. the strength, modulus and strain to failure) of the CFRP laminate material, the adhesive and fracture toughness properties. The same is true for an accurate assessment of defect criticality.

2.3 CASE STUDY 5 - CFRP/GFRP PIPE REPAIRS

Case study 5 focuses on composite repairs, manually over-wrapped composite laminates, that are used in the oil and gas industry for the repair of corroded pipework and pipelines. The repairs are used to rehabilitate pipework systems suffering either internal or external corrosion. Composite repairs are also applied to pipe systems that are leaking, i.e. a through pipe wall defect, usually caused by excessive internal corrosion.

The materials typically used in composite repairs are;

Fibre types - Glass or carbon

Matrix types - Epoxy, Vinyl ester or Polyurethane.

Repair laminate constructions used in commercially available composite repairs are either quasi-isotropic (quadraxial) or bi-directional. The nature of the application implies that the composite repair has in most instances to withstand bi-axial loading. This bi-axial loading comes from the internal pressure (causing hoop loading) and system loads such as thermal expansion and bending (causing axial loading). For repairs to leaking pipework, the laminate also has to withstand directly the internal pressure of the pipe system such that the pressure load will not cause the laminate to de-bond or delaminate from the outer pipe surface.

3. DELAMINATION AND INTERFACIAL DE-BONDING

3.1 BACKGROUND

Delaminations or interfacial de-bonds are one of the principal defects that can occur in advanced composite components during manufacture, machining and in-service. Delamination or de-bonding refers to situations in which failure (or inadequate adhesion) occurs on a plane between adjacent layers within a laminate or secondary bonded material system. For laminated composites, this type of failure is dominated by the properties of the matrix and since matrix strengths and toughness tend to be relatively low, laminated composites are prone to the development of delaminations. In many types of composite structure (e.g. aircraft, marine) delaminations are the most common form of defect/damage. These planar defects are caused by contamination at material or ply interfaces, insufficient cure or out of life material, inclusions (e.g. backing film), certain loading conditions (e.g. impact, differences in thermal expansion coefficients) and poor machining practice. This type of defect has a severe detrimental affect on mechanical strength, particularly under compressive loads, and on the life expectancy of composite components. The occurrence of production/handling induced delaminations should be avoidable with good practice. Delaminations or de-bonds are mainly found in laminated polymer matrix composites and/or secondary bonded structures and can occur throughout a component including central, edge and radial (i.e. at radii of curved profiles) positions.

Impact damage often gives rise to local delamination. Even though the impact may be transverse to the laminate, damage will often propagate along the planes between adjacent layers since these planes do not benefit from the reinforcing effect of the fibres. Hence, sites of impact often form zones of interlaminar splitting. Within these delaminated zones there may also be other damage types such as matrix micro-cracking and fibre breakage. Growth of the defect (of concern from a fitness for service perspective) will in many cases occur however by extension of the delamination into the surrounding material that may not have been directly affected by the initial impact event.

Matrix micro-cracking in the through-thickness direction within individual layers of a laminate can give rise to delaminations [8]. Such cracking tends to occur perpendicular to the fibre direction within individual layers and extends through the entire thickness of the affected layer. Once a crack has developed, some opening of the crack is possible near the middle region of the affected layer, but the crack tips are restrained by their respective adjacent layers (which may have considerable stiffness). In response, a multi-axial stress

state develops at the crack tips, often with strong through-thickness tensile components. These tensile stresses may be sufficient to initiate interlaminar failure from the crack tips [9-10]. Hence, as the micro-cracking density is increased so the delaminated area increases. As with impact induced delamination, this type of damage will typically involve more than one mechanism but the delamination may be that which ultimately determines serviceability.

Through-thickness failures arising from overload or fatigue can also develop into delaminations. Laminated composites tend to be weak in the through-thickness direction and consequently are sensitive to loads giving rise to stresses in the through-thickness direction. Consideration of this aspect of the nature of laminated composites is essential in arriving at successful design solutions, but situations in which through-thickness failures occur must still be considered. The stresses of concern here are direct through-thickness tension and through-thickness shear. Delaminations occurring under the action of these stresses are often not associated with other damage types developing simultaneously. It is worth noting that the stresses giving rise to delamination may be small in magnitude (especially by comparison to typical laminate in-plane stress allowables) and often occur as secondary effects [11].

The direct stresses referred to above arise from a combination of the structural geometry and the applied loading [11-13]. Through-thickness stresses may also be developed at the edges of laminates, even when no externally applied through-thickness tension or shear loads exist [14-15]. In laminates containing adjacent layers with different elastic properties compatibility requirements at free edges mean that through-thickness stresses exist even under the action of purely in-plane loads. The magnitude of these stresses depend strongly on the materials and laminate construction. The resulting stresses will usually be smaller than the applied in-plane stresses with which they are associated, but since they act in a direction that is usually relatively weak delaminations can occur.

3.2 APPLICATION OF FRACTURE MECHANICS

Delamination is generally regarded as being governed primarily by fracture mechanics rather than strength of materials considerations [16]. Fracture mechanics assumes that failure is governed by an energy criterion relating changes, for an incremental extension of crack face area, in the work of the applied loads and internal strain energy to a material toughness parameter. The criterion can be expressed as:

$$\frac{d}{dA}(W - U) = G_c \quad (1)$$

where A represents crack face area, W is the work of the applied loads, U is the strain energy and G_c is the material fracture toughness (this being the energy required for a unit increase in crack surface area). The parameter $d/dA(W-U)$ is referred to as the applied strain energy release rate and is usually assigned the symbol G .

There are some important restrictions to the conventional fracture mechanics approach that should be considered in its application to delaminations. These are discussed in the following paragraphs.

The toughness parameter, G_c , is a property of the material that is only uniquely defined when stress-strain behaviour remains linearly elastic. Hence, approaches in which this is assumed to be the case are referred to as incorporating linear elastic fracture mechanics (LEFM). The assumption of linear elasticity is one that strictly has limited applicability. In the case of metals, yielding tends to occur at high stress levels and the crack tip (i.e. the region of primary interest) is in a zone where stress-strain behaviour is distinctly plastic. Nevertheless, LEFM has been shown to be a practically useful predictive tool in such circumstances, albeit with minor modifications to account for plasticity being incorporated in certain cases [17]. The situation in composite materials is complicated by the presence of different constituent materials with distinctly different elastic properties and strengths. Nevertheless, it has been shown that in composites a damage zone forms in the region of the crack tip and this, broadly, has effects similar to the plastic zone at the crack tip in a metal. Material behaviour in the damage zone may not be linearly elastic but, as with metals, the net effect is often not such as to limit the practical utility of the LEFM approach [18].

The uniqueness of the toughness parameter also depends on self-similarity in crack geometry and failure processes, i.e. the conditions on both sides of the crack must be the same and the failure process should not change with small increases in crack depth. These conditions will not normally restrict the applicability of fracture mechanics to homogeneous and isotropic materials such as metals. They are, however, potentially very important when applying fracture mechanics to composites since it is evident they will not widely apply. For example, in laminates undergoing delamination the material on either side of the delamination can be very different, e.g. a unidirectional layer adjacent to a woven layer. Furthermore, delamination usually involves a number of distinct failure processes in the zone of the delamination front, e.g. matrix micro-cracking, fibre de-bonding and fibre bridging. In addition, on the scale of the damage zone ahead of the crack front, the dominant damage mechanism may continuously change (in response to localised changes in composite morphology) as the crack advances. In these circumstances a unique toughness parameter is not strictly applicable. The above consideration suggests that the conventional fracture mechanics approach is not always theoretically consistent in application to the analysis of delaminations. This may indeed be true, however, the fracture mechanics concept of crack growth being governed by stability considerations as determined by changes in energy remains applicable. Hence, the conventional fracture mechanics approach as applied to delaminations is by nature a tool for engineering approximation rather than a basis for accurately describing and predicting the failure processes in detail. It is important that the fracture mechanics approach be recognised as such, even when applied to fitness for service assessment where its limitations may not always give rise to practical difficulty.

Equation 2 indicates that implementation of the fracture mechanics approach relies on estimation (typically by analytical or numerical techniques) of the applied strain energy release rate:

$$G = \frac{d}{dA}(W - U) \quad (2)$$

and comparison to the toughness parameter G_c (which is usually established by material tests). It is convenient, in simplifying both analysis and test requirements, to decompose the applied strain energy release rate and the toughness into parameters corresponding to three possible modes of cracking. Three strain energy release rates (G_I , G_{II} and G_{III}) and three toughness parameters (G_{Ic} , G_{IIc} and G_{IIIc}) are defined as corresponding to cracking modes I, II and III, respectively. Mode I considers crack opening, Mode II considers shearing and

Mode III considers tearing. In most practical cases of delamination it has been found that only Modes I and II are active and Mode III applied strain energy release rates are negligible [16].

