Determination of the adhesive fracture energy G_C of structural adhesives using DCB and Peel tests

Določitev raztržne žilavosti strukturnih adhezivov G_C z uporabo DCB in odluščnih preizkusov

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Abstract: Due to the increasing use of adhesively bonded load bearing joints in demanding Engineering applications, the failure properties of adhesives need to be known.The fracture testing of adhesive joints has been developed to yield engineering data used for comparative analysis between adhesives and also the different substrates used. A large number of different tests have been developed to measure the adhesive fracture toughness, G_C, of adhesive joints. In this work two different types of test are presented, an elastic plastic peel test and a double cantilever beam test, based on linear elastic fracture mechanics (LEFM). Ideally, adhesive fracture toughness should be a geometry independent value, a characteristic adhesive property.

Izvleček: Zaradi vse večje uporabe adhezivnih spojev v avtomobilski in letalski industriji je poznavanje mehanskih lastnosti adhezivov izrednega pomena. Preizkušanje zlepljenih spojev z uporabo strukturnih adhezivov je bilo v prvi vrsti razvito za pridobitev primerjalnih podatkov različnih adhezivov in podlag, uporabljenih pri spojih. Obstaja veliko različnih geometrijskih oblik preizkusov za določitev energije raztržne žilavosti strukturnih adhezivov. V tem delu sta predstavljena dva osnovna tipa geometrije, in sicer: elastoplastični odluščni preizkus in preizkus z uporabo dvojnega konzolnega nosilca (DCB), ki je osnovan na linearni mehaniki loma. Idealno je energija raztržne žilavosti adhezivov neodvisna karakteristična veličina adheziva.

Key words: fracture tests, adhesives, Peel tests, DCB test
Ključne besede: lomni preizkusi, adhezivi, odluščni preizkusi, DCB-preizkusi

Review paper

INTRODUCTION

Adhesive joints are an effective way of connecting structural components such as metals and polymers. Comparing to the traditional joining techniques riveting and welding adhesively bonded structures experience many advantages. The most important in aerospace and automotive industry are weight savings and good dynamic fatigue properties [1]. The effective bonding of sheet materials also makes it very appealing for the packing industry.

There have been a large number of different tests developed to obtain the fracture resistance of structural adhesive joints [1], among them are two of particular interest for this work: the double cantilever beam bending test (DCB), which is based on a linear-elastic fracture mechanics (LEFM), and the elastic-plastic T-peel test, both tests yield the adhesive fracture toughness G_C.

Guidance on conducting fracture tests is described in various standards, e.g. for a DCB test geometry there is a British standard BS 7991 [2], the existing ISO standards: ISO 8510-1 1990 [3] and ISO 8510-2 1990 [4] "Peel test for a flexible bonded to rigid specimen assembly, Part 1 90° peel and Part 2 180°", ISO 11339 1993 "180 peel test for flexible to flexible bonded assemblies" (T-peel test), indicate how to measure peel strength, force per unit width for peeling. To determine the adhesive fracture toughness from the measured peel strength described in the ISO standards, a special protocol was developed at the Imperial College, called ICPeel [5].

DCB TEST PRINCIPLES

Introduction

One of the most frequently used test geometries for generating Mode I adhesive fracture energy, G_{IC}, is the double cantilever beam specimen. In this test the substrates, usually made from metal, are bonded together with the adhesive and the crack is propagated along the adhesive layer in opening mode by pin loading at the beam-ends. The method used to determine the fractural resistance is based on linear elastic fracture mechanics (LEFM). From this test, both the resistance to crack initiation and propagation can be determined and the resistance curve (plot of G_{IC} vs. crack length) can be produced [2].

DCB specimen geometry

Generally a DCB test specimen is suited for testing joints, where relatively thin sheets of fibre composite materials are adhesively bonded, but may also be used for metallic substrates. A typical specimen used for metallic substrates is shown in Figure 1.

Test procedure

Test is preformed under normal conditions (23 °C ± 2 °C, 50 % ± 5 % r. h.) on a tensile testing machine, capable of producing a constant cross-head displacement rate between 0.1 mm/min and 5 mm/min in displacement control. A special fixture is used to introduce the load to the pins inserted into substrate beams.

The tensile testing machine compliance must be taken into account. If the machine compliance is not known, it should be determined using the calibrated specimens [2].

