

Determination of the mode I adhesive fracture energy G_{IC} of structure adhesives using the double cantilever beam (DBC) and tapered double cantilever beam (TDCB) specimens

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Foreword

This test method BS 7991 has been prepared under the direction of PRI/52, Adhesives standards policy committee with substantial input from the European Structural Integrity Society (ESIS) Technical committee 4 on Polymers, Adhesives and Composites.

The standard provides a method, based upon linear-elastic fracture-mechanics (LEFM), for the determination of the fracture resistance of structural adhesive joints under an applied mode I opening load, using the Double Cantilever Beam (DCB) and Tapered Double Cantilever Beam (TDCB) specimens.

The resistance to crack initiation is measured from both a release film inserted into the bondline during manufacture and from a mode I precrack. This dual initiation procedure ensures that a minimum value of fracture resistance G_{IC} can be identified. The test methods then specify that a resistance curve (R-curve) be drawn for the joint for which the steady-state values of G_{IC} associated with crack propagation have to be determined.

This method is practised because the adherends are of relatively simple form and round-robin tests have demonstrated that the repeatability and reproducibility of the results are of the same order as standardized fracture mechanics test methods for measuring G_{IC} of bulk polymers. However, there is an increased complexity in the procedures required for adhesive joint testing, and thus it is necessary to standardize the procedure in order to obtain reproducibility. The test does not necessarily reflect how the adhesive would perform in service. Such data would normally be obtained by performing tests that simulate and/or accelerate the expected loading and environmental conditions.

Excel spreadsheets for the test reports are available free of charge at <http://www.me.ic.ac.uk/materials/AACgroup/>.

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Summary of pages

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Introduction

The test methods specified in this standard enable the fracture resistance of structural adhesive joints to be determined under mode I tensile loading conditions. The use of either the double cantilever beam (DCB) specimen or the tapered double cantilever beam (TDCB) specimen is accommodated.

The methods describe the measurement of the resistance to both crack initiation and crack propagation through the adhesive layer. Points of crack initiation are determined directly from an insert film, moulded into the centre of the bondline during joint manufacture, and from a mode I precrack created during the test. The property measured by these methods is the mode I adhesive fracture energy, G_{IC} . G_{IC} may also be described as the critical strain energy release rate, the energy release rate or the fracture toughness of the joint.

The double cantilever beam (DCB) specimen is well suited for testing joints consisting of an adhesive bonding relatively thin sheets of fibre-composite materials, but may also be used when metallic substrates, which possess a relatively high yield stress, are employed [e.g. Figure 1c)].

The tapered double cantilever beam (TDCB) is designed so that, over a large range of values of crack length, the rate of change of compliance with crack length is constant and so is independent of the value of crack length. This is useful since:

- a) relatively tough adhesives can be tested without plastic deformation of the arms occurring;
- b) the substrates can possess a relatively low yield stress, but again no plastic deformation of the arms is incurred during the test; and
- c) the measurement of the adhesive fracture energy G_{IC} is independent of the crack length a ;

There are three analysis methods for both the DCB test and the TDCB tests. The corrected beam theory (CBT) method and the experimental compliance method (ECM) are considered to be the more accurate methods for determining the values of G_{IC} .

NOTE DCB specimens are cheaper to manufacture so are the test specimen of first choice provided plastic deformation of the substrates is avoided. For tougher adhesives and substrates with lower yield stresses, i.e. in joints more likely to violate LEFM test conditions, the TDCB is favoured.

To develop a linear change of compliance with crack length, the height of the specimen is varied by contouring the substrate beam so that the specimen geometry factor m is a constant [equation (1)].

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

a is the crack length; and
 h is the thickness of the substrate beam at a ;

The equations used to calculate adhesive fracture energy G_{IC} in the double cantilever beam (DCB) test method (analysis methods 1 to 3) and in the tapered double cantilever beam (TDCB) test method (analysis methods 4 to 6) are described here.

Analysis method 1: Simple beam theory (SBT) — Double cantilever beam (DCB)

The value of the adhesive fracture energy G_{IC} is calculated using equation (2):

$$G_{IC} = \frac{P^2}{2B} \cdot \frac{dC}{da} \quad (2)$$

where

C is the compliance and is given by δ/P ; and
 B is the width of the specimen;
 P is the load measured by the load-cell of the testing machine.