In some specific cases delamination may be strongly dominated by one mode with the other playing a negligible role. In such cases direct comparison can be made between the strain energy release rate and toughness parameter for the dominant mode. However, in general, consideration must be given to mixed mode loading and growth. In mixed mode cases, it has been shown that the failure condition for each mode cannot be regarded as independent of the energy release rate of the other modes [18]. Hence, equation 2 must be expressed as an interactive criterion. Numerous criteria, many of which are quite different in approach, have been proposed. Reeder [19] performed a review of available criteria in 1992 and concluded that much remains to be understood about the phenomenon of mixed mode fracture. Nevertheless, while it is apparent that no rigorous theory explaining the intrinsic nature of interaction exists, several empirical approaches that offer satisfactory estimation of measured behaviour are available. The power law approach, see for example Russel and Street [20], has been shown to reasonably accurately predict behaviour across a range of cases and is now widely applied. This power law criterion can be expressed as:

$$\left(\frac{G_I}{G_{Ic}} \right)^\alpha + \left(\frac{G_{II}}{G_{IIc}} \right)^\beta = 1 \quad (3)$$

Note that in order to use the criterion the empirical constants α and β must first be determined. These should strictly be established by performing mixed mode testing on the material under consideration. It is apparent however that in many cases of delamination in laminates consisting of unidirectional layers or where laminates are bonded together using an adhesive interface, both α and β are approximately one [16, 21]. There is insufficient evidence to suggest that these values can be assumed for α and β in other types of material and there are reported results showing that $\alpha = \beta = 1$ is not an accurate representation in some cases [22]. Nevertheless, analysis of a range of test data does suggest that taking $\alpha = \beta = 1$ may represent a conservative, or only marginally un-conservative, approach in many cases [18, 19, 21, 23], i.e. it appears unusual for α or β to be significantly less than one.

4. METHODS FOR MEASUREMENT OF MODE I AND II FRACTURE TOUGHNESS

4.1 MODE I - OPENING

The standards available for measuring the critical strain energy release rate for Mode I loading (G_{Ic}) of composites and adhesives are:

- BS ISO 15024:2001 - Fibre-reinforced plastic composites - Determination of mode I interlaminar fracture toughness, G_{Ic} , for unidirectionally reinforced materials [24] (equivalent to ASTM D 5528 [25])
- ISO/DIS 25217 - Adhesives - Determination of the mode I adhesive fracture energy G_{Ic} of structural adhesives using the double cantilever beam and tapered double cantilever beam specimens [26]

BS ISO 15024 is suitable for unidirectional carbon and glass fibre-reinforced thermoset and thermoplastic materials. The standard recommends the use of a double cantilever beam (DCB) specimen which is loaded in tension through loading blocks (as shown in Figure 1(a) - dimensions in Table 2) or piano hinges. Specimens should contain a thin ($\leq 13 \mu\text{m}$) layer of PTFE at mid-thickness to act as an initial delamination. The specimens are quasi-statically loaded until delamination growth from the tip of the starter crack is observed at which point the load is removed. The specimens are then re-loaded and the onset of stable delamination growth is monitored. During loading the delamination length is measured by observing the crack growing through a series of lines marked at set intervals (1 and 5 mm) on the side of the specimen. The points at which the delamination front passes through the marked intervals are marked on the load-deflection trace. Data reduction is then performed to determine the strain energy release rates for crack delamination initiation and propagation.

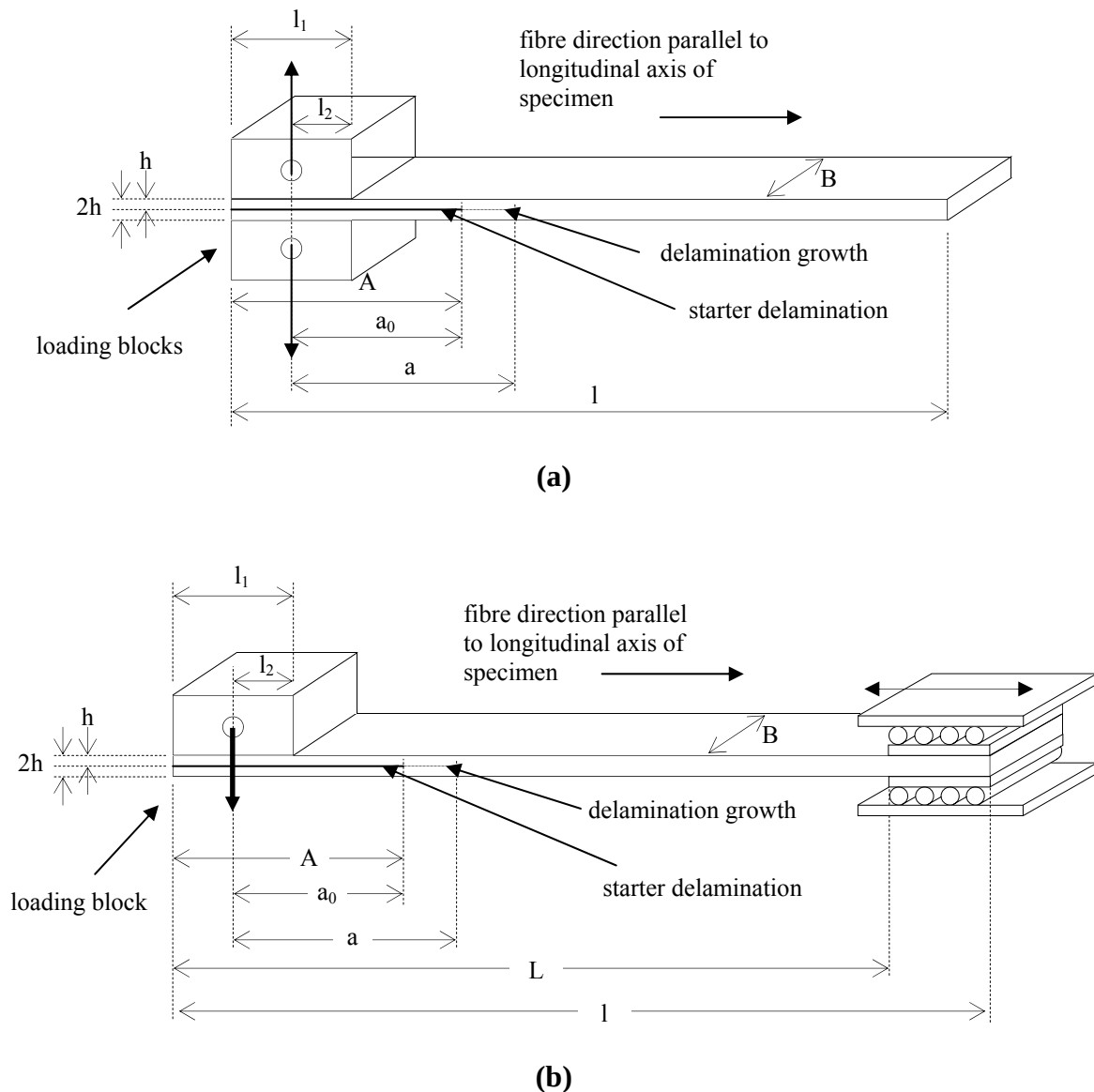


Figure 1: (a) Double cantilever beam (DCB) and (b) End loaded split (ELS) beam specimen geometries for Mode I and II fracture toughness respectively

Table 2: Details of DCB and ELS Specimen Dimensions

Dimension		Value (mm)	
Symbol	Definition	Mode I Double cantilever beam (DCB)	Mode II End loaded split (ELS) beam
B	Width	20 (but can use 15-30)	
2h	Thickness	~3 for CFRP ~ 5 for GFRP	
l	Length	≥ 125	≥ 170
L	Free length	n/a	≥ 100
l_1	Loading block width	≤ 15	
l_2	Loading block hole centre	$l_1/2$	
h	Mid-plane depth	half thickness	
A	Insert length	60	
a	Delamination crack length	a_0 + measured delamination length	
a_0	Initial delamination crack length	$60 - l_2$	

ISO/DIS 25217 is suitable for determining the Mode I fracture energy (G_{IC}) of structural adhesives. The standard provides methods for using both plain and tapered DCB specimen configurations. The DCB specimen dimensions, test methodology and data reduction techniques are similar to those set out in BS ISO 15024. For structural adhesives that exhibit unstable or “stick-slip” crack propagation, ISO/DIS 25217 provides guidance on how this phenomenon should be dealt with and how to calculate the initiation fracture energy value (N.B. it is not possible to calculate propagation values for G_{IC} for adhesives that exhibit unstable crack growth behaviour). In contrast, whilst BS ISO 15024 acknowledges that “stick-slip” behaviour can occur, it does not provide as much guidance on how it should be dealt with.

4.2 MODE II - SHEARING

There are currently no standardised methods for measuring Mode II fracture toughness, however there are several test geometries that have been used with varying degrees of success, including:

- End notched flexure (ENF)
- Stabilised end notched flexure (SENF)
- Four point end notched flexure (4ENF)
- Centre notched flexure (CENF)
- End loaded split beam (ELS)
- Cantilever beam enclosed notch (CBEN)

The most widely used test method for measuring the critical strain energy release rate for Mode II loading (G_{IIC}) has tended to be the three-point bend end notch flexure (ENF) test [27]. However, more recently the end loaded split (ELS) configuration has seen favour as this specimen is considered to be better suited to measurement of G_{IIC} values on account of

its improved crack propagation stability [27].