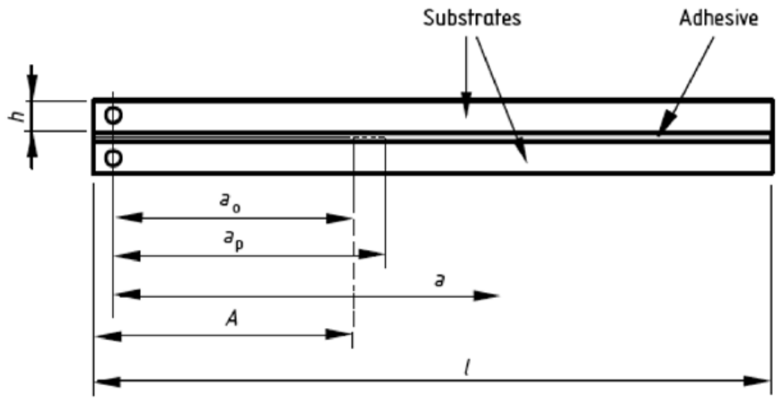

Figure 1: DCB test specimen geometry [2]. Where: *A* - insert film length, distance between the end of the specimen and the tip of the insert film, *a* - crack length, distance between the load line and the tip of the crack, a_0 - initial crack length, a_p - precrack length, distance from the load line to the tip of the precrack, *B* - specimen width, *h* - arm thickness, h_a - adhesive layer thickness, *l* - specimen length.
Slika 1: Geometrija DCB-preizkušanca. Oznake: *A* - dolžina vstavljenega traku, razdalja med koncem preizkušanca in začetkom razpoke, *a* - dolžina razpoke, razdalja med linijo obremenitve in vrhom razpoke, a_0 - začetna dolžina razpoke, a_p - dolžina predrazpoke, *B* - širina preizkušanca, *h* - širina konzolnega nosilca, h_a - debelina adheziva, *l* - dolžina preizkušanca.

During the test progress, recording of the complete load versus displacement curves are taken. At the same time the crack is measured using a travelling microscope or a video camera.

Analysis methods or determining the values G_{IC}

There are three analyses methods that may be used to calculate G_{IC} from the DCB test data, where $_I$ denotes Mode I loading condition.
(1) simple beam theory (SBT),
(2) corrected beam theory (CBT), and
(3) experimental compliance method (ECM).
All of them are essentially derived from Equation (2.1), and all require the monitoring of load, crack opening displacement, and crack growth to determine variation of compliance with crack growth. A brief outline of every analysis method is discussed at this point.

Simple beam theory.

The value of adhesive fracture energy G_{IC} may be deduced from:

$$G_C = \frac{1}{2B} P^2 \frac{dC}{da} \tag{2.1}$$

where *C* is the compliance and is given by load-line *displacement(δ)/load(P)*. The compliance change with crack length was derived by MOSTOVOY at al. [6] where bending and shear deflection contribute to the specimen compliance. The specimen was treated as a pair of cantilever beams with length *a,* representing the crack length, measured from the point of loading. The dC/da may be written as

$$\frac{dC}{da} = \frac{8}{E_S B}(\frac{3a^2}{h^3} + \frac{1}{h}) \quad (2.2)$$

where E_S is the flexural or tensile modulus of the substrate. This value is quoted for the standard grade materials, otherwise should be measured from an independent modulus test.

Inserting expression for dC/da into equation (2.1) gives G_{IC}

$$G_{IC} = \frac{12P^2a^2}{E_S B^2 h^3}(1 + \frac{1}{3}\frac{h^2}{a^2}) \quad (2.3)$$

This value can be further simplified if the condition $a^2 >> h^2$ is met, it means that the crack length is much larger than the beam arm thickness and deflection due to shear stress can be neglected

$$G_{IC} = \frac{12P^2a^2}{E_S B^2 h^3} \quad (2.4)$$

where h, B, and E_S are the height, width and Young's modulus of the substrate, respectively.

Corrected beam theory

The simple beam theory does not account for the important effect of beam root rotation, which affects compliance and G_{IC}. It has been shown that this effect can be modelled by adding a length, Δ, to the measured crack length [8]. Adhesive fracture energy may be calculated using the following equation

$$G_{IC} = \frac{3P^2\delta}{2B(a+\Delta)}\frac{F}{N} \quad (2.5)$$

where δ is the measured load-line displacement, F is a correction factor which accounts for the reduction in bending moment caused by large displacements and N is the load block correction. When piano hinges are drilled directly through the substrate, as is the case for metal substrates, N = 1. Further information can be found [8, 2, 9], where detailed explanations and derivation of the variables are provided.

