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Fracture mechanics test standards for polymers and composites

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Abstract
This research is based on the highlighting of the tests and tests standard that it is related to Fracture Mechanics. There are very many tests, but the research focuses on the most important tests which are the impact tests and fracture roughness tests.
In the first two chapters I presented the impact test, a widely utilized standardized test method the charpy impact test, with its quantitative and qualitative results. In the second chapter I emphasized the fracture toughness test's three-point beam bending tests. The research has in plan to explain in detail the test and tests standard pertaining to Fracture Mechanics.

Keywords: Fracture Mechanics, Fracture Toughness, Cleavage and Fracture, Double-Cantilevered Beam

Introduction

Fracture mechanics tests provide information on the growth of a fracture within a material and have been extensively applied to polymers and adhesives. The quantities determined through fracture mechanics tests are the critical stress intensity factor (K_c) and the critical strain energy release rate (G_c). The stress intensity factor is related to the geometry of the test specimen and crack tip. G_c is a material property.
The common fracture test methods for adhesives are based on the double-cantilevered beam (mode I) and end notch flexure (mode II) tests. Mode I (crack opening) tests impose severe cleavage stresses on bonded joints; some common test specimens are illustrated in Fig 1.

Fracture tests require an initial notch or pre-crack and the precise geometry of this notch will influence the results and is a source of uncertainty (variability) in the tests. Results from the initial part of the test are normally excluded from analyses with G determined from the regions of steady state crack growth. Fracture toughness is recognised as an important adhesive property, contributing to mechanical and impact performance.

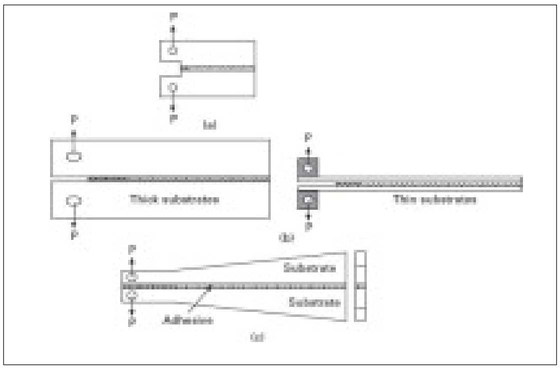

Fig 1: Cleavage and fracture tests; (a) compact tension, (b) double cantilevered beam, (c) tapered double cantilevered beam

1. Impact tests

The most important fracture tests can be divided in two categories: impact tests, and fracture toughness tests. The purpose of fracture testing is to establish the resistance of a metal to fracture.

In the impact tests, only the energy absorbed or the extent of cracking after a specified blow is determined. The fracture toughness tests are more quantitative and fundamental. These tests try to obtain fundamental parameters: the plane strain fracture toughness, the energy release rate, the crack opening displacement, the crack-tip opening displacement, and the *J* integral. The most common impact test (Charpy) and fracture toughness test are briefly described below.

1.1 Charpy impact test

The charpy impact test, also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. Absorbed energy is a measure of the material's notch toughness. It is widely used in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply. A disadvantage is that some results are only comparative. The test was pivotal in understanding the fracture problems of ships during World War II.

The test was developed around 1900 by S. B. Russell (1898, American) and Georges Charpy (1901, French). The test became known as the Charpy test in the early 1900s due to the technical contributions and standardization efforts by Charpy.

1.1.1 Quantitative results

The quantitative result of the impact tests the energy needed to fracture a material and can be used to measure the toughness of the material. There is a connection to the yield strength but it cannot be expressed by a standard formula. Also, the strain rate may be studied and analyzed for its effect on fracture.

The ductile-brittle transition temperature (DBTT) may be derived from the temperature where the energy needed to fracture the material drastically changes. However, in practice there is no sharp transition and it is difficult to obtain a precise transition temperature (it is really a transition region). An exact DBTT may be empirically derived in many ways: a specific absorbed energy, change in aspect of fracture (such as 50% of the area is cleavage), etc.

1.1.2 Qualitative results

The qualitative results of the impact test can be used to determine the ductility of a material. If the material breaks on a flat plane, the fracture was brittle, and if the material breaks with jagged edges or shear lips, then the fracture was ductile. Usually, a material does not break in just one way or the other and thus comparing the jagged to flat surface areas of the fracture will give an estimate of the percentage of ductile and brittle fracture.

