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Composites and reinforcements fibres — Determination of the fracture energy of bonded plates of carbon fibre reinforced plastics (CFRPs) and metal using double cantilever beam specimens

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 13, *Composites and reinforcement fibres*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The potential benefits to the users of CFRP/metal assemblies of implementing the adhesive fracture energy of DCB specimen based on this document are:

a) expanding CFRP applications to the fields where it could be used in combination with metallic components;

b) the detection or the prevention of physical properties loss — such as ion migration and time-related degradation in sealant film, injected calking layer and glass fibre reinforced plastics (GFRPs) layer;

c) demonstrating the conformity to specified conditions for type certification requirements in the engineering such as aircraft developments;

d) evaluating the procedures for maintenance, repair and overhaul (MRO) in the engineering operations such as CFRP in aerospace, or in constructions such as steel bridges and industrial applications (e.g. pipework repair, etc.)

Composites and reinforcements fibres — Determination of the fracture energy of bonded plates of carbon fibre reinforced plastics (CFRPs) and metal using double cantilever beam specimens

SAFETY STATEMENT — Persons using this document should be familiar with normal laboratory practice, if applicable. This document does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user to establish appropriate safety and health practices. It is recognized that some of the materials permitted in this document might have a negative environmental impact. As technological advances lead to more acceptable alternatives for such materials, they will be eliminated to the greatest extent possible. At the end of the test, care should be taken to dispose of all waste in an appropriate manner.

1 Scope

This document specifies the test method for the determination of adhesive fracture energy of adhesively bonded plates of carbon fibre reinforced plastic (CFRP) and metal using a double cantilever beam (DCB) specimen. The test method is also applicable to bonded joints between metals and other composite materials, such as glass fibre reinforced plastics.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 291, *Plastics — Standard atmospheres for conditioning and testing*

ISO 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

ISO 10365, *Adhesives — Designation of main failure patterns*

ISO 25217, *Adhesives — Determination of the mode 1 adhesive fracture energy of structural adhesive joints using double cantilever beam and tapered double cantilever beam specimens*

3 Terms, definitions and symbols

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.2 Symbols

A	insert film length (mm), i.e. the distance between the end of the specimen and the tip of the insert film (see Figure 1)
a	crack length (mm), i.e. the distance between the load-line (intersection of plane through pin-hole centres and plane of crack) and the tip of the precrack or crack on the edge of the specimen (see Figure 1)
a_p	pre-crack length (mm), measured from the load-line to the tip of the precrack (see Figure 1)
a_0	insert film length (mm) between the load-line and the tip of the insert film (see Figure 1)
Δa_i	crack growth at i-th load step in the stick-slip behaviour of the crack propagation (see Figure 1)
b	width of the specimen (mm) (see Figure 1)
C	compliance δ/P of the specimen (mm/N)
C_0	initial compliance of the specimen, neglecting start-up effects, e.g. due to play in the specimen fixture (mm/N) (see Figure 2)
$C_{0+5\ \%}$	initial compliance of the specimen, C_0, raised by a factor 1,05 (mm/N) (see Figure 2)
E_f	flexural modulus of the arms of the substrate beam, calculated from the crack propagation using DCB test (GPa)
E_1	flexural modulus of the carbon fibre reinforces plastic (CFRP) beam in DCB specimen (GPa)
E_2	flexural modulus of the metal beam in DCB specimen (GPa)
$(EI)_{eq}$	equivalent stiffness (N·m^2) (see Figure 7)
F	large-displacement correction
G_C	adhesive fracture energy for the applied opening mode (J/m^2)
H	height of the load-block (mm) (see Figure 1)
h_1	thickness of the carbon fibre reinforces plastic (CFRP) beam (mm) in DCB specimen (see Figure 1)
h_2	thickness of the metal beam (mm) in DCB specimen (see Figure 1)
h_a	thickness of the adhesive layer (mm) (see Figure 1)
I_1	moment of inertia of area in CFRP (m^4)
I_2	moment of inertia of area in metal (m^4)
l	total length of the specimen (mm) (see Figure 1)
l_1	distance from the centre of the loading pin to the mid-plane of the arm of the substrate beam to which the load-block is attached (mm) (see Figure 1)
l_2	distance between the centre of the pin-hole in the load-block and the edge of the load-block, measured towards the tip of the insert (starter film) or the tip of the precrack (mm) (see Figure 1)
l_3	total length of the load-block (mm) (see Figure 1)

MAX/5 % either the maximum load on the load-displacement curve or the point of intersection of a straight line with the load-displacement curve with the slope of the straight line corresponding to $C_{0+5\ \%}$ (see Figure 2)

N load-block correction

NL onset of nonlinearity on the load-displacement curve (see Figure 2)

P load measured by the load-cell of the test machine (N)

$P(\delta)$ is the experimentally obtained load value indicating the maximum extent of the portion of load-displacement curve, from the origin O to the point A in Figure 3"

$P_{\mathrm{l}}(\delta)$ is a linearly increasing load value indicated by the dashed line a in Figure 3, and it is calculated by Formula (8):

PROP increments of the crack length during stable crack growth (propagation) that are marked on the load-displacement curve (see Figure 2)

VIS onset of visually recognizable crack growth at the edge of the specimen that is marked on the load-displacement curve (see Figure 2)

Δ crack-length correction for a beam that is not perfectly built-in (mm) (see Figure 7)

δ displacement of the cross-head of the test machine (mm)

ρ radius of curvature of the bonded plate specimen (m) (see Figure 6)

4 Principle

A double cantilever beam (DCB) specimen is used to determine the adhesive fracture energy of structural bonded joint between a metal and CFRP components

Resistance to both crack initiation and propagation is determined. The resistance to crack initiation is determined from both a non-adhesive insert placed in the adhesive layer and from a precrack. The resistance to crack propagation is determined from the precrack. The adhesive fracture energy versus applied opening load is estimated and a resistance-curve (R-curve), i.e. a plot of the value of the adhesive fracture energy versus crack length, is determined.