Experimental compliance method

In order to estimate the change of compliance in relation to crack growth, compliance is plotted against crack length and then curve fitted using the Berrys method [9], which employs a power-law compliance calibration

$$C = ka^n \quad (2.6)$$

where k and n are regression coefficients determined from experiments. Differentiating this equation with respect to crack length, a, and combining the differential with Equation (2.1) leads to

$$G_{IC} = \frac{nP\delta}{2Ba}\frac{F}{N} \quad (2.7)$$

Elasto-plastic peel tests

Introduction

Peel test is a widely used method for measuring the peeling energy between flexible joints [1]. The level of the bond strength is a critical issue since laminates act as engineering structures, therefore it is very important to be able to control adhesive fracture toughness. Ideally, adhesive fracture toughness should be a characteristic adhesive property, independent of test geometry such as the thickness of the peel arm or peel angle [1]. Due to the fact of wide application of peel tests, several test geometries have been used. Two particular forms used in this work are the fixed arm peel test and T-peel test (Figures 3, 4). Since the T peel test may be seen as a two fixed arm tests combined, the fixed arm peel test is analysed firstly and then extended to T-peel test.

Peel specimen geometry

There are two basic types of test geometry, a fixed arm peel test, and a T-peel test. The specimen for the peel test should be of a rectangular shape, where the two parts of the joint have already been adhered but where there is a region of unadhered material (of nominal length 30 mm) [5]. The peel arms should be thick enough to withstand the expected tensile force, their dimensions are carefully measured and assembled with great caution. The overall dimensions of peel specimen need not be rigidly defined but for many tests a total length of 100 mm and width of 20 mm proves to be quite satisfactory. An example of fixed arm peel test geometry is shown on Figure 2. Mirroring the fixed arm geometry, about the bond line, derives the T-peel test geometry. Symbols used for peel geometry are given below.

Experimental procedure

The choice of peel fixture is not unique but the jig should incorporate a number of facilities. Most important among them is that the fixture should be able to select the peel angle in the range up to 180 ºC. The peel specimen is fixed at the bottom of the supporting frame of the tensile testing machine (Instron), and attached to the load cell and the testing machine crosshead. A peel test speed (crosshead speed) of 10 mm/min can be used as a standard with a 90º peel angle. However, the peel speed will be influenced by the peel angle. For the fixed peel arm testing, the peel arm is clamped to a load cell and the specimen base is bolted to a linear bearing trolley, which moves in the horizontal direction as to keep the position of the crack front constant. For the T-peel specimens two clamps are used to grip the specimen in position, with one clamp attached to the testing machine load cell, the other to the base of the machine.

Analyses of the fixed arm peel test

In order to peel one laminate from another, or from a rigid support, requires energy in the form of external work to be applied to the laminate, Figure 3. Since the peel arm may exhibit plastic or viscoelastic behav-

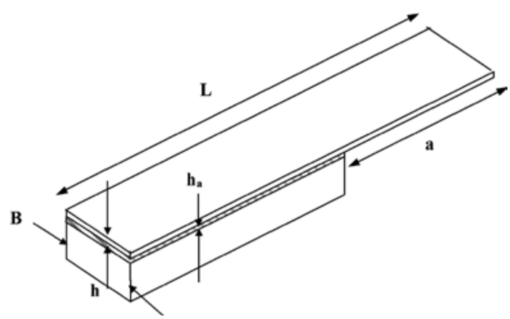

Figure 2. Fixed arm peel test specimen geometry. Where, a - crack length, distance between the load line and the tip of the crack, B - specimen width, h - arm thickness, h_a - adhesive layer thickness, L - specimen length.

Slika 2. Geometrija enostransko vpetega odluščnega preizkušanca. Oznake: a - dolžina razpoke, razdalja med linijo obremenitve in vrhom razpoke, B - širina preizkušanca, h - širina konzolnega nosilca, h_a - debelina adheziva, L - dolžina preizkušanca.