The ELS specimen geometry (Figure 1b) is similar to the Mode I DCB specimen. Specimens are typically ~3 and 5 mm thick for unidirectional carbon and glass fibre-reinforced materials, respectively. The specimen width is the same as for the DCB test (20 mm) and a PTFE film $\leq 13 \mu\text{m}$ thick is used to provide a starter delamination. Specimens are loaded quasi-statically and a delamination is initiated and grown from the PTFE insert. In the same way as for Mode I testing, the crack growth is monitored throughout the test and related to the load displacement response. Data reduction is then performed to give a value for the strain energy release rate.

4.3 DETERMINATION OF SPECIMEN THICKNESSES FOR BI-MATERIAL INTERFACES

As was stated in Sections 4.1 and 4.2, the Mode I and II methods have been developed for ~3 and 5 mm thick unidirectional CFRP and GFRP systems, respectively. For the work undertaken in this project, the material systems tested are predominantly of other formats i.e. not unidirectional, but the specimens are made up of different materials i.e. bi-material interfaces. With this in mind the approach was to design the specimen arms using material thicknesses to give approximately the same flexural rigidities (EI) as for representative unidirectional 1.5 and 2.5 mm thick CFRP and GFRP materials. Also, the thicknesses of specimen arms for bi-material coupons were chosen to give, as close as possible, the same values of EI so that equal bending in each arm was obtained. This was done to ensure that crack growth was along the material interface and not deflected away from the interface due to unequal bending. The way in which the specimen arm thicknesses were calculated is shown in equations 4 and 5.

$$(E_{\text{carbon}}) \times \left(\frac{bh_{\text{carbon}}^3}{12} \right) = (E_{\text{steel}}) \times \left(\frac{bh_{\text{steel}}^3}{12} \right) \quad (4)$$

$$h_{\text{steel}} = \sqrt[3]{\frac{E_{\text{carbon}}}{E_{\text{steel}}} h_{\text{carbon}}^3} \quad (5)$$

The thicknesses of materials used for each material combination are shown in Table 3. Due to the ply thicknesses of materials used and method of preparation (e.g. resin infusion, hand lay-up etc.) it was not always possible to design the specimens with equal flexural rigidities. Therefore, for some of the material combinations where a degree of unequal bending was

Table 3: Approximate Thicknesses for DCB (Mode I) and ELS (Mode II) arms

Case study	Area	Interface of interest	Details of DCB and ELS arms					
			CFRP		GFRP		Steel	
			E ₁₁ (GPa)	h (mm)	E ₁₁ (GPa)	h (mm)	E (GPa)	h (mm)
1	Wind turbine blade	GFRP/adhesive/GFRP			25	~4		
2	Bridge strengthening	UD CFRP/adhesive/ steel	360	~3			230	~3
5	Pipe repairs	CFRP/glass layer/steel	40	~5			230	~3
		CFRP/steel	40	~5			230	~3

Case study 1

GFRP (~4 mm) / SP340 adhesive bond (~0.5 mm)



Case study 2

UD carbon (~3 mm) / adhesive bond (~0.5 mm) / steel (3 mm)



Case study 5 – CFRP/GFRP pipe repairs

Carbon (~5 mm) / glass layer / steel (3 mm)



Carbon (~5 mm) / steel (3 mm)



Figure 2: Material combinations used and approximate thicknesses

seen, woven/epoxy GFRP laminates were bonded to specimens to equalise the mismatch in flexural rigidity. Figure 2 shows the material combinations used and approximate thicknesses of the specimen arms and adhesive layers.

For material combinations that consisted of CFRP and steel substrates, a degree of curvature was observed in specimens due. It is noted that for the composites used in these combinations were ambient temperature cure systems.

5. EXPERIMENTAL PROCEDURES AND RESULTS

The following sections detail the experimental approaches followed and results.

5.1 CASE STUDY 1 - WIND TURBINE

5.1.1 Mode I

Initial Mode I tests for the biaxial GFRP - SP340 structural adhesive - biaxial GFRP DCB specimens resulted in sudden initiation of the crack from the PTFE insert into the adhesive followed by either “stick-slip” behaviour in the adhesive and/or further crack growth with a

degree of fibre bridging. Therefore, ISO/DIS 25217 was followed for further tests to determine G_{IC} initiation values only. Tests were undertaken at a rate of 1.5 mm/min, which was equivalent to the loading rate used in web pull-off tests undertaken in the case study. As it was not possible to monitor crack propagation, specimens were loaded until crack initiation occurred and then the test was stopped. Specimens were broken open to reveal more accurate information as to the starter crack length used in calculation of the G_{IC} initiation values. The load-displacement plots for these specimens are shown in Figure 3 and it was observed that the load-displacement traces were relatively linear up to crack initiation.

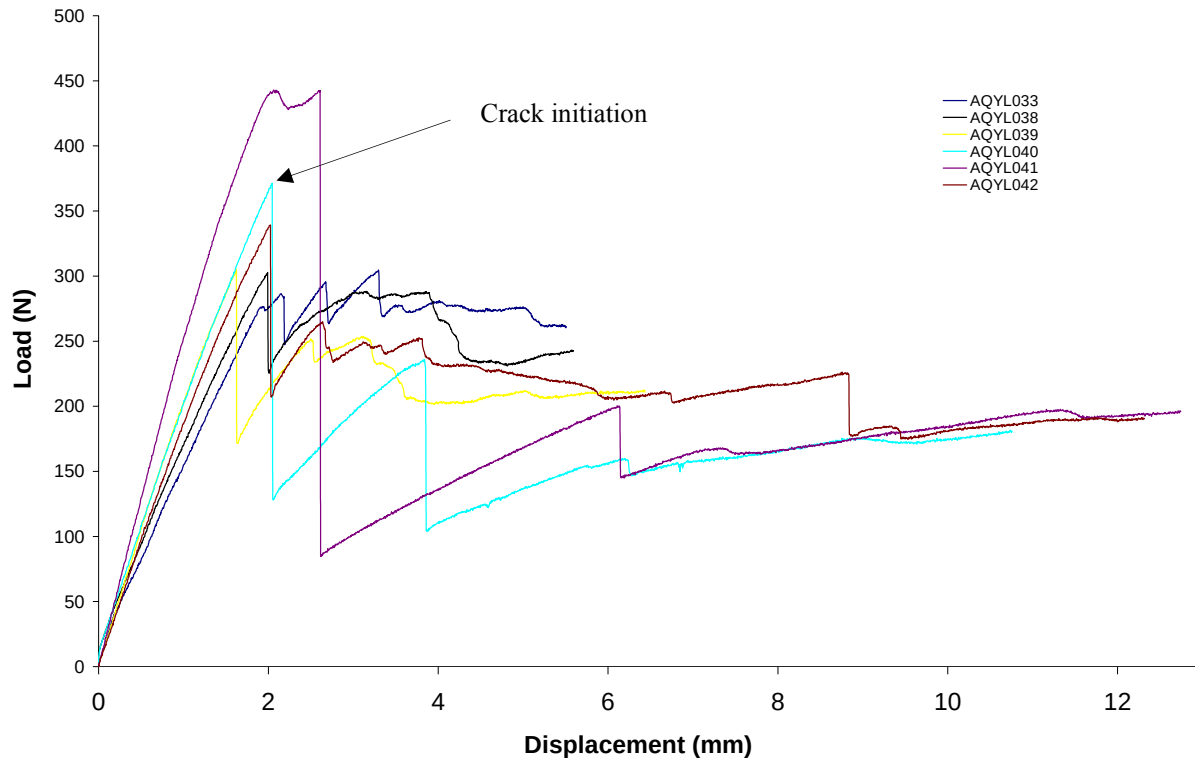


Figure 3: Load-displacement plots for biaxial GFRP - SP340 structural adhesive DCB specimens

The G_{IC} results calculated using simple beam theory (SBT) as per clause 8.2.2.1 of ISO/DIS 25217 are shown in Table 4. A mean value of $722 \pm 147 \text{ J/m}^2$ was obtained.

Additional trials were undertaken at much slower rates (0.05-0.1 mm/min) to try to overcome the “stick-slip” behaviour seen in the first set of tests. However, at these slow test rates the load-displacement responses showed a good degree of non-linearity, with gradual crack initiation and at higher loads. The reason for this is that there is more time for the plastic zone ahead of the crack tip to grow. This in turn not only increases the degree of non-linear behaviour, but relieves the stress concentration at the crack tip hence the larger initiation loads.