For thin adhesive layers, it has been shown by Mostovoy et al. [1] and Kinloch [2] that from simple beam theory, dC/da may be expressed as equation (3):

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

where

E_s is the independently-measured flexural or tensile modulus of the substrate.

Hence, by combining equations (1), (2) and (3), equation (4) is obtained and G_{IC} can be calculated:

$$G_{IC} = \frac{4P^2}{E_s B^2} \left(\frac{3a^2}{h^3} + \frac{1}{h} \right) = \frac{4P^2}{E_s B^2} \cdot m \quad (4)$$

Analysis method 2: Corrected beam theory (CBT) — Double cantilever beam (DCB)

The simple beam theory expression for the compliance of a perfectly built-in DCB specimen will underestimate the compliance as the beam is not perfectly built-in (Hashemi et al. [3], Blackman et al. [4]).

The adhesive fracture energy G_{IC} is calculated using equation (5a), or (5b) if load-blocks are used:

$$G_{IC} = \frac{3P\delta}{2B(a + |\Delta|)} \cdot F \quad (5a) \quad G_{IC} = \frac{3P\delta}{2B(a + |\Delta|)} \cdot \frac{F}{N} \quad (5b)$$

where

N is a load-block correction;

F is a large displacement correction;

δ is the displacement; and

Δ is a crack-length correction for a beam that is not perfectly built-in.

The large displacement correction F and the load-block correction N are calculated as shown in equations (6) and (7) respectively (Hashemi et al. [3]):

$$F = 1 - \frac{3}{10} \left(\frac{\delta}{a} \right)^2 - \frac{3}{2} \left(\frac{l_1 \delta}{a^2} \right) \quad (6)$$

$$N = 1 - \left(\frac{l_2}{a} \right)^3 - \frac{9}{8} \left[1 - \left(\frac{l_2}{a} \right)^2 \right] \frac{l_1 \delta}{a^2} - \frac{9}{35} \left(\frac{\delta}{a} \right)^2 \quad (7)$$

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; and

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

The flexural modulus E_f is calculated as a function of the crack length a by using equation (8a) or (8b) if end blocks are used:

$$E_f = \frac{8(a + |\Delta|)^3}{CBh^3} \quad (8a) \quad E_f = \frac{8(a + |\Delta|)^3}{\frac{C}{N} Bh^3} \quad (8b)$$

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.

Analysis method 3: Experimental compliance method (ECM) or Berry's method — Double cantilever beam (DCB)

The logarithm of the compliance, or of the normalized compliance C/N , if load-blocks are being used, versus the logarithm of the crack length a are plotted. The slope of this plot n gives G_{IC} as follows:

$$G_{IC} = \frac{nP\delta}{2Ba} \cdot F \quad (9a) \qquad G_{IC} = \frac{nP\delta}{2Ba} \cdot \frac{F}{N} \quad (9b) \quad (9)$$

The same large-displacement correction F and load-block correction N , if applicable, are used as for the corrected beam theory method.

Analysis method 4: Simple beam theory (SBT) — Tapered double cantilever beam (TDCB)

This is the same as in analysis method 1 except the value of m is a constant for this particular geometry.

Analysis method 5: Corrected beam theory (CBT) — Tapered double cantilever beam (TDCB)

The simple beam theory expression for G_{IC} described in analysis method 4 will incorrectly estimate the compliance of the specimen since:

- a) the positions of the loading pins, with their surrounding material, are not taken into account in deriving equation (4); and
- b) as for the DCB specimen, the specimen does not behave as a perfectly built-in cantilever beam.

Corrections (Blackman et al. [5]) lead to equation (10).

$$\frac{dC}{da} = \frac{8m}{E_s B} \left[1 + 0.43 \left(\frac{3}{ma} \right)^{\frac{1}{3}} \right] \quad (10)$$

Hence, combining equations (2) and (10), equation (11) is obtained.

$$G_{IC} = \frac{4P^2 m}{E_s B^2} \left[1 + 0.43 \left(\frac{3}{ma} \right)^{\frac{1}{3}} \right] \quad (11)$$

In deriving equation (10), the value of m is approximated to $3a^2/h^3$, i.e. the term $1/h$ in equation (1) is neglected. The error in the value of G_{IC} that is introduced by this approximation is insignificant and round-robin testing has demonstrated good agreement between the values of G_{IC} deduced via equations (11) and (2) for tapered beams manufactured with aluminium alloy substrates (Blackman and Kinloch [6]).