In the case where the CFRP/metal interlaminar toughness and interface are significantly tough, the plastic deformation of the metal beam preferentially occurs during the crack propagation. This causes the overestimation of fracture energy values. In such cases, double cantilever beam specimens with dissimilar thicknesses shall be used. An appropriate ratio of the two beams thickness (h_1/h_2) shall be determined such that the plastic deformation of the metal beams during the crack propagation is avoided.

5 Apparatus

5.1 Tensile-testing machine, capable of maintaining a crosshead displacement speed between 0,125 mm/min and 10 mm/min accurate to ±20 % and higher speeds accurate to ±10 %. The test tensile testing machine shall be equipped with a fixture to introduce the load to the pins inserted into the loading-blocks. Measurement of test system compliance is described in Annex C and Figure C.1.

The tensile testing machine shall comply with ISO 7500-1 and the force measurement system shall comply with ISO 7500-1:2018, class 1.

The opening displacement of the test specimen shall be deduced from the position of the test machine cross-head. The test machine shall be equipped with means for recording the complete load versus displacement curves (loading and unloading) during the test.

5.2 Travelling microscope or **video camera**, with suitable magnification, capable of measuring the crack length along the edge of the specimen to an accuracy of at least ±0,5 mm.

5.3 Micrometer or **vernier callipers**, capable of measuring the thickness of the substrate arms and bonded plates with an accuracy of at least ±0,05 mm.

5.4 Micrometer or **vernier callipers**, capable of measuring the width of the specimens with an accuracy of at least ±0,05 mm.

5.5 White spray-paint or **typewriter correction fluid** (“white ink”).

6 Specimens

6.1 Number of specimens

A minimum of five specimens shall be tested.

6.2 Conditioning

Most adhesives absorb small quantities of water from the atmosphere which can have a significant influence on the measured properties. Following specimen preparation, the adhesive will generally be dry. If testing is carried out within a few days of specimen manufacture, then it is not necessary to condition the specimen under controlled humidity since negligible absorption of water takes place in the thin adhesive layer. However, if the specimen is tested after longer times or if the influence of absorbed water on the properties is of interest, then the humidity shall be controlled by conditioning and the properties will depend on the conditioning time (see ISO 291).

In addition, if composite substrates are used, it can be important to dry these prior to manufacture of the specimen. The properties of some adhesives are very sensitive to the presence of small amounts of moisture in a substrate prior to curing. The drying out of the substrates prior to cure will ensure that the integrity of the adhesive joint is not influenced by pre-bonding moisture effects.

6.3 Manufacture of adhesive joint specimens

6.3.1 General

The DCB specimen shall be as shown in Figure 1. The thickness of the film to be inserted in the adhesive layer during manufacture shall be less than 13 µm. The film shall be non-stick. For joint specimens bonded at temperatures below 180 °C, a thin polytetrafluoroethylene (PTFE) film is recommended. For specimens bonded at temperatures above 180 °C, a thin polyimide film is recommended. Appropriate surface treatments for metallic substrates can be found in ISO 17212[5].

The thickness of the adhesive layer shall be carefully controlled and shall be less than 1 mm in accordance with ISO 25217. The thickness of the layer shall not vary by more than 20 % within a plate, nor shall the average thickness of the layer in one joint differ by more than 20 % from that in another joint. When fully cured, remove any excess adhesive by mechanical means that do not weaken the bond, to leave the joint with smooth sides.

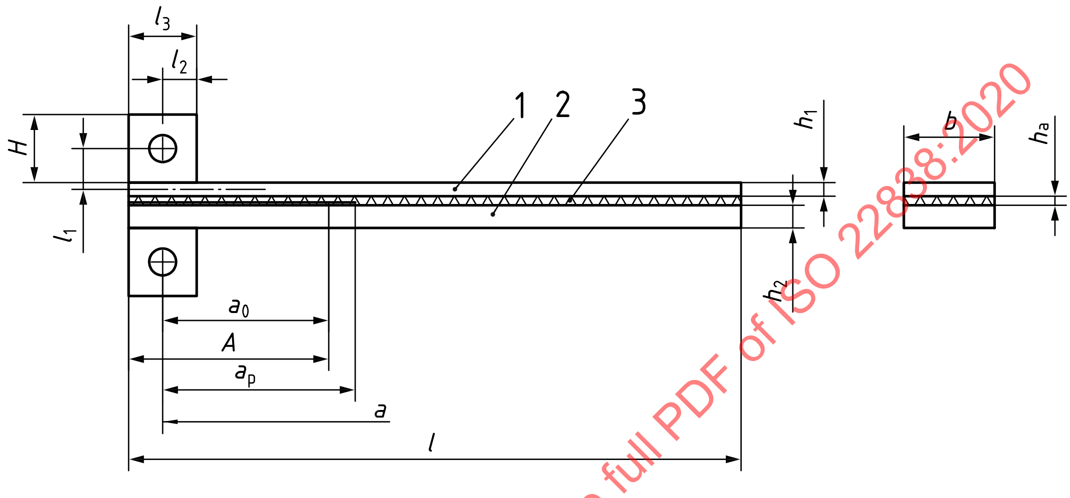
It should be recognized that the value of *G* measured from these tests depends upon the thickness of the adhesive layer in the joint. The value of the layer thickness shall be determined by the user, based upon the adhesive manufacturer's recommendations or upon consideration of the intended application.

It is not within the scope of this document to specify full manufacturing details of the specimens to be tested. Such information should be sought from the adhesive manufacturer and/or the substrate manufacturers.

Repeat the measurements of the total beam thickness after bonding. Determine the adhesive layer thickness, h_a, by subtracting the substrate thicknesses from the total thickness of the joint at each of the three locations.

6.3.2 DCB specimen measurements

Remove any excess adhesive from the sides of the beam. After bonding, measure the width of the DCB specimen with vernier calipers or a micrometer at three points along the length of the beam, at 30 mm from either end and at the mid-length. Measurement tolerance to be ±0,5 mm. Calculate the mean value, *b*.