In an effort to overcome the effects of fibre bridging seen in the initial results, additional specimens were manufactured comprising a 0.4 mm thick SP340 adhesive bond-line between two 10 mm thick steel adherends. Tests were again undertaken at a loading rate of

Table 4: G_{IC} Results for Biaxial GFRP - SP340 Structural Adhesive DCB Specimens

Specimen	Test speed (mm/min)	Max.load (N)	G_{IC} (J/m ²)
AQYL033	1.5	305	659
AQYL038	1.5	303	616
AQYL039	1.5	305	544
AQYL040	1.5	371	860
AQYL041	1.5	443	926
AQYL042	1.5	339	726
Mean		344.1	722
Standard deviation		55.4	147
Coefficient of variation (%)		16.1	20

1.5 mm/min. The load-displacement responses are shown in Figure 4. It was observed that initiation was again sudden followed in general by “stick-slip” behaviour. The initiation loads are higher and the displacements lower than for the first set of tests due to the overall stiffer nature for the steel DCB specimens. The G_{IC} results are shown in Table 5. The mean value of initiation G_{IC} achieved was 925 ± 189 J/m² which is slightly higher than for the biaxial glass fibre system. This is reasoned to be due to the higher transverse modulus of the substrate as has been postulated by Bell and Kinloch [28].

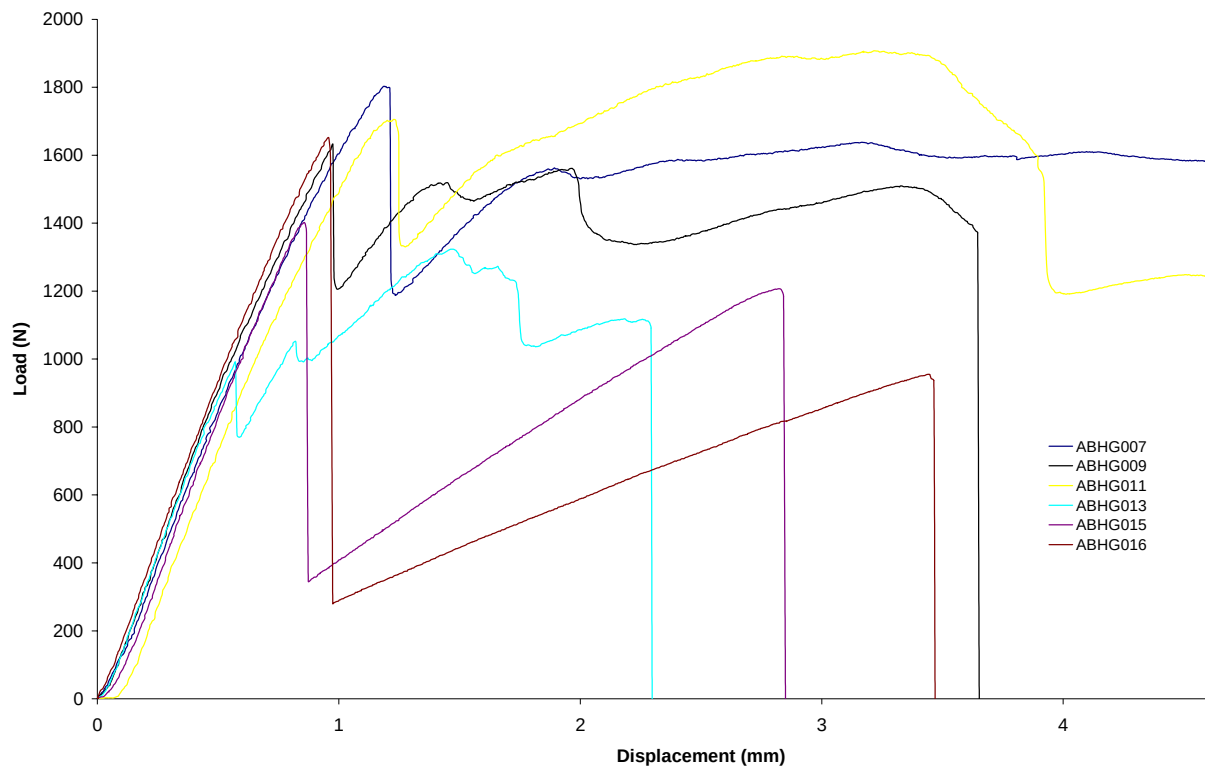


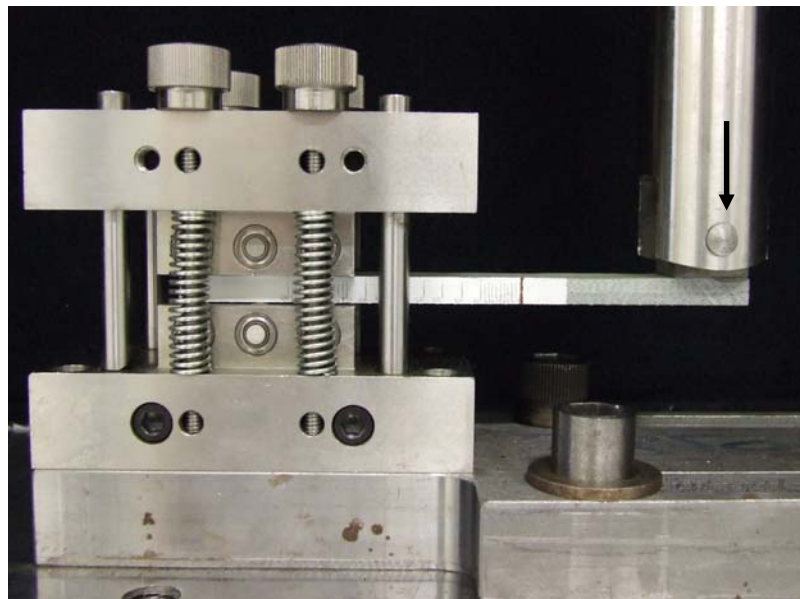
Figure 4: Load-displacement plots for steel - SP340 structural adhesive DCB specimens

Table 5: G_{IC} Results for Steel - SP340 Structural Adhesive DCB Specimens

Specimen	Test speed (mm/min)	Max.load (N)	G_{IC} (J/m ²)
ABHG007	1.5	1803	1182
ABHG009	1.5	1632	969
ABHG011	1.5	1701	1052
ABHG013	1.5	1324	637
ABHG015	1.5	1402	715
ABHG016	1.5	1652	992
	Mean	1586	925
	Standard deviation	184	208
	Coefficient of variation (%)	12	22

5.1.2 Mode II

The loading arrangement for the ELS Mode II tests is shown in Figure 5. However, it was not possible to undertake any successful Mode II tests for the biaxial GFRP - SP340 structural adhesive as crack initiation and propagation in the specimens was not achieved. This was thought to be due to the nature of the adhesive system used. As the Mode II fracture toughness data was deemed to be of less importance compared to the Mode I data, it was decided to use values quoted in the literature for similar types of structural adhesive and adherends. A conservative value of $\sim 3500 \text{ J/m}^2$ was taken from [29] as an assumed value for the modelling work undertaken in Case Study 1 [5]. This was based on a toughened epoxy adhesive (ESP 110) where the maximum initiation and propagation values had been determined as $\sim 3000 \text{ J/m}^2$ and $\sim 4700 \text{ J/m}^2$, respectively.

**Figure 5: ELS beam specimen and loading jig for measurement of Mode II properties**

5.2 CASE STUDY 2 - BRIDGE STRENGTHENING

The material combination used in this case study was an ultra high modulus (UHM) unidirectional CFRP bonded to a steel plate using Sikadur 31 adhesive. Unfortunately the first panel that was manufactured for these tests did not include a PTFE film to act as a starter crack and therefore a 0.3 mm wafering blade was used to machine a starter crack to 60 mm in length. It should be noted that spark eroding was also used to create a starter crack, but this did not achieve a crack of significantly better quality than the wafering blade. Later in the project an additional panel was produced that did include a PTFE film and a few additional tests were undertaken as comparisons to tests that used specimens with starter cracks created using the wafering blade. 300 x 300 mm panels were supplied to NPL by Babcock Marine Composites Group and specimens were machined from the panels to the dimensions required by the relevant standards.

5.2.1 Mode I

Loading blocks (20 x 20 x 20 mm with an 8 mm diameter hole) were bonded to specimen ends using two part Scotchweld 9323 adhesive. The sides of specimens were coated in white paint and pencil marked at 1 mm intervals from the tip of the starter crack for the first 10 mm and then 5 mm intervals thereafter so as to be able to trace crack growth during the tests. Specimens were loaded using an Instron at 1 mm/min (Figure 6) and crack growth along the length of the specimen was monitored using a travelling microscope. The load and displacement was recorded throughout the test and an event marker (a device used to register a voltage spike when depressed) was used to link the crack position to the load-displacement response. Each time the crack passed through a pencil mark the event maker was depressed. Specimens were loaded until 60 mm of crack growth had been achieved. Stable crack growth was observed for all specimens.



Figure 6: Mode I test apparatus

Corrected beam theory (CBT) as described in clause 10.2.2 of BS ISO 15024 was used to derive initiation and propagation values of G_{IC} . From the crack length and load-displacement data, the relation between the delamination length and the specimen compliance was established by plotting the cube-root of the compliance, $(C/N)^{1/3}$ (where C is the compliance and N is the load block correction factor) as a function of the delamination length, a.