Fig 2: A modern impact test machine

Fig 3: A vintage impact test machine. Yellow cage on the left is meant to prevent accidents during pendulum swing, pendulum is seen at rest at the bottom [1]

2. Fracture toughness test

Fracture toughness tests are performed to quantify the resistance of a material to failure by cracking. Such tests result in either a single-valued measure of fracture toughness or in a resistance curve. Resistance curves are plots where fracture toughness parameters (K, J etc.) are plotted against parameters characterizing the propagation of crack. The resistance curve or the single-valued fracture toughness is obtained based on the mechanism and stability of fracture.

Fracture toughness is a critical mechanical property for engineering applications. There are several types of test used to measure fracture toughness of materials, which generally utilise a notched specimen in one of various configurations. A widely utilized standardized test method is the charpy impact test whereby a sample with a V-notch or a U-notch is subjected to impact from behind the notch. Also widely used are crack displacement tests such as three-point beam bending tests with thin cracks preset into test specimens before applying load [2].

2.1 Three point flexural test

The three-point bending flexural test provides values for the modulud of elasticity in bending, flexural stress, flexural strain and the flexural stress-strain response of the material. This test is performed on a universal testing machine (tensile testing machine or tensile tester) with a three-point or four-point bend fixture.The main advantage of a three-point flexural test is the ease of the specimen preparation and testing. However, this method has also some disadvantages: the results of the testing method are sensitive to specimen and loading geometry and strain rate.

2.1.1 Testing method

The test method for conducting the test usually involves a specified test fixture on a universal testing machine. Details of the test preparation, conditioning, and conduct affect the test results. The sample is placed on two supporting pins a set distance apart.

Calculation of the flexural stress σ_f :

[1] Charpy impact test-Wikipedia, online URL available on the link: https://en.wikipedia.org/wiki/Charpy_impact_test, consulted-on-24-January-2021

[2] Fracture toughness-Wikipedia, online URL available on the link: https://en.wikipedia.org/wiki/Fracture_toughness, last-updated-9-January-2021, consulted-on-24-January-2021

$$\sigma_f = \frac{3FL}{2bd^2} \text{ for a rectangular cross section}$$

$$\sigma_f = \frac{FL}{\pi R^3} \text{ for a circular cross section}^{[1]}$$

Calculation of the flexural strain ϵ_f

$$\epsilon_f = \frac{6Dd}{L^2}$$

Calculation of flexural modulus E_f[2]

$$E_f = \frac{L^3 m}{4bd^3}$$

in these formulas the following parameters are used:

- σ_f = Stress in outer fibers at midpoint, (MPa)
- ϵ_f = Strain in the outer surface, (mm/mm)
- E_f = flexural Modulus of elasticity,(MPa)
- F = load at a given point on the load deflection curve, (N)
- L = Support span, (mm)
- b = Width of test beam, (mm)
- d = Depth or thickness of tested beam, (mm)
- D = maximum deflection of the center of the beam, (mm)
- m = The gradient (i.e., slope) of the initial straight-line portion of the load deflection curve, (N/mm)
- R = The radius of the beam, (mm)

2.1.2 Fracture toughness testing

The fracture toughness of a specimen can also be determined using a three-point flexural test.

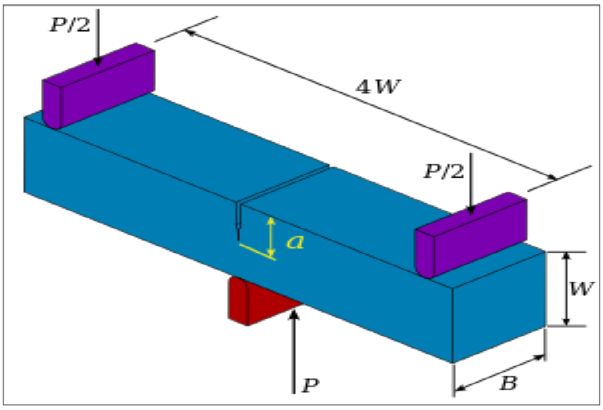

Fig 4: Single-edge notch-bending specimen (also called three-point bending specimen) for fracture toughness testing