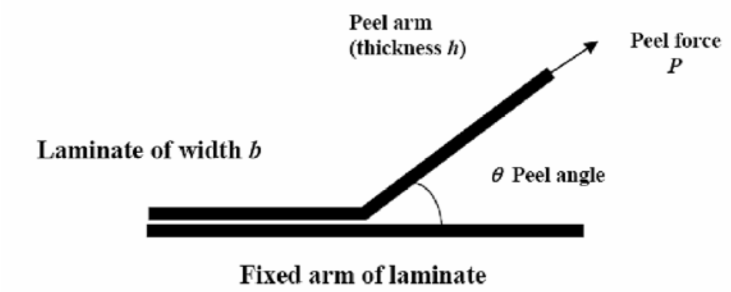

Figure 3. Fixed arm peel test specimen [5]
Slika 3. Enostransko vpet odluščni preizkušanec

iour, the historically used peel strength, which was the governing factor in the peel tests, was very geometry and material dependent. ESIS protocol was written by Moore and Williams [5] to transfer historically measured peel strength, which measures the strength of the adhesively bonded joint, to adhesive fracture energy, which is a measure of how well the two surfaces are bonded together. The protocol used was based on the work of Kinloch et al. [10] and Georgiou et al. [11] where they used the energy balance argument and derived the adhesive fracture energy, which relates external work added to the system (U_{ext}), strain energy stored in the peel arm (U_s), energy dissipated during tensile deformation of the peel arm (U_{dt}) and the energy dissipated during the bending of the peeling arm near the peel front (U_{db}).

$$G_C = \frac{1}{B}\left(\frac{dU_{ext}}{da} - \frac{dU_s}{da} - \frac{dU_{dt}}{da} - \frac{dU_{db}}{da}\right) \quad (3.1)$$

Where G_C stands for a geometry independent property and is a characteristic value for a particular adhesive [1,10]. To convert peel strength (P/mm) to adhesive fracture energy, the following equation is used

$$G_C = G - G_P \quad (3.2)$$

where G is the peel strength-measured load, G_P is the plastic arm energy caused by bending the peel arm. When no tensile strain in the peel arm is assumed, input energy G may be written as

$$G = \frac{P}{B}(1 - \cos\theta) \quad (3.3)$$

If zero bending stiffness is considered, this expression is also used as the adhesive fracture energy, where θ is the peel angle as shown in Figure 3.

This would be the case for a material of infinite stiffness and no bending stiffness. However, if there is an elastic-plastic deformation in the peeling arm, it is necessary to have knowledge of the tensile characteristics of the peel arm material and the full expression for G_C becomes

$$G_C = \frac{P}{B}(1 + \varepsilon - \cos\theta) - h\int_0^{\varepsilon} \sigma d\varepsilon - G_{db} \quad (3.4)$$

where ε is the tensile strain, σ is the stress, h is the height of the peel arm and G_{db} accounts for plastic or viscoelastic bending of the peel arm given by

$$G_{db} = -\frac{1}{B}\frac{dU_{db}}{da} \quad (3.5)$$

Analysis of the T-peel test

In Figure 4, the specimen configuration of T-peel-test is shown. The analysis adopts the same steps as in the fixed peel arm, except that now two peel arms are considered instead of one. If one peel arm is stiffer than the other, as in the case of unbalanced peeling, two different peel angles are present rather then two 90° angles. Since the angles are correlated via $\Phi = \pi - \theta$, only one angle should be considered. The Equation (3.3) becomes:

$$G_1 = \frac{P}{B}(1+\cos\theta) \tag{3.6a}$$

$$G_2 = \frac{P}{B}(1-\cos\theta) \tag{3.6b}$$

where subscripts 1 and 2 stand for each peel arm. In a similar manner there will be two forms of plastic peel arm dissipative energy, which results in two forms of fracture toughness energy expressions:

$$G_{C1} = G_1 - G_{P1} \tag{3.7a}$$

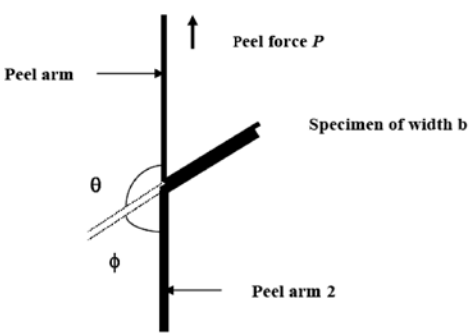

Figure 4. T-peel-test specimen [5]
Slika 4. Odluščni preizkušanec v obliki črke T ali T-odluščni preizkušanec

$$G_{C2} = G_2 - G_{P2} \tag{3.7b}$$

The adhesive fracture toughness is simply the sum of the last two equations:

$$G_C = G_{C1} + G_{C2} \tag{3.8}$$

When balanced T-peel test is assumed, $\Phi = \theta = 90^\circ$, $\cos\theta$ becomes equal to zero, and all the equations derived for fixed arm peel test at 90º may be multiplied by 2, hence describe the situation in T-peel test.