Key

1 composite (CFRP) beam

2 metal beam

3 adhesive layer

Figure 1 — Geometry of DCB bonded plate specimen with load-blocks

6.4 Preparation of specimens

Apply a thin layer of white spray-paint, or typewriter correction fluid (“white ink”), on the edges of the specimen after conditioning to facilitate the detection of crack growth.

NOTE Some typewriter correction fluids and paints contain solvents which can harm the adhesive or the laminate matrix material of a composite substrate. A material with an aqueous solvent is usually safe to use.

Apply marks every 1 mm from the tip of the insert or the precrack for at least the first 10 mm, then apply marks every 5 mm. Apply marks for every 1 mm for the final 5 mm.

Measure the radius of curvature of the warped specimen following the method illustrated in 7.6.

If the specimen radius of the curvature, ρ, is smaller than 1,5 m, such specimens shall not be tested in order to avoid the effect of thermally induced residual stress. The value of ρ shall be calculated using Formula (2) and as shown in Figure 6.

For the DCB test specimen, the extent of crack propagation should be approximately 50 mm. If early breakage happens at shorter propagation, the data should be recorded with information of failure mode as defined by ISO 10365.

7 Procedure

7.1 Test set-up and data recording

The test shall be performed at one of the temperatures specified in ISO 291 or at another temperature agreed between the interested parties. After mounting the specimen in the fixture of the test machine, support the end of the specimen, if necessary, to keep the test beam orthogonal [i.e. at 90 degrees (90°)] to the direction of the applied load. Record the load and the displacement signals of the test machine electronically throughout the test, including the unloading cycle.

If using a tensile-testing machine with a paper chart recorder, the ratios of cross-head speed to chart speed are recommended to be about 1:10.

Measure the crack lengths, with the respective load and displacement along both edges of the specimen to an accuracy of at least ±0,5 mm using a travelling microscope, a scale, a vernier calliper or a video camera with suitable magnification (5.2). Calculate an average of both lengths.

7.2 Initial loading (precracking stage)

For testing from the insert (starter film), load the specimen at a constant cross-head rate of 1,0 mm/min to 5,0 mm/min.

NOTE Lower values are more accurate for crack-length measurement.

Record the point on the load-displacement curve at which the onset of crack movement from the insert is observed on the edge of the specimen, on the load-displacement curve or in the sequence of load-displacement signals [see VIS in Figure 2 a)].

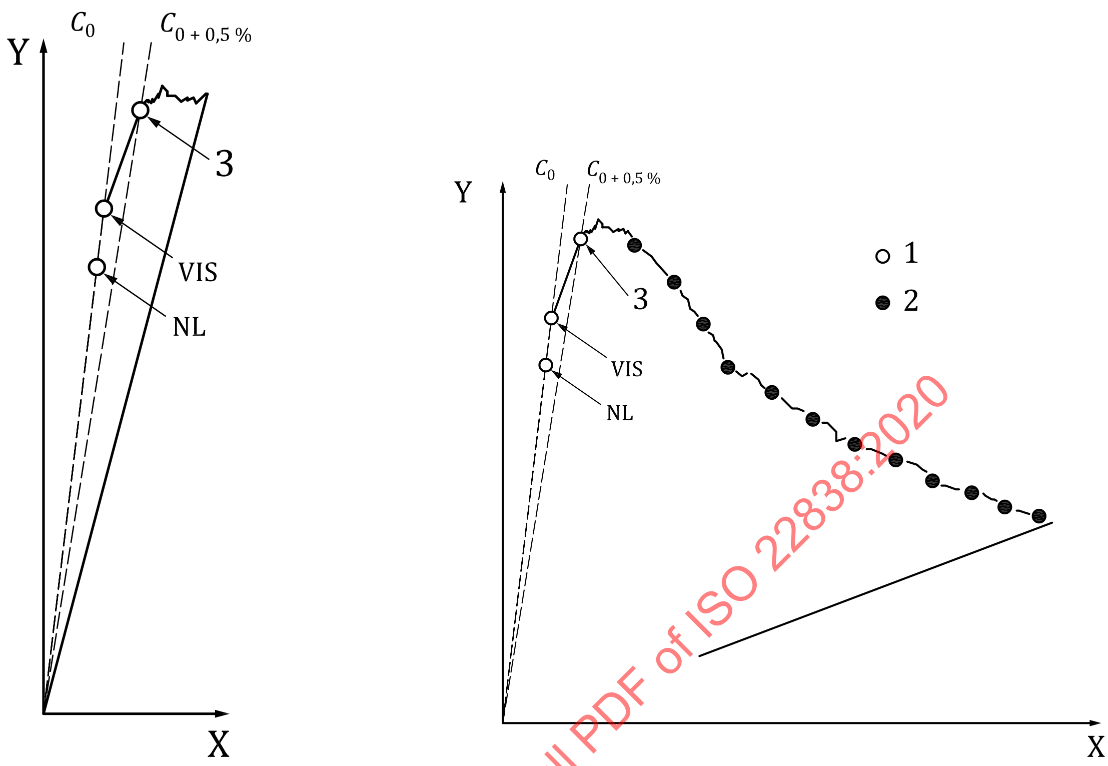
Stop the loading as soon as the crack is seen to move on the edge of the specimen. Completely unload the specimen at a constant cross-head rate of up to five times the loading rate. Mark the position of the tip of the precrack on both edges of the specimen.

7.3 Re-loading: Testing from the precrack

For testing from the precrack which has been formed as a result of the test procedure in 7.2, load the specimen at a constant cross-head rate of 1,0 mm/min to 5,0 mm/min.

NOTE 1 Lower values are more accurate for crack-length measurement.