The stress intensity factor at the crack tip of a single edge notch bending specimen is

$$K_{\rm I} = \frac{4P}{B}\sqrt{\frac{\pi}{W}}\left[1.6\left(\frac{a}{W}\right)^{1/2} - 2.6\left(\frac{a}{W}\right)^{3/2} + 12.3\left(\frac{a}{W}\right)^{5/2} - 21.2\left(\frac{a}{W}\right)^{7/2} + 21.8\left(\frac{a}{W}\right)^{9/2}\right]$$

where P is the applied load, B is the thickness of the specimen, a is the crack length, and W is the width of the specimen. In a three-point bend test, a fatigue crack is created at the tip of the notch by cyclic loading. The length of the crack is measured. The specimen is then loaded monotonically. A plot of the load versus the crack opening displacement is used to determine the load at which the crack starts growing. This load is substituted into the above formula to find the fracture toughness K_{Ic}.

The ASTM D5045-14 and E1290-08 Standards suggests the relation.

$$K_{\rm I} = \frac{6P}{BW}\, a^{1/2}\, Y$$

where

$$Y = \frac{1.99 - a/W\,(1 - a/W)(2.15 - 3.93a/W + 2.7(a/W)^2)}{(1 + 2a/W)(1 - a/W)^{3/2}}$$

The predicted values of $K_{\rm I}$ are nearly identical for the ASTM and Bower equations for crack lengths less than 0.6W. In the first picture we can noticed a concrete samples in test machine 1940. In the second picture we can observed a Test equipment in a universal test machine for testing flexible three-point.

Fig 5: 1940s flexural test machinery working on a simple of concrete

Fig 6: Test fixture on universal testing machine for three-point flex test [3]

2.2 Determination of tear resistance

2.2.1 Kahn tear test

The tear test (e.g. Kahn tear test) provides a semi-quantitative measure of toughness in terms of tear resistance. This type of test requires a smaller specimen, and can, therefore, be used for a wider range of product forms. The tear test can also be used for very ductile aluminium alloys (e.g. 1100, 3003), where linear elastic fracture mechanics do not apply.

3 Three-point flexural test-Wikipedia, online URL available on the link: https://en.wikipedia.org/wiki/Three-point_flexural_test, last-updated-14-July-2020, consulted-on-24-January-2021

3. Cleavage and fracture

3.1 The wedge cleavage test: (ISO 10354, ASTM D 3762), it is generally referred to as the Boeing wedge test, uses a wedge between two flat surfaces to force the separation of the adhesive force and to apply a split tension in the area of the crack tip. Over time, a controllable scale attached to the fitting is often used to monitor the length of the crack. Stressed samples may be exposed to unfavorable media and chemicals at the top of the crack may accelerate degradation. The crack growth limit is usually reached within days, making this test attractive as a simple and reliable method to quickly assess durability. The fracture energy G can be determined from the length of the crack a, the wedge displacement w, the connection module E and the thickness of the link h.

$$G = \frac{Ew^2h^3}{16}\left[\frac{3(a+0.6h)^2+h^2}{(a+0.6h)^3+\mathrm{ah}^2}\right]$$

This test is considered not to be particularly accurate to measure the breaking strength, because the driving force depends on the insertion distance of the wedge and the resistance to the joint. The accuracy of the fracture energy may be affected by the adhesive and plastic deformation of the adhesive (reducing the separation force). Although samples can be made with initial cracks in the interface, it is not certain that cracks will continue to expand along the interface. Analysis of the finished components shows that before the propagation of cracks the maximum deformation and deformation area in the specimen is close to the interface.

3.2 Compact tension test samples (ASTM D 1062): is manufactured by bonding an adhesive having the same geometry as the solid compressed force sample. Fig 7a. The sample shall be 25 mm wide and 25 mm long. On each side of the adhesion line, the adhesion depth is generally 12 mm. The specimen is loaded until the end of the connection that produces the breakout force. The test shall be carried out at a constant loading rate or at a lateral movement speed until the joint has completely fail. The maximum load shall be recorded.