In order to determine G_C, from peel tests, elastic and plastic deformations are taken into account, and two tests must be conducted:
(1) Peel test
(2) Tensile test of the peel arm material
All the detailed calculations regarding peel tests are given in references [5, 10, 11] and while theoretical calculations can be very complex, software that may be used to conduct the calculation is available on the Imperial College web site [12].

Results and discussion

In DCB experiment mild steel beam arms (E = 207 GPa) and ESP110 (E = 4 GPa) adhesive were used. The geometry details of the DCB test specimen are given in Table 1.
All data analysis were preformed using the Microsoft Excel© spreadsheets, which were written at Imperial College and can be obtained freely from [9,12]. The spreadsheets automatically performed all the data reduction, plots and calculations of G_C, using the presented theory.

Table 1. DCB-test specimen data
Tabela 1. Geometrijski podatki za DCB-preizkušanec

	Label	[mm]
Specimen length	L	190
Arm thickness	H	20
Specimen width	B	25
Initial crack length	a_0	50
Adhesive layer thickness	h_a	0.4

In Figure 5 a typical load versus crosshead displacement curve is shown. Due to load take up effects, there was initial non-linear trace, which was removed by extrapolating the linear part and resetting the intercept to zero displacement. The first, linear part up until maximum load applied, depicts the elastic loading history before the crack growth. During the crack growth the compliance of the DCB is increasing and the load is dropping. Another way of presenting the results is via load versus crack growth, starting at the beginning of the crack growth, Figure 6.

When very stiff DCB specimens are tested, significant displacement errors could be introduced. For that reason a system compliance value was measured and a correction was made. Figure 7 shows the resistance curves corrected for the effect of system compliance via the three analyses methods previously presented. The resistance curves are constructed to show how the values of G_{IC} develop during crack growth. It may be seen that SBT is in disagreement with CBT and ECM, most likely due to incorrect assumptions made in SBT derivation. Neglecting the crack root rotation, as is the case in SBT derivation, may leads to substantial errors.

The initial and mean propagation values of G_{IC} were directly deduced from the spreadsheet, Table 2. The mean propagation was simply the mean of all the non-initiation G_{IC} values.

Table 2. Initiation and mean propagation values of G_{IC} for the DCB joints
Tabela 2. Začetna in srednja vrednost napredovanja G_{IC} pri DCB-spojih

	G_{IC}(SBT)/(J/m^2)	G_{IC}(CBT)/(J/m^2)	G_{IC}(ECM)/(J/m^2)
Initiation	345	434	458
Mean propagation	636	978	977

For the peel test experiment the substrate material was made of Aluminium-alloy 5754 (E = 69 GPa) and the adhesive used was ESP110 (E = 4 GPa). Details of the dimensions of the peel joints are given in Table 3.

Table 3. T-peel-test specimen data
Tabela 3. Geometrijski podatki za T-odluščni preizkušanec

	Label	[mm]
Specimen length	L	295
Arm thickness	H	1
Specimen width	B	20
Initial crack length	A	180
Adhesive layer thickness	h_a	0.4

An example of a typical load versus crosshead displacement for a T-peel specimen is shown in Figure 8. The load fluctuates significantly with displacement during the crack growth as the crack moves form one substrate interface to the other (load is expressed in N per mm width as peel force). The load versus crosshead displacement trace for the 90° peel test differs considerably from the T-peel trace as is shown