Record, on the load-displacement curve or in the sequence of load-displacement signals, the point at which the onset of crack movement from the insert is observed to occur [see VIS in Figure 2 b)].



a) Testing from the insert with initiation points NL, VIS and MAX/5 %

b) Testing from the precrack with initiation points NL, VIS and MAX/5 % and propagation points (PROP)

Key

X displacement, δ

Y load, P

1 initiation values

2 propagation values

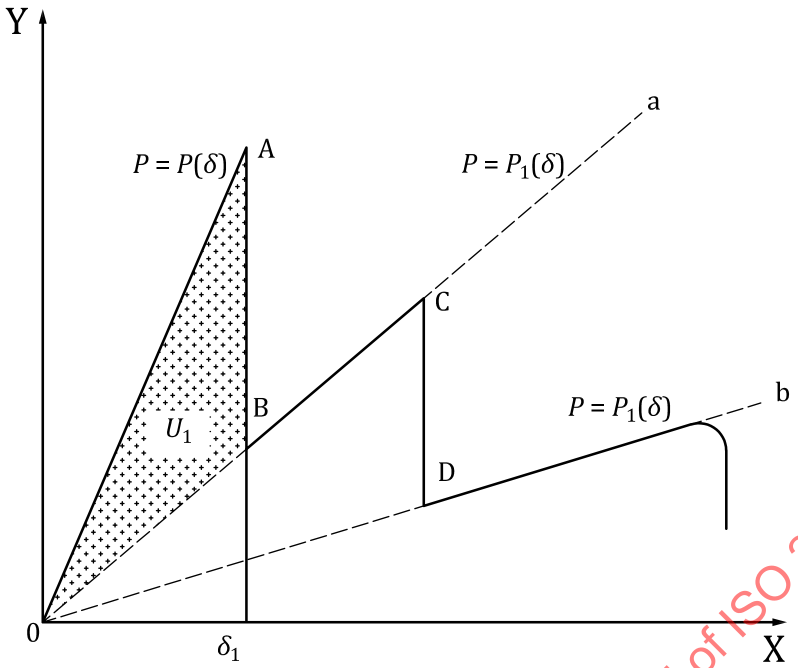
3 MAX/5 % — 5 % value as that point on the load-displacement curve at which the compliance has increased by 5 % of its initial value

NL point of deviation from linearity determined by drawing a straight line from the origin.

VIS first point at which the crack is observed.

NOTE This figure shows an example where the MAX and the 5 % offset points coincide such that they lie on the same point on the curve. This is not generally the case. Usually, these points will be separated. The MAX/5 % point is assigned to the point $C0$+5 % or MAX, whichever occurs first.

Figure 2 — Schematic load-displacement curve for the DCB test of continuous growth case



Key

X displacement, δ

Y load, P

Figure 3 — Schematic load-displacement curve for the DCB test of stick-slip case

After this, the testing procedure is divided into two cases: 1. Continuous growth case and 2. Stick-slip case.

1) Continuous growth case: Note as many crack-length increments as possible in the first 5 mm on the corresponding load-displacement curves, ideally every 1 mm. Subsequently, note crack lengths at every 5 mm, until the crack has propagated about 50 mm from the tip of the precrack. Note every 1 mm for the last 5 mm of crack propagation. Record a minimum number of 10 propagation points.

2) Stick-slip case: When the first load drop occurs from load level A to B as indicated in Figure 3. Stop the loading immediately. Measure the crack lengths along the both edges and calculate an average of crack length at the first step, a_1. Determine crack length growth at the first step, $\Delta a_1 = a_1 - a_p$, and record it. Then, start the loading again until the second load drop occurs from load level C to D. Stop the loading immediately. Measure the crack lengths along the both edges and calculate an average of crack length at the second step, a_2. Determine crack length growth at the second step, $\Delta a_2 = a_2 - a_1$, and record it. Repeat this procedure until the crack has propagated about 50 mm or other phenomena has occurred, such as crack branching away from the adhesive layer, or bending failure in one of the beam arms of the specimen.

Next, unload the specimen at a constant cross-head rate of up to five times the loading rate. Record whether the load-displacement curve returns to its initial point and, if not, follow the procedure in 7.4.

NOTE 2 This might indicate that permanent plastic deformation of the arms of the specimen has occurred.

Mark the position of the tip of the crack, i.e. mark the distance between the load-line and the tip of the crack on both edges of the specimen.

NOTE 3 This might indicate asymmetric loading or other problems with the test.

Break the specimens open to enable the locus of joint failure to be visually assessed. Visually assess the locus of joint failure in accordance with ISO 10365.

7.4 Determination of the thickness ratio of the CFRP and metal beams

7.4.1 Theoretical prediction of thickness ratios

Thickness ratios can be also estimated by the following equations regarding to flexural rigidity. The flexural rigidity of metal should be nearly equal to that of CFRP, in order to equalize deflection of the metal and f CFRP beams as shown below:

$$E_1 I_1 \approx E_2 I_2$$

where 1 equals CFRP and 2 equals metal.

$$\frac{E_1 b h_1^{\,3}}{12} \approx \frac{E_2 b h_2^{\,3}}{12}$$

$$E_1 \mathrm{h}_1^{\,3} \approx E_2 h_2^{\,3}$$

$$\sqrt[3]{E_1}\, h_1 \approx \sqrt[3]{E_2}\, h_2$$

7.4.2 Procedure to detect the occurrence of plastic deformation during a DCB adhesive joint test

In the case where the CFRP/metal interface is extremely tough, the plastic deformation of the metal beam occurs during the crack propagation. This causes the overestimation of fracture energy values. In such cases, an appropriate ratio of the two beams thickness (h_1/h_2) shall be determined such that the plastic deformation of the metal beams during the crack propagation is minimum within the specimens to be tested.

The procedure to detect the occurrence of plastic deformation is shown in Figure 4. The load, propagation and unload cycles are repeated during the DCB test. In the case of the test with occurrence of large plastic deformation, the metal beam remains permanently deformed after unloading, and thus the displacement does not return to zero (or the point at which the initial loading curve is extrapolated to zero load) shown in Figure 4 a). On the other hand, the test specimen fractured only with elastic deformation returns to zero displacement in every cycle after unloading as shown in Figure 4 b). Measure the values of the distance between the intercept of the loading lines with the displacement axis and that of the unloading lines with the axis, ignoring any initial nonlinearity.