3.3 The double-cantilevered beam (DCB): test as described in ASTM D 3433, Fig 7b is used to measure the initiation and propagation energy of a mode I crack. The critical deflection energy release rate (G_{IC}) depends on the length of the crack and is calculated using the following formula.

$$G_{\mathrm{IC}} = \frac{4P^2\,(3a^2+h^2)}{Eb^2h^3}$$

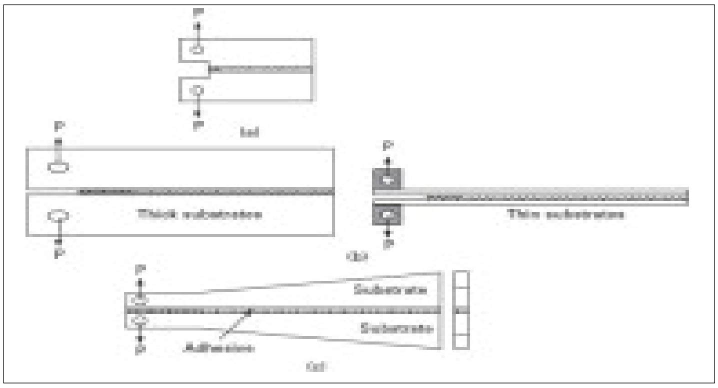

Fig 7: Cleavage and fracture tests; (a) compact tension, (b) double cantilevered beam, (c) tapered double cantilevered beam

where P is the applied load, E is the young adhesive module, b is the width of the sample, a is the length of the crack and h is the thickness of the adhesive.

The sample consistency test using the double cone beam test (TDCB) described in ASTM D3433, Fig 7c has nothing to do with the length of the crack. The rate of passage C is directly linked to load P, width, b, module of adhesion E and bending moment m. The G_{IC} is directly proportional to the rate of change of compliance with cracklength, a, which is obtained by the following formula.

$$G_{\mathrm{IC}} = \frac{4P^2}{Eb^2}m$$

The taper height is chosen such that m is constant with crack length a from the relationship.

$$m = \frac{3a^2}{h^3} + \frac{1}{h}$$

3.4 A composites test method I (ASTM D 6671)

Mode II tests for adhesives are limited. Tests based on a bonded version of the end notch flexure specimen, a composites test method (ASTM D 6671), have been used with limited effect to determine in-plane (shear) fracture toughness. The specimen is essentially the double-cantilevered beam specimen loaded in three- or four-point flexure, see Fig 8: For small displacements (and negligible transverse shear deformation), strain energy release is calculated using.

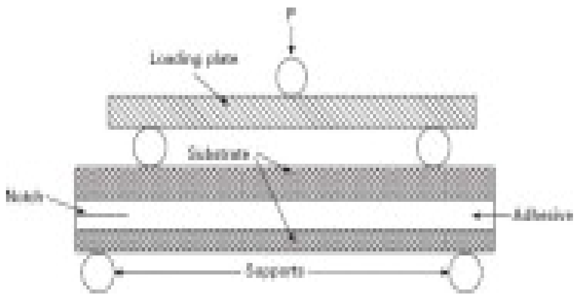

Fig 8: Schematic of the four-point end notch flexure test for mode II fracture toughness

$$G_{IIC} = \frac{9P^2a^2}{16Eb^2h^3}$$ [4]

4. Fracture and fatigue test methods in hydrogen gas

4.1 Screening tests

Other test methods, such as fracture mechanics tests can also be used as screening tests [62]. Given the reality that most hydrogen-induced failures of structural components result from hydrogen enhanced crack growth under either cyclic or quasi-static loading, screening tests that circumvent crack initiation are very effective. Assuming that the design pressure remains constant, the increase in the tensile strength of the material will allow a reduction in wall thickness and a corresponding increase in wall tension, resulting in a higher stress factor *K* at manufacturing defects. In order to maintain the same degree of fault tolerance, the material fracture threshold must be increased. Using this rationale the necessary fracture threshold (K_{TH}) has been determined to scale with the tensile strength as.

$$K_{TH} = 60 * (\text{UTS}/950)\text{MPa}\sqrt{m} \quad 7.2$$

K_{TH} is measured using either constant displacement or rising load fracture threshold test methods. The test result is not used as a design parameter for the vessel. If the result satisfies the criterion of equation (7.2) the material is considered to be fit for service in this particular application.[5]

5. Review of standard procedures for delamination resistance testing

5.1 Stress-based interlaminar tests

The preceding sections have focused on fracture mechanics tests, but there are also several stress-based delamination resistance tests. Descriptions of through-thickness test methods are available elsewhere, here only a brief overview will be given. Fig 9: shows some of the tests available to obtain interlaminar strength properties. Among these only the ILSS specimen is recognized as an ISO test method, ASTM standards are available for the 90° bend and Iosipescu specimens.