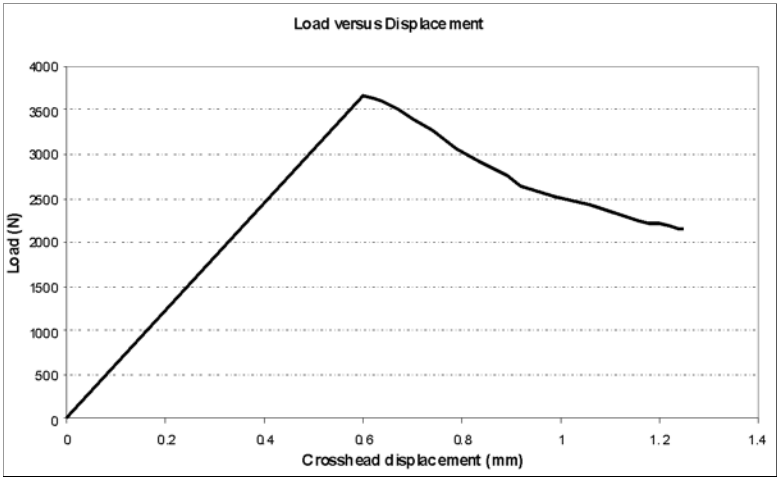

Figure 5. A typical load-displacement trace for a DCB joint [7]
Slika 5. Značilen potek krivulje obremenitev-pomik čeljusti, pri DCB-spojih

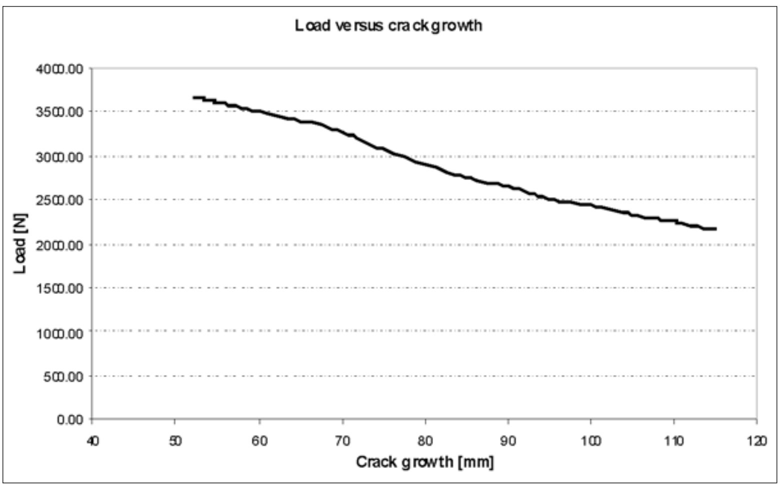

Figure 6. A typical load-crack growth trace for a DCB joint [7]
Slika 6. Značilen potek krivulje obremenitev-rast razpoke, pri DCB-spojih

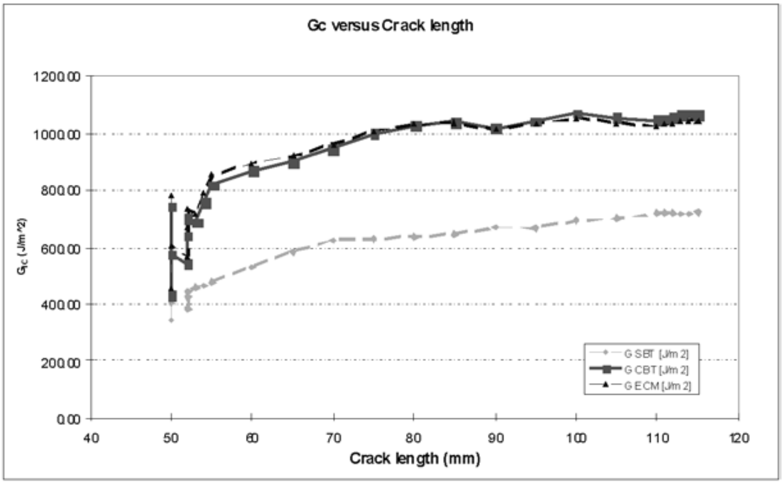

Figure 7. A typical set of resistance curves for a DCB joint [7]
Slika 7. Značilne krivulje raztržne žilavosti DCB-spojev