The DCB tests are carried out with the specimens with dissimilar thicknesses of CFRP and metal beams, h_1 and h_2, respectively. The thicknesses are varied ranging from 1 to 5 mm with every 1 mm intervals, to find the best combination of the thicknesses (h_1 and h_2) to avoid plastic deformation.

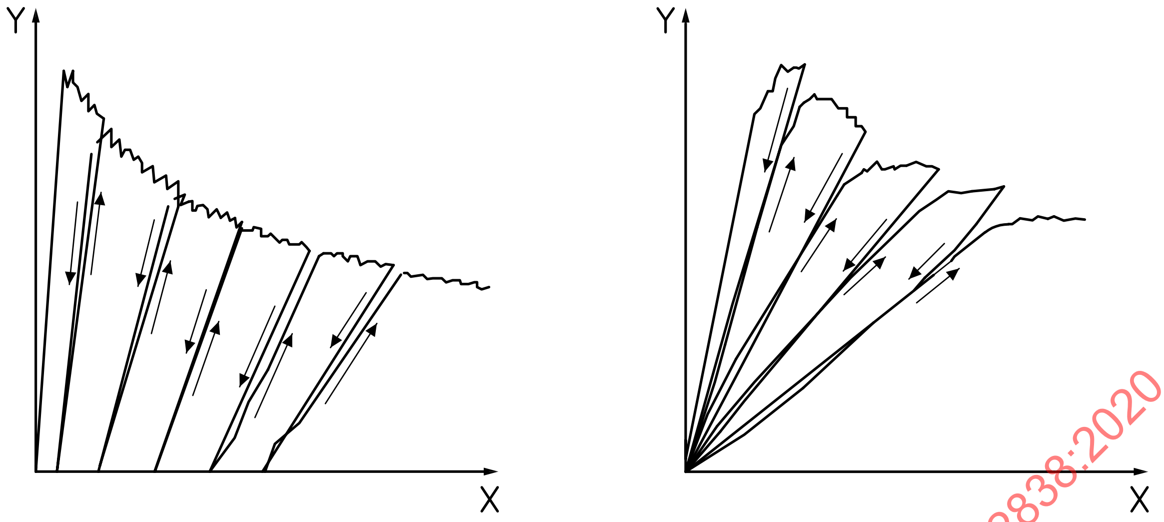
If CFRP beam is found to be broken during the crack propagation or metal beam remains plastic deformation within the range of the thicknesses from 1 to 5 mm, the thicknesses of the beams to be tested shall be extended to 10 mm.

Carefully break the joint open after the complete test cycle is finished. Visually determine whether plastic deformation has occurred: plastic deformation of the substrate arms will have occurred if they remain permanently deformed on separation.

Generally, thickness of CFRP beam (h_1) is smaller than that of metal beam (h_2), i.e. $h_1 \leq h_2$. When the CFRP beam is found to be broken during the crack propagation, the total thickness ($h_1 + h_2$) shall be increased.

In this case, mode I fracture shall be dominant during application of the opening load

Note the straightness of the beams after breaking open in the test report.



a) Typical load displacement curves obtained in load and unload cycles with crack propagation with plastic deformation of metal beam

b) Typical load displacement curves obtained in load and unload cycles with crack propagation with no plastic deformation of metal beam

Key

X displacement, δ

Y load, P

Figure 4 — Typical load-displacement curves for the DCB specimens obtained by loading propagation and unloading cycles during the DCB test

7.5 Measurement of machine compliance

If the stiffness of the tensile-testing machine together with its associated grips and pins is not known, determine the compliance associated with the machine set-up as specified in Annex A. Take the compliance into account in the calculations presented in Clause 8, unless extensometry is used to measure the opening displacement of the specimen during the test, when the system compliance correction described in Annex A shall be neglected. Conduct the system compliance measurement after the fracture tests have been conducted so that the maximum load obtained from the fracture tests, and hence the load range over which the system compliance is to be measured, is known. Correct the displacement measured during the DCB test to take account of the deflections in the loading system. For each test, use the corrected values of the displacement in the calculations.

7.6 Measurement of curvature induced by coefficient of thermal expansion difference between metal and composite beams

The bonded plate specimen of metal and composites are usually warped as indicated in Figure 5.

NOTE Upper beam is CFRP and lower beam is aluminium.

Figure 5 — Warping of the specimen induced by difference of thermal expansion coefficients

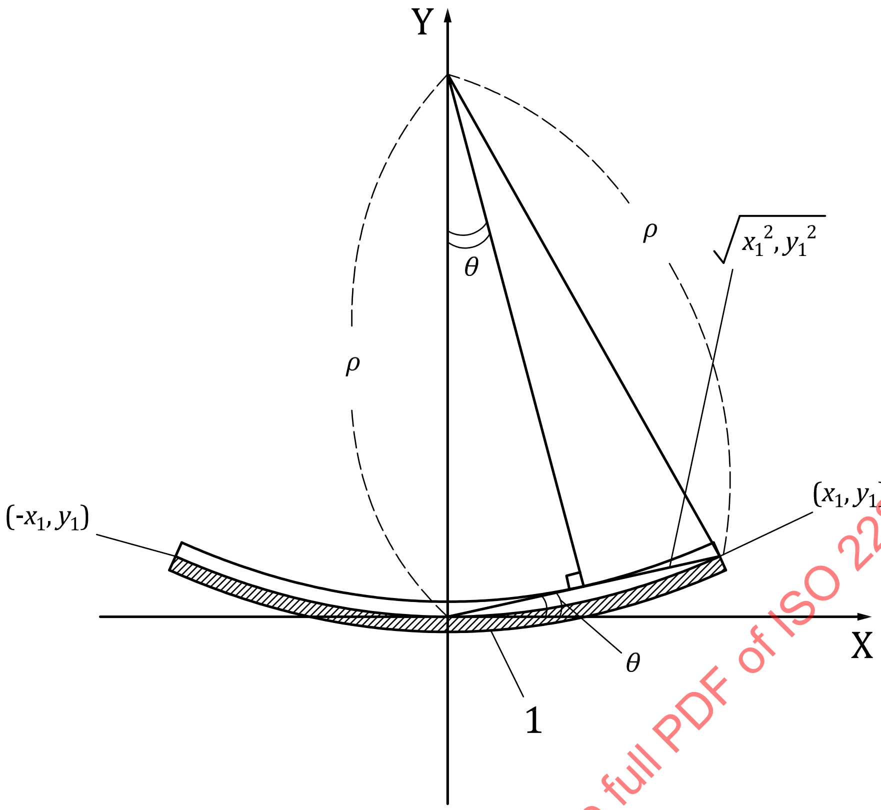
This warping is caused by the difference of coefficients of thermal expansion of CFRP and metal and the temperature drop from the bonding temperature to the room temperature. This warping implies that the internal thermal stress between CFRP beam and metal beam is generated. This internal stress affects fracture energy measurements. So, consideration of the warping effect upon the fracture energy (G_C) is indispensable in order to obtain its true value. For consideration of this effect, measurement of the radius of the curvature should be performed first. The measurement procedure is explained as follows.