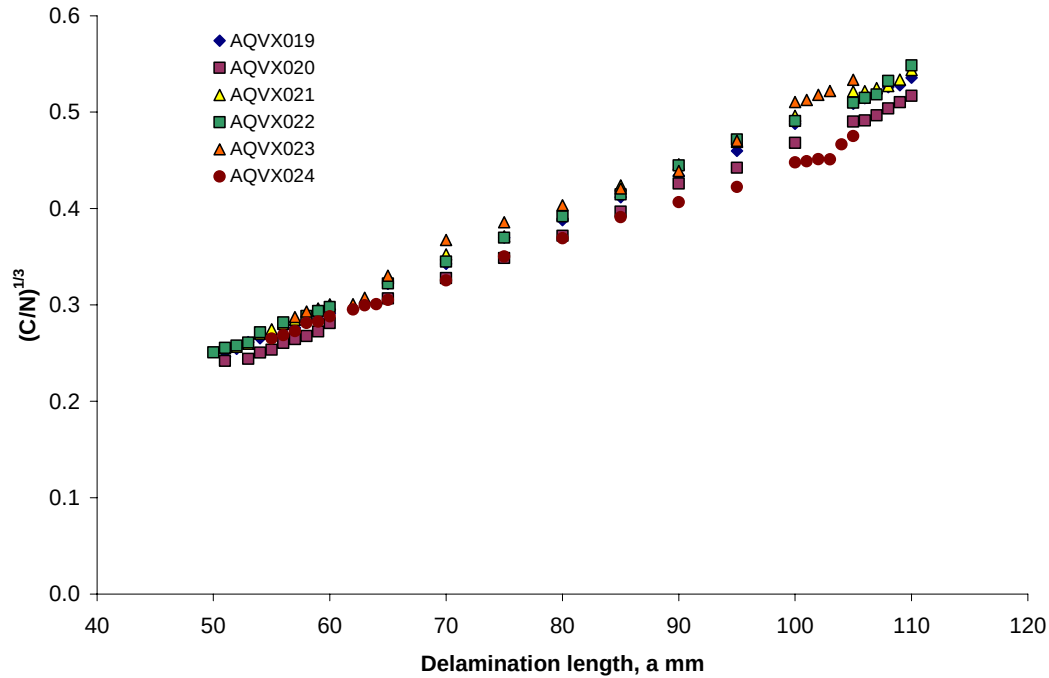


Figure 7: Compliance vs. delamination length for UHM UD carbon/adhesive/steel

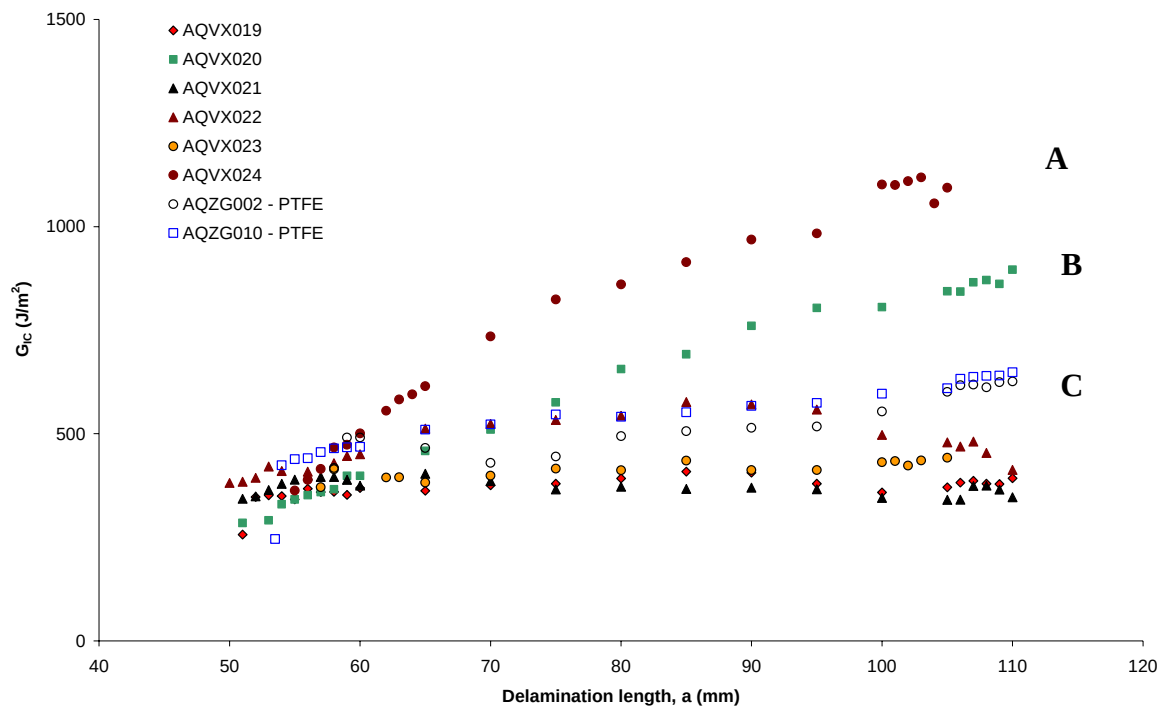


Figure 8: G_{IC} vs. delamination length for UHM UD carbon/adhesive/steel

Figure 7 shows the specimen compliance vs. delamination length plots for the specimens tested and it was observed that the compliance behaviour was generally linear. Figure 8 shows the G_{IC} values as a function of delamination length. With reference to Figure 8, was observed that there were some difference in the G_{IC} vs. delamination length relationships. These differences can be attributed to the degree of fibre bridging observed in specimens post delamination initiation. For the trace marked 'A' in Figure 8, fibre bridging was seen to occur across ~50% of the specimen width (Figure 9(a)) resulting in an increase in the G_{IC} values with delamination width. It is noted that for this specimen the initial crack front was not cut square.

For the trace marked 'B' in Figure 8, fibre bridging was seen to occur across ~20% of the specimen width (Figure 9(b)) resulting in an increase in the G_{IC} values with delamination width, although not as large an increase as for the trace marked 'A'. For the trace marked 'C' in Figure 8, no fibre bridging was seen (Figure 9(c)) resulting in a relatively flat trend in G_{IC} values with delamination width.

Also plotted on Figure 8 are the results of two specimens that did contain a PTFE film starter crack. These specimens produced similar results as to the wafered crack specimens. The G_{IC} initiation values are provided in Table 6 and a mean value of 333 J/m^2 was achieved.

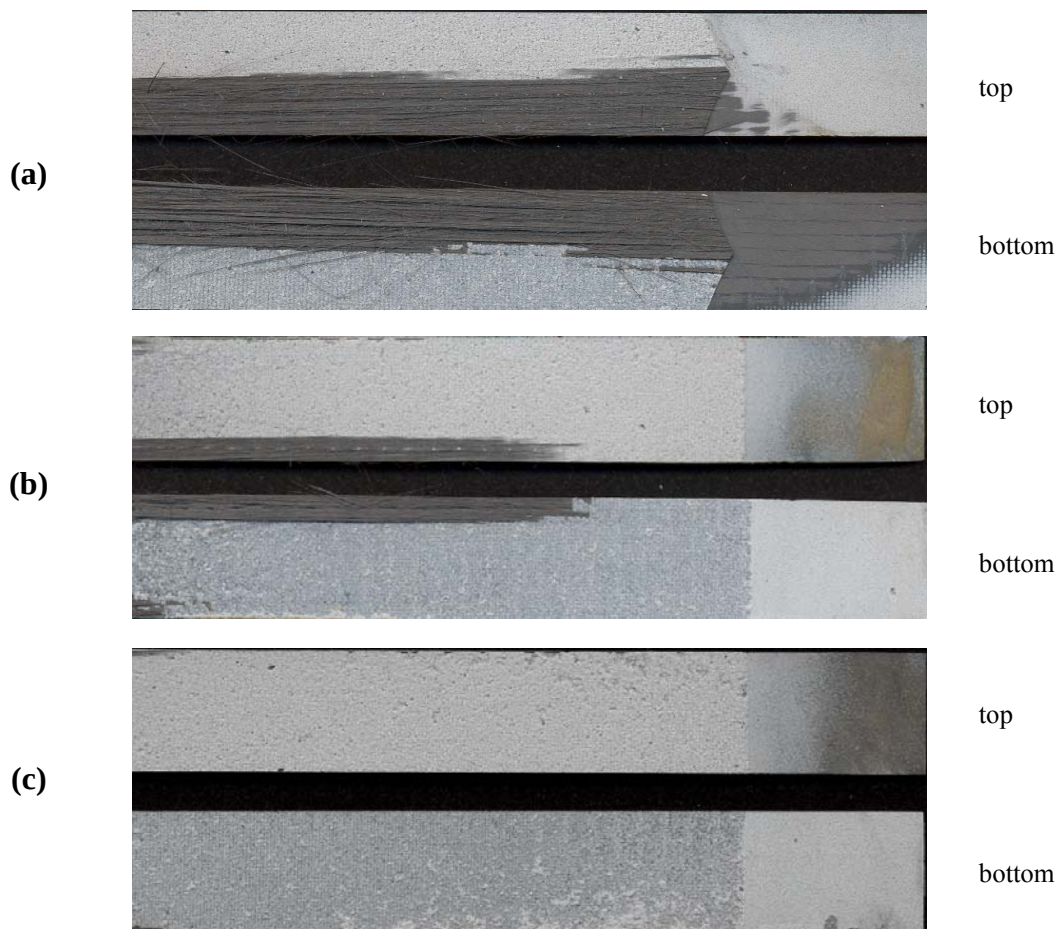


Figure 9: Fracture surfaces for UHM UD carbon/adhesive/steel DCB specimens showing varying degrees of fibre bridging