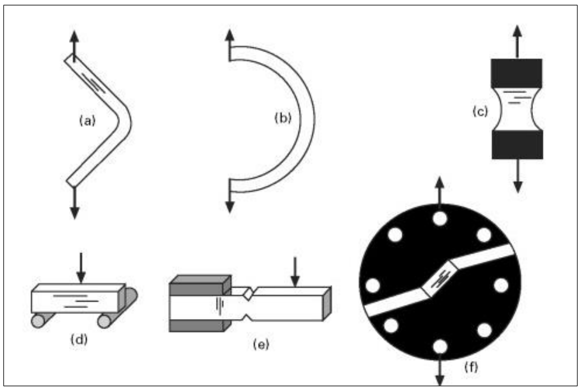

Fig 9: Interlaminar strength test specimens. Tension: (a) 90° bend; (b) C- specimen; (c) ILTT. Shear: (d) ILSS; (e) Iosipescu. Tension and shear: (f) Arcan fixture

The 90° bend specimen provides a means of obtaining interlaminar tensile strength from a simple test. A standard ASTM test procedure exists, which is based on work by Jackson and Martin who analysed unidirectional samples with a 90° bend loaded in tension. A close alternative is to use a C- shaped specimen, this is particularly interesting for the study of tubular structures. The choice of these tests on angular or curved structures reflects the difficulty in introducing loads directly into flat plates.

The four point ILSS test: is preferable but is rarely used. Alternative shear tests such as the so-called Iosipescu configuration allow interlaminar shear strengths to be measured, provided sufficiently thick samples are available. Finally, the Arcan fixture can be used to obtain interlaminar strengths under a range of loadings combining tension and shear. Fixtures allowing compression and shear can also be designed. This is a very attractive fixture, in some ways the stress equivalent of the MMB specimen. Its main disadvantage is the stress concentrations at the specimen ends, but the use of 'beaks' on the blocks which hold the composite can reduce these. The modified fixture has been applied to adhesives and should be suitable for composite specimens [6].

6. Delamination in adhesively bonded joints

6.1 Mixed-mode (I/II) loading: Mixed-mode bending (MMB)

A number of different LEFM test methods have been employed to measure the mixed-mode fracture toughness of adhesive joints and are shown schematically in Fig 10. A wide variety of adhesives and substrate materials have been investigated.

One of the most popular mixed-mode tests for composite delamination testing has been the mixed-mode bending (MMB) test developed at NASA Langley by Reeder and Crews (1992) and now an ASTM standard (ASTM 2004). The popularity stems from the ability to vary the mixed-mode ratio (or mixity) over a wide range with a single test apparatus. The mixed-mode ratio can be varied from almost pure mode I to almost pure mode II by simply adjusting the length of the lever arm.

This test has also been adopted for use in testing adhesively bonded joints as shown schematically in Fig 10a. Ducept and co-workers (Ducept *et al.*, 2000) used the MMB test to investigate mixed-mode failure criteria for composite-composite joints bonded with an epoxy adhesive. They used glass/epoxy composite substrates with a two part epoxy adhesive (Redux 420) and fitted empirical failure criteria to their data. Liu, Gibson *et al.* (2002a,b) used the MMB test to investigate mixed-mode fracture of adhesively bonded aluminium alloy substrates.

These authors made some modifications to the test specimen to avoid plastic deformation of the substrate arms and additionally refined the analytical model to incorporate the effects of the adhesive layer, elastic foundation and shear deformation ahead of the crack tip.

However, the MMB test is not without problems and various difficulties remain with the method, perhaps the most serious of which is the degree of scatter in the data when the mode-mix is substantially mode II, as is discussed in the following section.