Place a specimen on a section paper so that the specimen curve should be tangential to a selected horizontal line of the section paper at the defined origin. The centre point of the specimen should coincide with the defined origin. The centre point means both the centre in the thickness direction and the centre along the ark length. Adjust the detailed position of the specimen so as to the coordinate values of x_1 and y_1 as shown in Figure 6 in right and left halves become the same. Determine x_1 and y_1 in the accuracy of the section paper. The angle between the horizontal line and chord, θ, can be calculated by Formula (1).

$$\theta = \tan^{-1} \frac{x_1}{y_1} \qquad (1)$$

By a simple geometrical relation, the radius of the curvature ρ is calculated by Formula (2).

$$\rho = \frac{\sqrt{X_1^2 + Y_1^2}}{2\sin\theta} \qquad (2)$$



Key

1 plate assembly of metal and composites, usually warped (specimen)

X horizontal coordination from the centre point of the specimen

Y vertical coordination from the centre point of the specimen

θ angle between the horizontal line and chord

ρ radius of the curvature

Figure 6 — Geometry for a measurement of the radius of curvature of a warped specimen

If a digital dimension measurement system is available and capable of the radius of curvature calculation, its results can be adopted.

8 Data analysis

8.1 Determination of the raw data from the load-displacement trace

8.1.1 General

Disregard any initial nonlinearity in the load-displacement trace by extrapolating the linear region of the loading curve back to zero load, as described in Annex A. Determine the initiation values (see 8.1.2) and propagation values (see 8.1.3) from the load-displacement trace.

8.1.2 Initiation values

Determine the crack length for the initiation values from the insert as the distance between the load-line and the tip of the insert, a_0. Determine the crack length for the initiation values from the precrack as the distance between the load-line and the tip of the precrack, a_p (see Figure 1). Determine the following initiation values, shown in Figure 2, for testing from the insert (starter film) and from the precrack for each specimen:

a) NL: Determine the point of deviation from linearity by drawing a straight line from the origin, ignoring any initial deviations due to take-up of play in the loading system. Perform a linear fit on the load- displacement curve, starting at 5 % of the maximum load, using a consistent criterion for deviation from linearity (such as the half-thickness of the plotter trace).

NOTE A region of nonlinear behaviour usually precedes the maximum load, even if the unloading curve is linear. Experience has shown that it is difficult to determine reproducibly the position of NL on the load-displacement curve.

b) VIS: Determine the first point at which the crack is observed to move from the tip of the insert or of the precrack on the edge of the specimen.

c) MAX/5 %: Determine the 5 % value as that point on the load-displacement curve at which the compliance has increased by 5 % of its initial value, C_0, as follows. Draw a best straight line to determine the initial compliance, C_0, ignoring any initial deviation due to take-up of play in the loading system, and draw a new line with a compliance equal to $C_{0+5\,\%}$. Mark the intersection of this new line with the load-displacement trace. Use whichever point occurs first, i.e. the maximum load (MAX) or the load at 5 % increase in the initial compliance.

8.1.3 Propagation values

Determine propagation values [PROP in Figure 2 b)] from the precrack.

8.2 Determination of adhesive fracture energy

8.2.1 General

When the thicknesses of CFRP and metal beams as determined in accordance with 7.4 are identical ($h_1 = h_2$), corrected beam theory (CBT) is employed. When the specimen is asymmetric in terms of the beam thickness, the method for DCB test with dissimilar thickness is employed.

8.2.2 DCB test with identical thickness: Corrected beam theory (CBT)

Treat the beam as containing a slightly longer crack length, $(a+|\Delta|)$; find $|\Delta|$ experimentally by plotting the cube root of the normalized compliance, $(C/N)^{1/3}$ as a function of crack length, a (see Figure 7). The load-block correction, N, is described in Formula (5).

Extrapolate a linear fit through the data in the plot to yield Δ as the negative X-intercept. Use only the propagation (PROP) values for the linear fits, i.e. exclude all the initiation values from the linear fits.

Calculate the fracture energy, G_C, using Formula (3):

$$G_C = \frac{3P\delta}{2b(a+|\Delta|)} \cdot \frac{F}{N} \tag{3}$$

Calculate all applicable initiation and propagation values of G_C.

NOTE 1 The large-displacement correction, F, becomes important if $\delta/a > 0{,}4$.