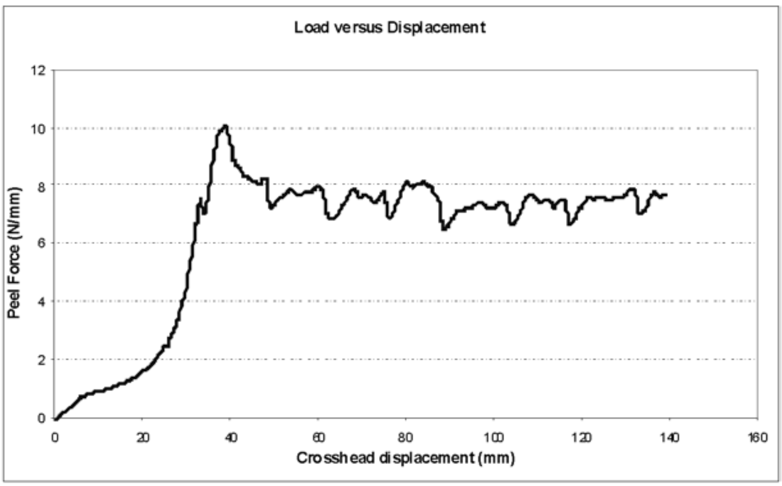

Figure 8. A typical load-displacement trace for a T-peel test
Slika 8. Značilen potek krivulje obremenitev-pomik čeljusti za T-odluščni preizkušanec

in Figure 9. Only minor load fluctuations with displacement during crack growth are observed. It can be said that the load reaches a steady state value after a certain amount of crack growth.

Using the spreadsheet for peel tests and the data obtained from the experiment the values of G_I can be easily obtained, although the calculations may look fairly complicated. Since the mean steady state peel force is used in the calculations, the G_I represents the propagation value. It is almost impossible to detect the beginning of the crack growth for these tests therefore the initiation value of G_I is not attainable.

Table 4. Propagation values of G_C for the peel tests

Tabela 4. Obremenitev in G_C odluščnih preizkusov

	P/(N/mm)	G_I/(J/m^2)
T-peel	7.43	1370
90° peel	5.00	922

From table 4 it may be seen that the adhesive fracture toughness between T-peel and 90 ° peel tests differ greatly, which is most likely due to an unsteady crack growth. There is a combination of adhesive and cohesive fracture, for which cohesive and adhesive fracture toughness should be determined.

CONCLUSIONS

Firstly, a LEFM-based approach was presented via DCB test geometry. To calculate G_{IC} (Mode I loading condition) from a DCB specimen, three methods were presented. Corrected beam theory and Experimental compliance method both yield accurate results, whereas Simple beam theory can only be applied under specific conditions.

Secondly, two types of elastic plastic peel tests were presented. Fixed arm peel test

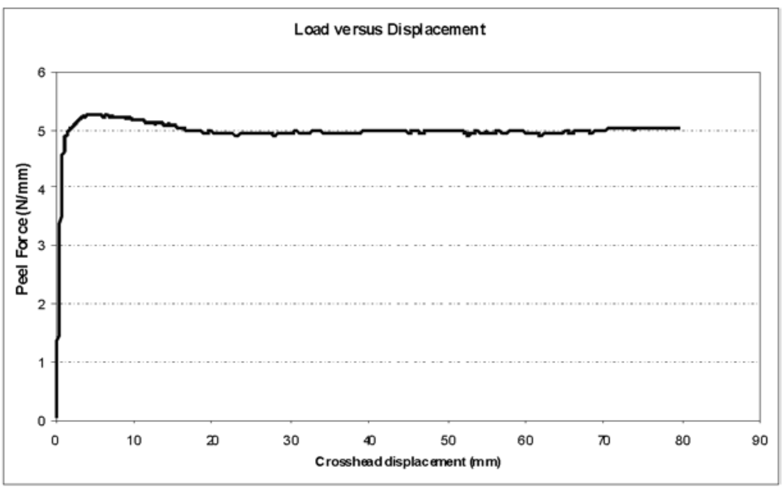

Figure 9. A typical load-displacement trace for a 90° peel test

Slika 9. Značilen potek krivulje obremenitev-pomik čeljusti za 90-stopinjski odluščni preizkušanec

(90° peel test) and the T-Peel test were introduced to show how the plastic deformation and root rotation of the beam arms is accounted for in determining the fracture toughness of adhesives. All the steps needed to transfer experimentally obtained data, peel strength to fracture toughness of the adhesive, were outlined. Additionally, the experimental results, the load versus crosshead displacement traces, were shown for DCB and Peel tests. All data manipulations were made using the Microsoft Excel© spreadsheets. It may be seen that the SBT gives inferior results comparing to CBT and EC methods.