Table 6: Initiation G_{IC} Results for UHM UD CFRP/Adhesive/Steel DCB Specimens

Specimen	Test speed (mm/min)	G_{IC} (J/m²)
AQVX019	1	256
AQVX020	1	285
AQVX021	1	343
AQVX022	1	381
AQVX023	1	371
AQVX024	1	362
AQZG002	1	417
AQZG010	1	246
Mean		333
Standard deviation		63
Coefficient of variation (%)		19

5.2.2 Mode II

Mode II tests were undertaken using the ELS specimen and the jig shown in Figure 5. A single loading block was bonded to the UHM CFRP arm of specimens and the specimens were coated with white paint and marked as for the Mode I tests with the exception that pencil marks were made every 1 mm ahead of the crack tip. Specimens were loaded at 1 mm/min. and an event marker was used to link the crack position to the load-displacement response. After some initial trials, it was evident that the UD CFRP needed to be reinforced as some premature failures occurred in the CFRP arm. A woven GFRP material was bonded to the CFRP and repeat tests were undertaken.

G_{IIC} values were then calculated according to the Experimental Compliance Method (ECM) detailed in the ELS protocol within [27]. G_{IIC} as a function of delamination length is plotted in Figure 10. A mean initiation value of 1669 J/m² was achieved.

5.3 CASE STUDY 5 - CFRP/GFRP PIPE REPAIRS

The material combinations used in this case study were:

- Quadraxial CFRP - steel
- Quadraxial CFRP - one ply of biaxial woven GRP - steel

It is noted that the GFRP layer in the second of the combinations is included as a means of protecting against galvanic corrosion.

As for Case Study 2, the first panels that were manufactured for these tests did not include a PTFE film to act as a starter crack and therefore a 0.3 mm wafering blade was used to machine a starter crack to 60 mm in length. Additional panels were produced that did include a PTFE film and some additional tests were undertaken as comparisons to tests that used specimens with starter cracks created using the wafering blade.

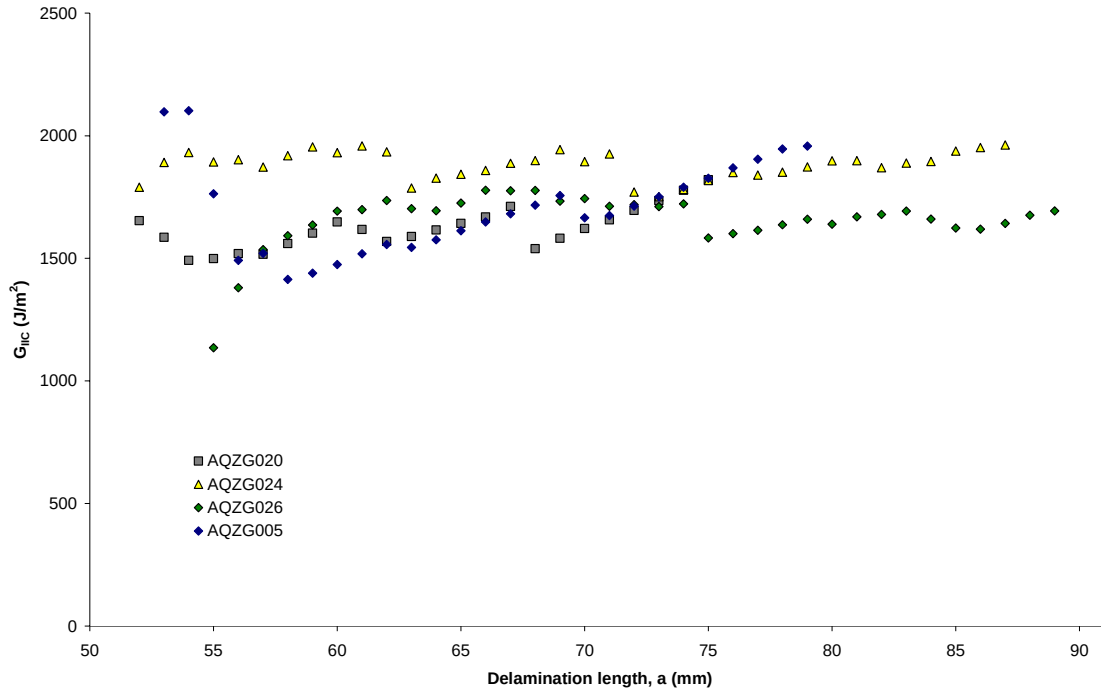


Figure 10: Compliance vs. delamination length for UHM UD carbon/adhesive/steel

5.3.1 Mode I

Tests were undertaken using the same method as described in Section 5.2.1.

The compliance vs. delamination length results for the quadraxial CFRP/steel DCB specimens are shown in Figure 11 and it was observed that the compliance behaviour was generally linear. The G_{IC} values as function of delamination length are shown in Figure 12. The G_{IC} initiation values showed quite a degree of variation from ~ 750 - 1500 J/m². The specimens containing the PTFE film starter crack showed no significant differences to the wafered notch specimens. For all specimens, after crack initiation the G_{IC} values tended to show an increase with increasing delamination length due to fibre bridging. Delaminations tended to run into the composite rather than grow along the interface between the steel and composite. Also, it was observed that for specimens where the crack ran in a 0° ply the G_{IC} values were higher than for those specimens where the crack ran in a 45° ply - see Figure 13. For the quadraxial CFRP/steel DCB samples a mean initiation value of 1082 J/m² was achieved.

The compliance vs. delamination length results for the quadraxial CFRP/GFRP ply/steel DCB specimens are shown in Figure 14 and it was observed that the compliance behaviour was generally linear. The G_{IC} values as function of delamination length are shown in Figure 15. The G_{IC} initiation values showed a large degree of variation from ~ 440 - 1270 J/m². A specimen containing a PTFE film starter crack was tested for comparison and resulted in the lowest G_{IC} initiation value of ~ 440 J/m² compared to ~ 700 J/m² for the wafered notch specimens. For all specimens, after crack initiation the G_{IC} values tended to show an increase with increasing delamination length due to fibre bridging. The chief failure mode was