Calculate the large-displacement correction, F, and the load-block correction, N, as shown in Formulae (4) and (5), respectively:

$$F = 1 - \frac{3}{10}\left(\frac{\delta}{a}\right)^2 - \frac{3}{2}\left(\frac{l_1\delta}{a^2}\right) \tag{4}$$

$$N=1-\left(\frac{l_2}{a}\right)^3-\frac{9}{8}\left[1-\left(\frac{l_2}{a}\right)^2\right]\frac{l_1\delta}{a^2}-\frac{9}{35}\left(\frac{\delta}{a}\right)^2 \quad (5)$$

where

l_1 is the distance from the centre of the loading pin to the mid-plane of the arm of the substrate beam to which the load-block is attached;

l_2 is the distance from the loading-pin centre to the edge of the block (see Figure 1).

NOTE 2 If the displacement correction, F, is < 0,9 then, ideally, the test specimen is redesigned, for example with thicker substrates, to reduce the required displacements and thus reduce the large-displacement correction factor.

Calculate the flexural modulus, E_f, as a function of the crack length, a, by using Formula (6):

$$E_f=\frac{8(a+|\Delta|)^3}{\frac{C}{N}bh_1^3} \quad (6)$$

This calculation is a useful check on the procedure as a value of the flexural modulus, E_f, independent of crack length should be obtained.

If the maximum variation of E_f is more than 10 % of the average, consider the values of G_C as suspect.

In this case, the value E_f calculated from Formula (6) shall not be quoted as a modulus value.

8.2.3 DCB test with dissimilar thicknesses: modified beam theory for DCB specimens with dissimilar thicknesses

For DCB test specimens with dissimilar thicknesses, equivalent stiffness, $(EI)_{eq}$, is introduced to calculate G_C. See Formulae (7) and (8):

$$\delta=\frac{Pa^3}{(EI)_{eq}} \quad (7)$$

$$G_C=\frac{3P^2(a+\Delta)^2}{2B(EI)_{eq}} \quad (8)$$

Δ and $(EI)_{eq}$ are determined by a least squares plot of plotting the cube root of the normalized compliance, $(C/N)^{1/3}$ as a function of crack length, a, (see Figure 7). Extrapolate a linear fit through the data in the plot to yield Δ as the negative X-intercept, and $(EI)_{eq}$ are calculated from the slope of the linear fit. Use only the propagation (PROP) values for the linear fits, i.e. exclude all the initiation values from the linear fits. The method is calculation of G value from $(EI)_{eq}$, obtained experimentally, without knowing each E_1I_1 and E_2I_2. Whereas, Annex B describes confirm $(EI)_{eq}$ and following G value using E_1I_1 and E_2I_2.

8.2.4 DCB test with identical and dissimilar thicknesses: Area method

Calculate the released energy at the first load step, U_I, in Figure 3 by using load-crack opening displacement data by using Formula (9):

$$U_I = \int_0^{\delta_1} (P(\delta) - P_1(\delta))d\delta \tag{9}$$

$$P_1(\delta) = \frac{P(\delta_1)}{\delta_1} \times \delta \tag{10}$$

Newly created delamination area at the first load step A_1 was calculated by the crack length growth Δa_1 and the specimen width b, using Formula (11):

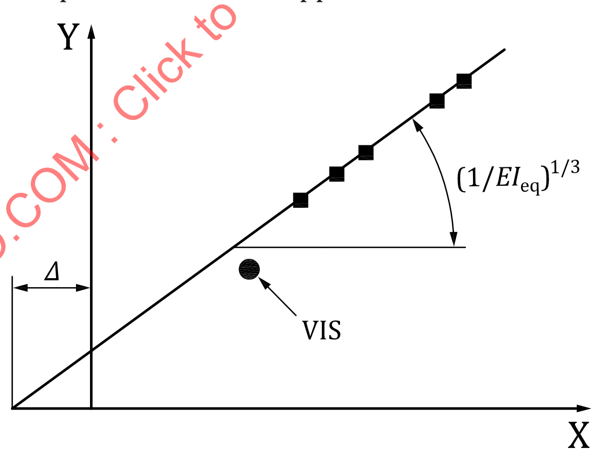
$$A_1 = \Delta a_1 \times b \tag{11}$$

Fracture energy at the first step, $G_{1,}$ can be calculated simply by Formula (12).

$$G_1 = \frac{U_1}{A_1} \tag{12}$$

Fracture energy at the i-th load step G_i can be calculated by replacing U_1 by U_i and A_1 by A_i in Formula (10), respectively.

Although the above calculation was explained by using the illustration of the stick-slip case (see Figure 3), this area method procedure can be applied to the continuous growth case.



Key

X crack length, a

Y $(C/N)^{1/3}$

Δ x-axis intercept

Figure 7 — Correction for the corrected beam theory (CBT), double cantilever beam (DCB) and asymmetric double cantilever beam (ADCB) test specimens

9 Precision

The precision of this test method is not known because interlaboratory data are not available at the time of publication.

10 Test report

The test report shall include the following information:

a) a reference to this document, i.e. ISO 22838:2020, indicating the method of analysis;

b) all details necessary to fully identify the materials tested (e.g. characteristics of CFRP, metal material, and adhesive);

c) the bonding condition used in preparing the specimens;

d) the number of specimens tested, the test date and the test laboratory;

e) the average thickness, average width, thickness variation along the length, and length of the specimen, the type of insert material used and the thickness and length of the insert;

f) the radius of the curvature ρ of the specimen;

g) relative humidity and temperature of the testing laboratory;

h) the dimension of the load blocks, and the adhesives used for bonding them to the specimen;

i) the displacement rates for loading and unloading for testing from the insert and from the precrack;

j) a copy of the load-displacement curve for each specimen;

k) a copy of the load-displacement curve for loading-unloading cycle test (see Figure 4);

l) the method for the calculation of G_C;

m) the initiation points of G_C (NL, VIS or MAX/5 % — see Figure 2), obtained from both the insert (starter film) and from the precrack using the corresponding measured value of the crack length, a, i.e. a_0 or a_p;

n) the propagation values of G_C [PROP in Figure 2 b]], determined from the precrack as a function of crack length, a;