The adhesive fracture toughness, G_C, from the DCB and 90° peel tests agreed well. On the other hand the value for the T-peel test is higher, which is in disagreement with the statement of characteristic adhesive property. In order to obtain an excellent agreement, further studies must be performed, where special care must be dedicated to the test specimen preparation and test procedure to ensure cohesive fracture through the adhesive layer.

Povzetek

Adhezivna sredstva so učinkovit način spajanja različnih strukturnih elementov, kot so kovine in polimeri. V primerjavi s tradicionalnimi metodami spajanja imajo adhezivni spoji številne prednosti, med katerimi so za letalsko in avtomobilsko industrijo najpomembnejša zmanjšanje mase. Obstaja veliko različnih geometrij preizkusov za določitev energije loma strukturnih adhezivov. V tem delu sta predstavljena dva osnovna tipa geometrije: elasto-plastični odluščni preizkus in preizkus z uporabo dvojnega konzolnega nosilca (DCB), ki je osnovan na linearni mehaniki loma. Natančna navodila in opis opravljanja različnih preizkusov so predstavljena v različnih standardih, npr. za DCB obstaja BS 7991 [2], za odluščne preizkuse imamo več ISO-standardov: ISO 8510-1 1990 [3], ISO 8510-2 1990 [4] in ISO 11339 1993. Za izračun energije loma iz izmerjene sile pri različnih preizkusih je bil na Imperial Collegeu razvit ICPeel [5] protokol.

Najbolj razširjen preizkus za izračun energije loma, GIC, pri načinu obremenjevanja I, je DCB-preizkus z uporabo dvojnega konzolnega nosilca (Slika 1), kjer sta konzoli navadno kovinski in razpoka poteka vzdolž adheziva ob obremenitvi na krajiščih konzol. S tem preizkusom lahko določimo odpornostno energijo pričetka rasti in energijo rasti razpoke ter izračunamo krivulje energije loma v odvisnosti od dolžine razpoke. Za izračun energije loma obstajajo tri teorijske metode:
(1) enostavna teorija konzolnega nosilca;
(2) popravljena teorija konzolnega nosilca;
(3) eksperimentalna metoda s podajnostjo (ang. compliance).

Odluščni preizkusi se uporabljajo za določanje odluščne energije pri fleksibilnih spojih, kjer je težko ločiti med energijo loma adheziva in deformacijsko energijo posameznih elementov spoja. Idealno je energija loma adhezivov neodvisna, karakteristična veličina adheziva. Med različnimi geometrijami odluščnih preizkusov sta v tem delu predstavljeni dve:

enostransko vpet odluščni preizkušanec (Slika 2) in odluščni preizkušanec v obliki črke T ali T-odluščni preizkušanec (Slika 4). Pri enostransko vpetem odluščnem preizkušancu obstaja več variacij, ki se razlikujejo v kotu med fiksiranim in obremenjenim delom preizkušanca, npr. 90-stopinjski odluščni preizkus (Slika 3). V primeru preslikanja enostransko vpetega odluščnega preizkušanca preko adhezivne plasti dobimo T-odluščni preizkušanec, kar olajša analizo odluščnih preizkušancev.

Pri DCB- preizkusih so bili uporabljeni jekleni konzolni nosilci (E = 207 GPa) in adheziv z oznako ESP110 (E = 4 GPa) Geometrijski podatki DCB-preizkušanca so podani v Tabeli 1.

Pri odluščnih preizkusih je bila kot podlaga uporabljena aluminijeva zlitina 5754 (E = 69 GPa) in enak adheziv kot v prejšnjem primeru ESP110 (E = 4 GPa). Vsi geometrijski podatki, uporabljeni pri odluščnih preizkusih, so zbrani v Tabeli 3.

Prikazane so značilne krivulje obremenitev-pomik čeljusti za vse obravnavane preizkuse (Slike 5, 8, 9). Na Sliki 6 je viden padec obremenitve med potekom rasti razpoke pri DCB- preizkusu. Za DCB-preizkus so prikazane krivulje energije loma (Slika 7), izračunane iz eksperimetalnih podatkov in z uporabo ICPeel-protokola, ki obsega predstavljeno teorijo.

Iz Tabel 2 in 4 je razvidno, da se energija loma adheziva med DCB in 90°-odluščnim preizkusom dobro ujema, medtem ko je vrednost pri T-odluščnem preizkusu višja in se ne ujema z načelom o karakteristični lastnosti energije loma adheziva.

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