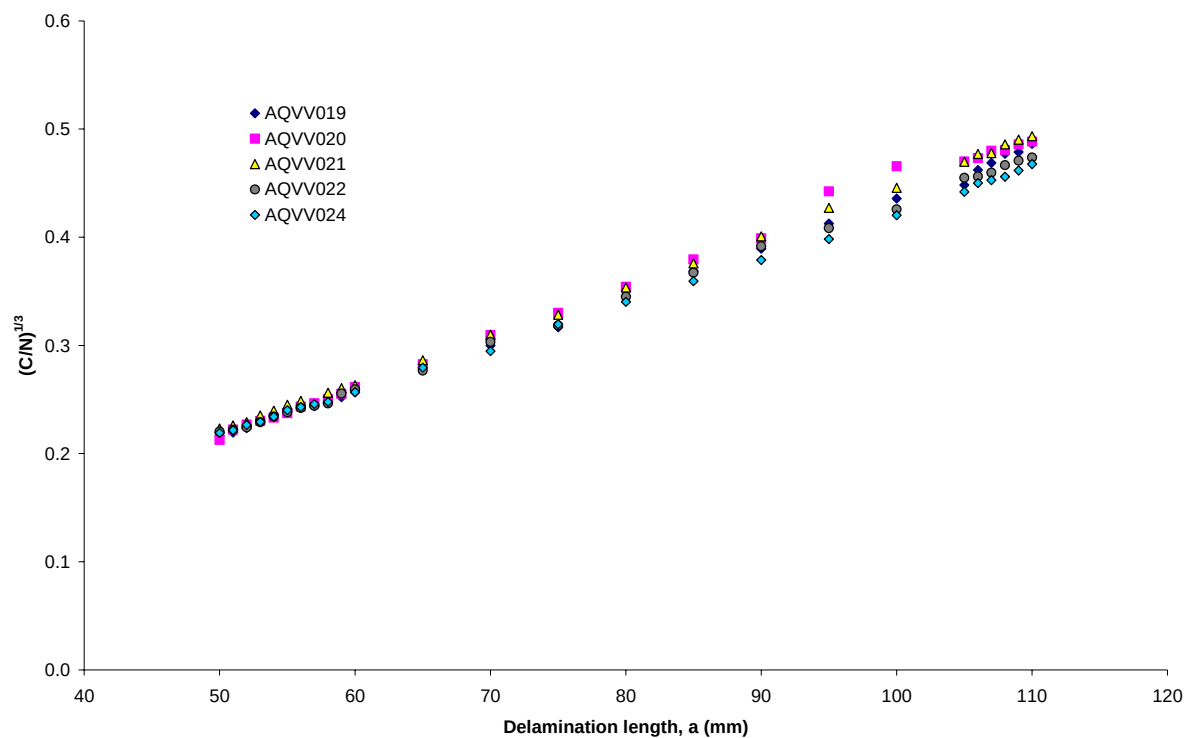


Figure 11: Compliance vs. delamination length for quadraaxial CFRP/steel

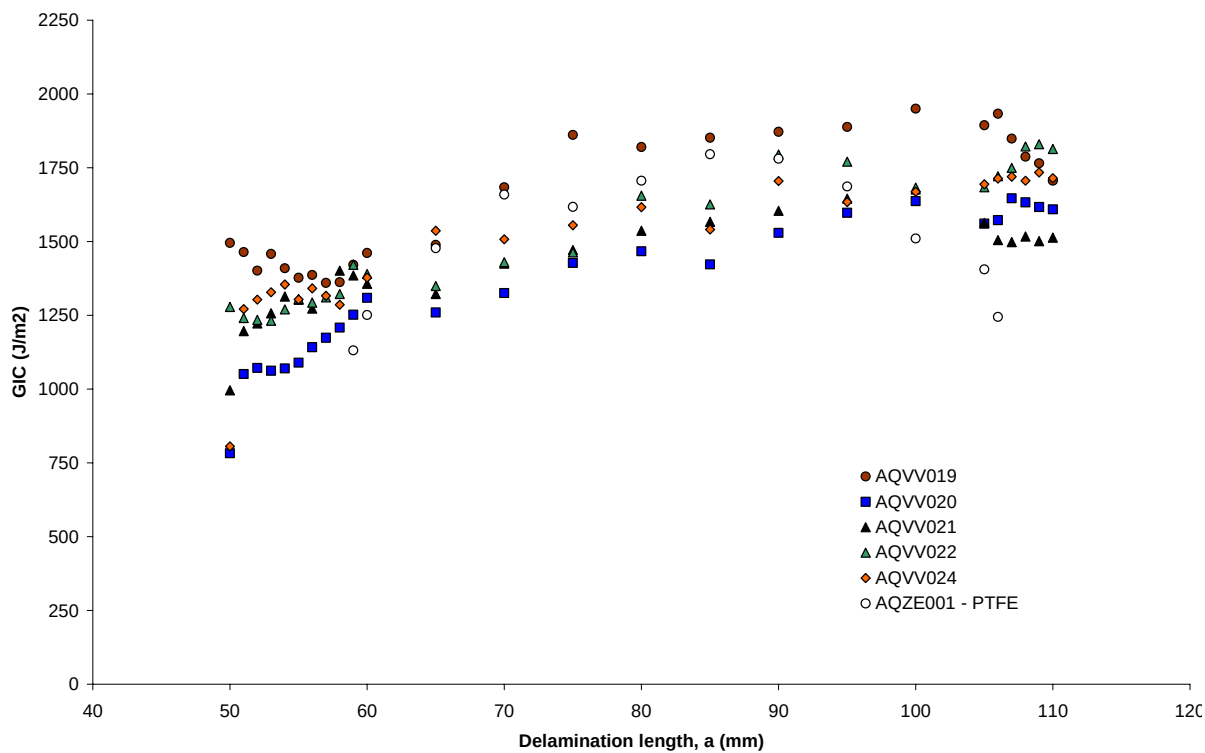


Figure 12: G_{IC} vs. delamination length for quadraaxial CFRP/steel



Crack in 0° ply



Crack in ±45° ply

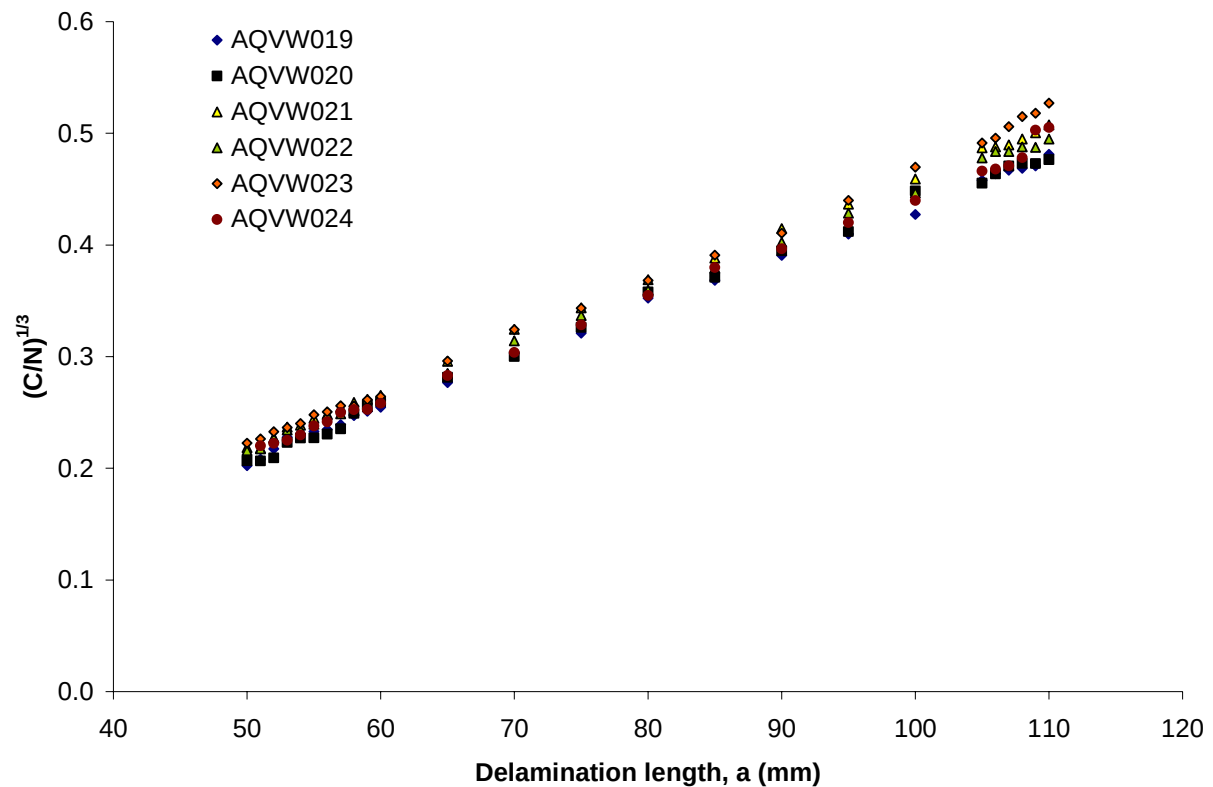
Figure 13: Delamination growth mechanisms for quadraxial CFRP/steel

observed to be delamination growth between the CFRP and GFRP ply, but one specimen also showed not only this mode of growth but also crack growth into the carbon laminate as well (Figure 16). This specimen achieved the highest initiation and propagation G_{IC} values - see Figure 15. For the quadraxial CFRP/GFRP ply/steel DCB samples a mean initiation value of 939 J/m^2 was achieved.

5.3.2 Mode II

Tests were undertaken using the same method as described and used in Section 5.2.2.

Tests for both material combinations proved to be difficult to undertake successfully, primarily as it was difficult to monitor crack initiation and propagation accurately. Therefore only a limited number of results were achieved. G_{IIC} values were calculated according to the Experimental Compliance Method (ECM) detailed in the ELS protocol within [27].