Analysis method 6: Experimental compliance method (ECM) — Tapered double cantilever beam (TDCB)

The adhesive fracture energy G_{IC} is calculated using equation (2), where the values of C plotted against the crack length a produces a linear graph.

$$G_{IC} = \frac{P^2}{2B} \cdot \frac{dC}{da} \quad (2)$$

1 Scope

This standard specifies a method, based upon linear-elastic fracture-mechanics (LEFM), for the determination of the fracture resistance of structural adhesive joints under an applied mode I opening load using the double cantilever beam (DCB) and tapered double cantilever beam (TDCB) specimens.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this British Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

BS EN ISO 291:1997, *Plastics — Standard atmospheres for conditioning and testing*.

BS 5214-1:1995, *Rubber and plastics test equipment; tensile, flexural and compression types (constant rate of traverse) — Description*. [ISO 5893:1993]

BS EN ISO 10365:1992, *Adhesives — Designation of the main failure patterns*.

3 Symbols and abbreviated terms

For the purpose of this standard, the following symbols and abbreviated terms apply.

A	insert film length, distance between the end of the specimen and the tip of the insert film NOTE 1 See Figure 1.
a	crack length, distance between the load-line (intersection of plane through pin-hole centres or centres of the hinge axes and plane of crack) and the tip of the precrack or crack on the edge of the specimen NOTE 2 See Figure 1.
a_p	precrack length, measured from the load-line to the tip of the mode I precrack
a_0	insert film length, distance between the load-line to the tip of the insert film NOTE 3 See Figure 1.
B	width of the specimen
C	compliance δ/P of the specimen
C_{cs}	compliance of the calibration specimen used to measure the system compliance
C_{max}	compliance of the specimen at maximum load
C_{sy}	compliance of the tensile loading system
C_{total}	compliance of the tensile loading system and the calibration specimen used to measure this NOTE 4 See Annex A.
C_0	initial compliance of the specimen neglecting start-up effects, e.g. due to play in the specimen fixture NOTE 5 See Figure 2.
$C_0 + 5\%$	initial compliance C_0 of the specimen increased by 5 % NOTE 6 See Figure 2.
E_f	flexural modulus of the arms of the substrate beam, calculated from the DCB mode I crack propagation test
E_s	independently measured flexural, or tensile, modulus of the arms of the substrate beam
F	large displacement correction
G_{IC}	critical strain energy release rate, or adhesive fracture energy, for applied mode I opening load
H	thickness of the load-block
h	thickness of substrate beam at a crack length a
h_a	thickness of the adhesive layer
l	total length of the specimen
l_1	distance from the centre of the loading pin or of the piano hinge axis to the mid-plane of the arm of the substrate beam to which the load-block or the piano hinge is attached NOTE 7 See Figure 1.

l_2	distance between the centre of the pin-hole of the load-block and its edge, measured towards the tip of the insert (starter film) or the tip of the mode I precrack NOTE 8 See Figure 1.
l_3	total length of the load-block (See Figure 1)
MAX/5 %	either maximum load of 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 $C_0 + 5\%$ NOTE 9 See Figure 2.
m	specimen geometry factor NOTE 10 See equation (1).
N	load-block correction
NL	onset of non-linearity on the load–displacement curve NOTE 11 See Figure 2.
n	slope of a plot of $\log_{10} C$ versus $\log_{10} a$, or $\log_{10} (C/N)$ versus $\log_{10} a$, if load-blocks are being used
P	load measured by the load-cell of the testing machine
PROP	increments of the crack length during stable crack growth (propagation) that are marked on the load–displacement curve NOTE 12 See Figure 2.
r^2	correlation coefficient of linear fits
r.h.	relative humidity during test
T	test temperature
T_d	conditioning (drying) temperature of the joint
T_{mc}	maximum cure temperature of the adhesive
t_c	duration of curing of the adhesive
t_d	duration of conditioning (drying) of the joint
VIS	onset of visually recognizable crack growth on the edge of the specimen that is marked on the load–displacement curve NOTE 13 See Figure 2.
Δ	crack-length correction for beam that is not perfectly built-in
δ	displacement of the cross-head of the testing machine
δ_{cor}	the displacement of the cross-head, corrected for system compliance effects

4 Principle

A double cantilever beam (DCB) specimen or a tapered double cantilever beam (TDCB) is used to determine the adhesive fracture energy G_{IC} of structural adhesive joints.