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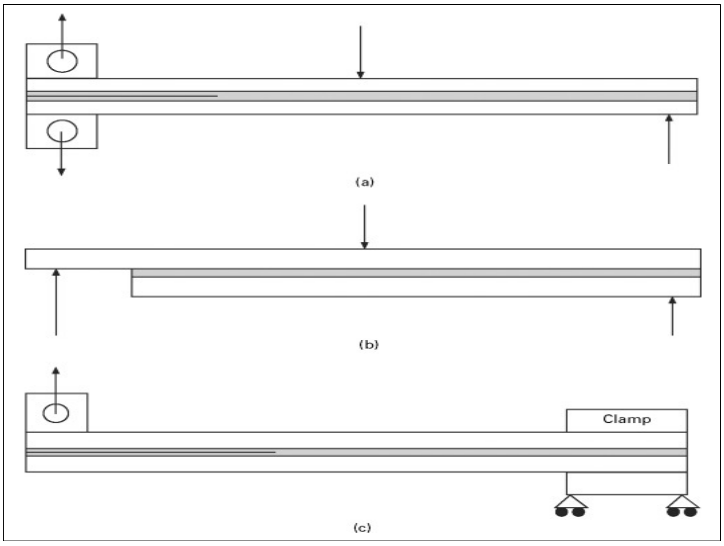

Fig 10: Mixed-mode (I/II) adhesive joint test specimens: a) the mixedmode bend (MMB) specimen, b) the mixed-mode flexure specimen and c) the asymmetric double cantilever beam (ADCB), also know as the fixed-ratio mixed-mode (FRMM) specimen

Another popular mixed-mode test for adhesive joints has been the mixedmode flexure (MMF) test proposed by Fernlund and Spelt (1994) and shown schematically in Fig 10b. Results have been reported for joints consisting of aluminium bonded with both a brittle epoxy adhesive and a tough epoxy adhesive (Papini, Furnlund *et al.* 1994).

Parvatareddy and Dillard (1999) investigated the effect of mode mix on joints consisting of titanium substrates bonded with an epoxy adhesive, FM-5. The MMF test was used, together with mode I DCB and mode II ENF tests. Their results indicated that $G_{IC} > G_{IIC}$ or $G_{I/IIC}$ – an unusual result which the authors suggested may have been due to the crack interacting with the woven glass scrim carrying the adhesive.

Finally, the asymmetric double cantilever beam (ADCB) specimen, also known as the fixed-ratio mixed mode (FRMM) test specimen has also been employed by various workers, as shown in Fig 10c. This test provides a constant mixed-mode ratio of $G_I/G_{II} = 4/3$ [7].

More fracture mechanics testing services

- Pre-cracking
- Fatigue testing
- Corrosion fatigue testing
- Tensile testing
- Charpy/Izod impact testing
- Bend testing
- Shear testing
- SENT testing
- SENB testing
- Stress Corrosion Cracking (SCC)
- Torque testing
- Ring flattening/Flat ring testing
- Nick break testing
- Fillet fracture testing
- Drop weight testing
- Hardness testing
- Fracture mechanics in sour environment
- Compact Tension (CT) testing
- Centre Cracked Tension (CCT) testing
- Surface Cracked Tension (SCT) testing [8]

Conclusion

The most important fracture tests can be grouped in two categories: impact tests, and fracture toughness tests. The purpose of fracture testing is to establish the resistance of a metal to fracture. In the impact tests, only the energy absorbed or the extent of cracking after a specified blow is determined. The fracture toughness tests are more quantitative and fundamental.

Among the impact test and fracture toughness test, the research showed another important Fracture mechanics tests.

The research contains an abstract, an introduction, 6 chapters, conclusion, bibliography.

The firts chapter aims to present the impact test, this mean the charpy impact test along with its quantitative and qualitative results.

The second chapter intends to explain the fracture toughness test with its three point flexural test, which contains the testing method, the fracture toughness testing and also the determination of tear resistance with kahn tear test.

The third chapter presents cleavage and fracture and its four tests: the wedge cleavage test, the compact tension test samples (ASTM D 1062), the double-cantilevered beam (DCB), a composites test method (ASTM D 6671).

The fourth chapter aims to show the fracture and fatigue test methods in hydrogen gas with the screening tests.

The fifth chapter contains the stress-based interlaminar tests: a standard ASTM test, the four point ILSS test.

The sixth chapter propose to present the delamination in adhesively bonded joints with the mixed mode (I/II) loading: mixed-mode bending (MMB), mixed mode flexure (MMF).

In the end the research contains a conclusion and references.

[7] B.R.K. Blackman, (2008) in Delamination Behaviour of Composites

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