**Figure 14: Compliance vs. delamination length for quadraxial CFRP/GFRP layer/steel**

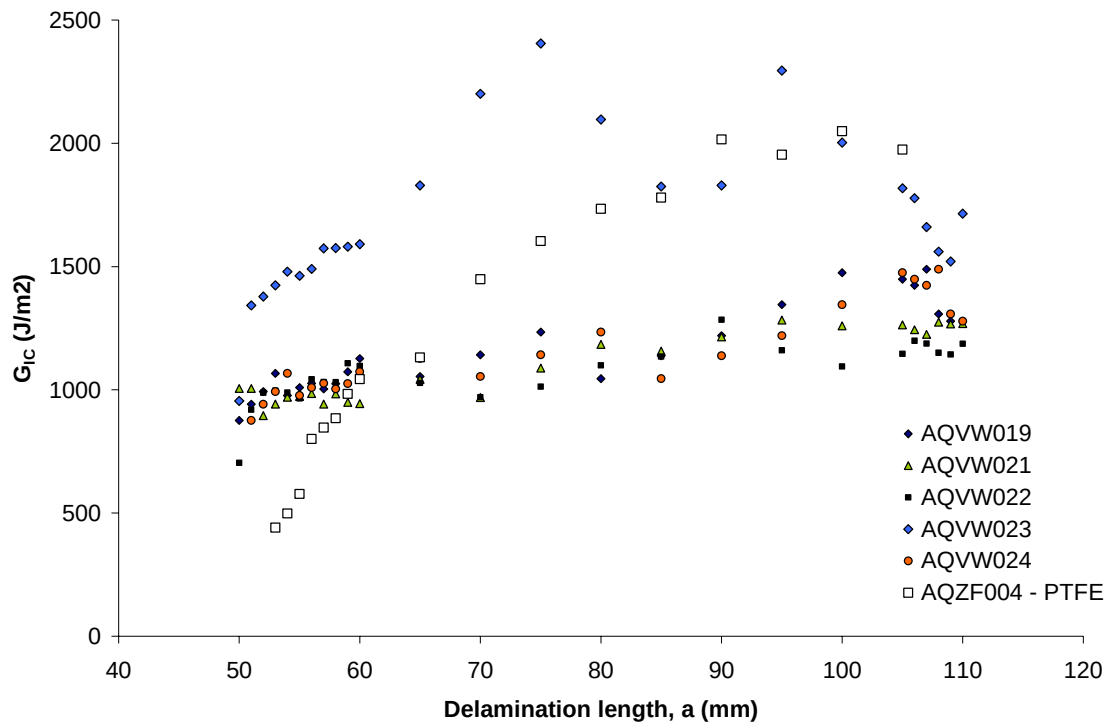
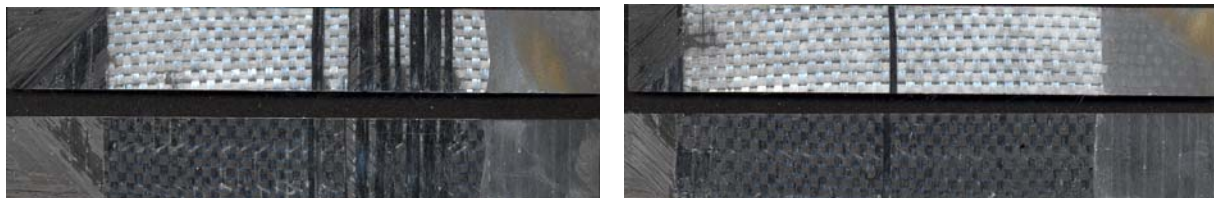


Figure 15: G_{IC} vs. delamination length for quadraxial CFRP/GFRP layer/steel



Crack running between CFRP laminate and GFRP ply, plus in CFRP laminate

Crack running between CFRP laminate and GFRP ply

Figure 16: Delamination growth mechanisms for quadraxial CFRP/GFRP layer/steel

The Mode II results for the quadraxial CFRP/steel and quadraxial CFRP/GFRP ply/steel material combinations are shown in Figures 17 and 18 respectively and have been included in this report to highlight the large degree of scatter in the G_{IIC} initiation results that was observed along with increases in G_{IIC} associated with fibre bridging.

Due to the limited number of successful tests undertaken and the degree of scatter in the results, the values obtained should only be treated as approximate, order of magnitude figures.

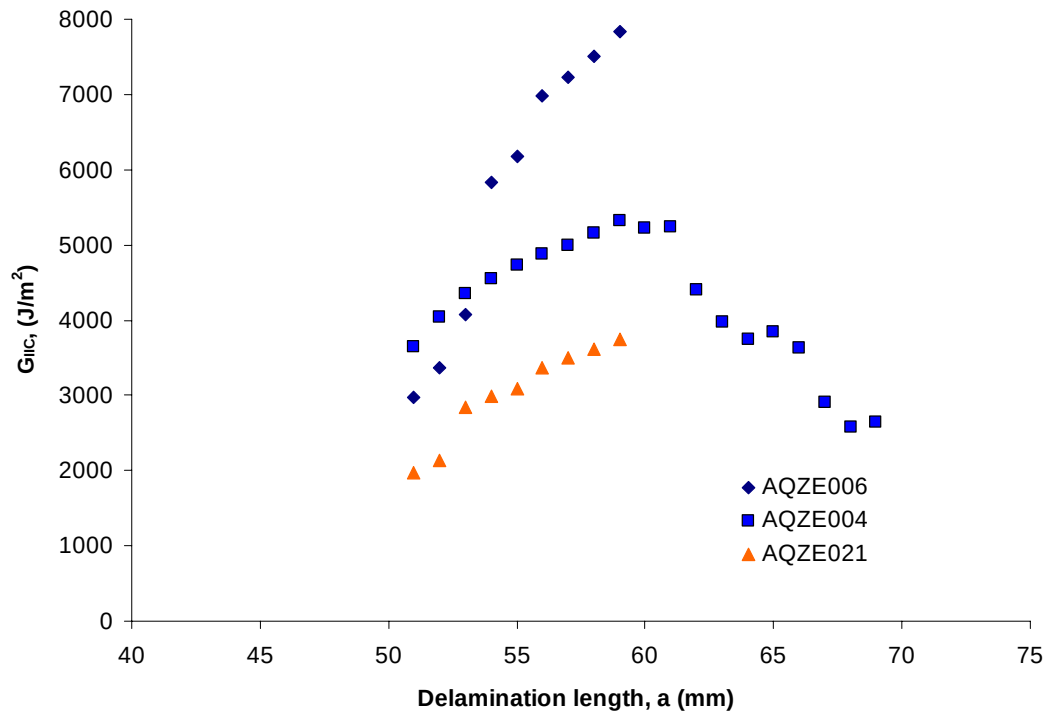


Figure 17: G_{IIC} vs. delamination length for quadraxial CFRP/GFRP layer/steel

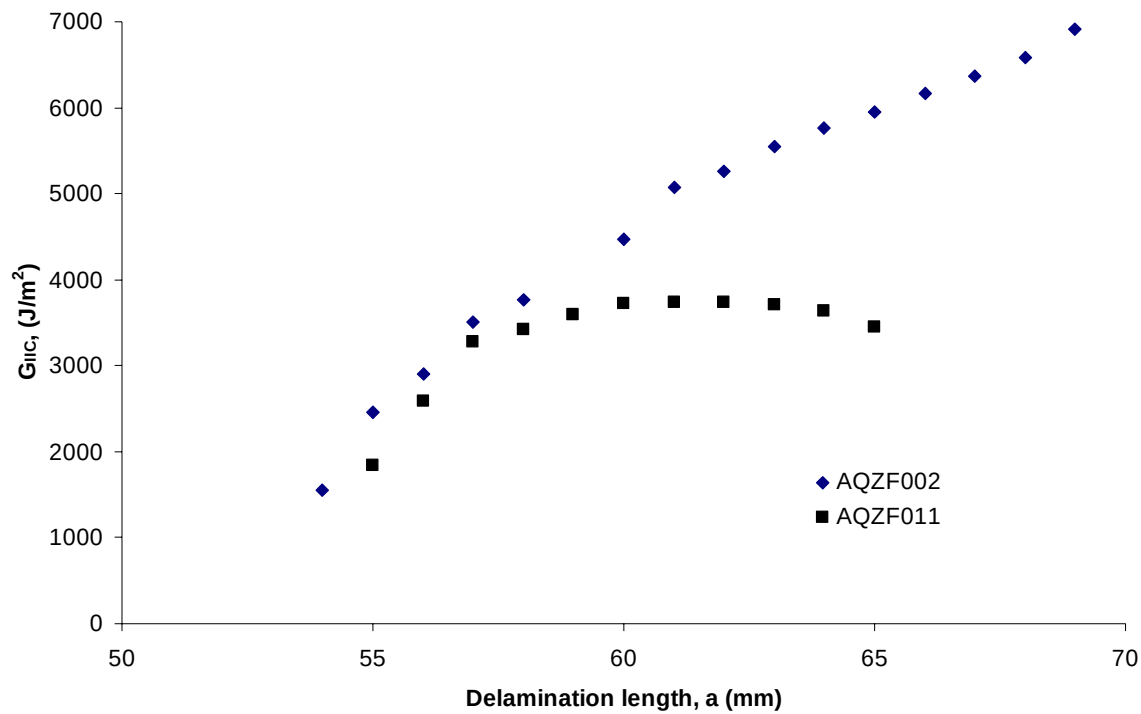


Figure 18: G_{IIC} vs. delamination length for quadraxial CFRP/GFRP layer/steel

6 CONCLUSIONS

A number of Mode I and II tests have been undertaken for several material systems consisting of similar and dissimilar material interfaces used in the ACLAIM project case studies.

The measurement of Mode I and II fracture toughness data for these material systems is not an easy task, with Mode II data being particularly difficult to measure. Existing test standards or protocols for measuring fracture toughness properties for composites and adhesives have been developed around configurations where the material on each side of the delamination tip is the same and in the case of composites is unidirectional in format. The material systems tested in this study consisted of bi-material interfaces, of various formats and in some instances a degree of curvature in the specimens existed. Hence, the stress state at the delamination tip is more complicated than for the ideal cases catered for in the test methods used. **Data have been produced (summarised in Table 7) although it is noted that all values, and in particular the Mode II values, should be treated as approximate.**

Table 7: Summary of Mode I and II Fracture Toughness Results

Case study	Material	G_{IC} (initiation) J/m ²	G_{IIC} (initiation) J/m ²
1	GFRP/SP340 adhesive	650-960 (727)	3500 (assumed)
2	UD CFRP/adhesive/steel	246-417 (246)	1400-1800 (1400)
5	Quadraxial CFRP/steel	750-1500 (750)	~3000
	Quadraxial CFRP/GFRP layer/steel	440-1270 (440)	~1700

Lower bound values in brackets

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