Resistance to both crack initiation and propagation are determined. The resistance to crack initiation is determined from both a non-adhesive insert placed in the adhesive layer and from a mode I precrack. The resistance to crack propagation is determined from the mode I precrack. The adhesive fracture energy G_{IC} (also termed the critical strain energy release rate) for applied mode I loading is calculated and a resistance-curve (R-curve, i.e. a plot of the value of G_{IC} versus crack length) is determined.

5 Apparatus

5.1 Tensile testing machine, conforming to BS 5214-1:1995, capable of producing a constant cross-head displacement rate between 0.1 mm/min and 5 mm/min in displacement control. The testing machine shall be equipped with:

- a fixture to introduce the load to the pins inserted into the load-blocks or directly into the substrate beams; or
- grips to hold the piano hinges that both allow rotation of the specimen end (see Figure 1).

The testing machine shall incorporate a load-cell that shall be calibrated and be accurate to within $\pm 1\%$ for the chosen load-range.

NOTE Loads are typically expected to be in the range of 100 N to 5 000 N.

The opening displacement of the test specimen shall be deduced from the position of the cross-head. The testing 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 a video camera with a suitable magnification*, capable of measuring crack length along the edge of the specimen to an accuracy of at least ± 0.5 mm.

5.3 *Micrometer or vernier calipers*, capable of measuring the thickness of the substrate arms and bonded joints with an accuracy of at least ± 0.02 mm.

5.4 *Micrometer or vernier calipers*, capable of measuring the width of the joints with an accuracy of at least ± 0.05 mm.

5.5 *Typewriter correction fluid ("white ink") or white spray-paint*.

6 Specimens

6.1 Number of specimens

A minimum of four joints shall be tested.

6.2 Conditioning

Maintain the joints in normal laboratory conditions for a minimum of 24 h prior to testing, i.e. a temperature of $23\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$, and at a r.h. of $50\% \pm 5\%$.

6.3 Manufacture of adhesive joint specimens

A double cantilever beam (DCB) specimen shall be as shown in Figure 1a), Figure 1b) or Figure 1c). A tapered double cantilever beam (TDCB) specimen shall be as shown in Figure 1d),

The thickness of the film to be inserted in the bondline during manufacture shall be less than $13\text{ }\mu\text{m}$. The film shall be non-stick. The thickness of the adhesive bondline shall be carefully controlled and shall be less than 1 mm. The thickness of the bondline shall not vary by more than 20 % within a joint, nor shall the average bondline of one joint differ by more than 20 % from another joint in the sample.

NOTE 1 A PTFE film is recommended. If aluminium foil is used, the foil should be coated with releasing agent prior to use. Appropriate surface treatments for metallic substrates are found in prEN 13887.

NOTE 2 It should be recognized that the value of G_{IC} measured from these tests will depend upon the bondline thickness of the joint. The value of the bondline thickness should be determined by the user, based upon the adhesive manufacturer's recommendation or upon consideration of the intended application.

NOTE 3 It is not within the scope of this standard to specify full manufacturing details of the joints to be tested. Such information should be sought from the adhesive manufacturer and/or the substrate manufacturer.

When fully cured, any excess adhesive shall be removed by mechanical means to leave the joint with smooth sides.

6.4 Measurement of specimen dimensions

6.4.1 DCB substrates

Measure the thickness of each DCB substrate using a micrometer (5.3) before bonding. Make the measurements at three points along the length of the beam, at 30 mm from either end, and at the mid-length. Calculate the mean value of the thickness of each substrate h . Determine the bondline thickness h_a by subtracting the substrate thicknesses $2h$ from the total thickness of the joint.