o) a resistance-curve (R-curve), i.e. G_C versus crack length, a (see Figure 8), showing all initiation and propagation values from both the insert and the precrack;

p) in the cases where corrected beam theory (CBT) is adopted, report the x-axis intercept Δ of the linear fit of the cube-root of the normalized compliance, $(C/N)^{1/3}$, versus the delamination length, a, as well as the flexural modulus, E_f, of the substrate [from Formula (6)];

q) in the cases where modified corrected beam theory (MCBT) is adopted, report the x-axis intercept Δ and EI_{eq} calculated from the slope of the linear fit of d a least squares plot of plotting the cube root of the normalized compliance, $(C/N)^{1/3}$ as a function of crack length, a, (see Figure 7);

r) whether the locus of joint failure is

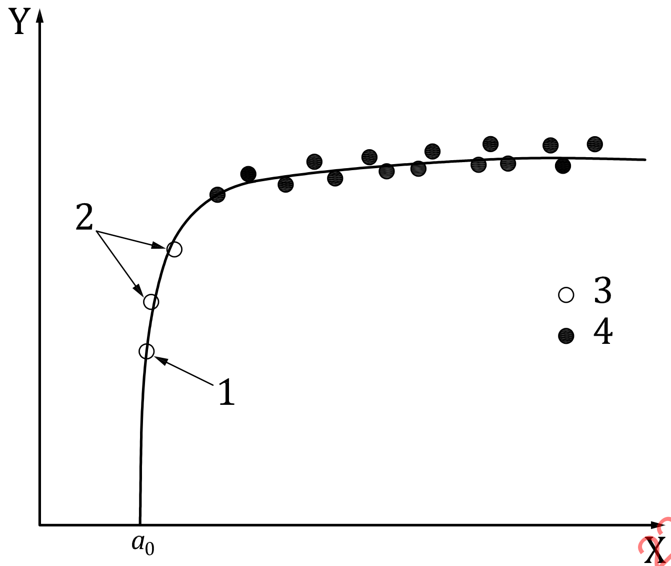
   1) cohesive, in the adhesive,

   2) apparently interfacial along the adhesive/substrate interface,

   or

   3) cohesive, in the substrate.

If a mixture of such failure paths is seen, estimate and record the percentage of each type.



Key

X crack length, *a*

Y G_C

1 lowest initiation point (lowest value among NL, VIS and MAX/5 % from insert or precrack)

2 other initiation points

3 initiation values

4 propagation values

Figure 8 — Schematic resistance-curve (R-curve) with G_C values for initiation (i.e. the lowest value among NL, VIS and MAX/5 %) and for propagation (PROP) versus observed crack length, *a*

Annex A
(informative)

Work flow chart as brief guideline

A work flow chart is described for a brief guideline of this document.

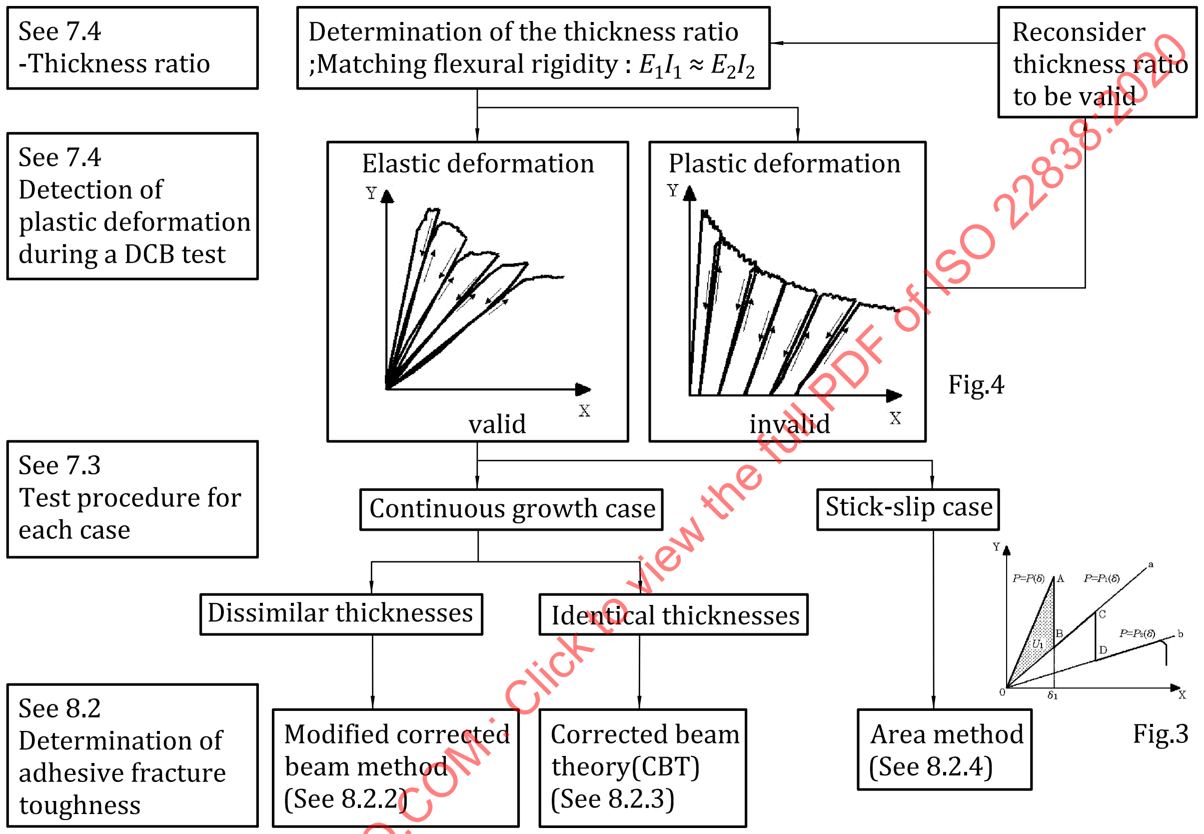


Figure A.1 — Work flow chart as brief guideline