IEC TS 62788-6-3

Edition 1.0 2022-08

TECHNICAL SPECIFICATION

Measurement procedures for materials used in photovoltaic modules – Part 6-3: Adhesion testing for PV module laminates using the single cantilevered beam (SCB) method

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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MEASUREMENT PROCEDURES FOR MATERIALS USED IN PHOTOVOLTAIC MODULES –

Part 6-3: Adhesion testing for PV module laminates using the single cantilevered beam (SCB) method

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IEC TS 62788-6-3 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
82/2012/DTS	82/2057A/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at http://www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62788 series, published under the general title *Measurement procedures for materials used in photovoltaic modules*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

This document describes the single cantilevered beam (SCB) test, useful for characterizing adhesion in photovoltaic (PV) modules. This method is grounded in fundamental concepts of beam and fracture mechanics [1][1], [4], and allows for a quantitative measurement of adhesion strength. A method for calculating the debond length, $a_{f,}$ has been developed as an option to physical measurement.

PV modules are multi-layer structures that depend on adequate adhesion between each layer to ensure their reliable operation. Adhesion testing is described in current IEC PV standards for module safety qualification (IEC 61730-2) and component characterization (IEC 62788 series). The most commonly used tests are peel tests at either 180° for components (IEC TS 62788-2 test and IEC 62788-1-1), or at 90° for modules (IEC 61730-2 MST 35).

Peel tests are in practice simple to carry out, and provide a peel strength value, different from adhesion strength. Viscoelastic properties of the polymeric material and the mechanics of the pull tab have a strong influence on the result, making these tests of limited value in comparing either different materials, or the same material after stress exposures.

In the SCB method, an elastic width-tapered cantilever beam is adhered to the sample. When the beam is loaded at its apex, delamination will initiate at the weakest interface and advance upon continued loading. This measurement allows for calculation of the critical value of the energy release rate, G_c, which is the adhesion property for a given material interface. The value defined by this method is less dependent of the viscoelastic properties of the polymeric material, and so more useful for measuring differences or changes in adhesive strength.

The SCB method can be conducted at either the coupon or module level. Because it does not require using the backsheet as a pull tab, it is more likely to able to test the adhesion of a thin outer layer of the backsheet. These considerations give this test method good flexibility to use in applications related to PV modules. Examples for several specific use cases are provided.

This document offers a generalized method for performing the test, with the expectation that best practices for utilizing this test method will be developed for specific applications.

Examples of this method being employed to quantify and define the threshold values of encapsulant and backsheet adhesion for PV module reliability may be found in the literature [1] through [5].

[1] Numbers in square brackets refer to the Bibliography.

MEASUREMENT PROCEDURES FOR MATERIALS USED IN PHOTOVOLTAIC MODULES –

Part 6-3: Adhesion testing for PV module laminates using the single cantilevered beam (SCB) method

1 Scope

This part of IEC TS 62788 provides a method for measuring the adhesion energy of most interfaces within the photovoltaic (PV) module laminate.

In contrast to other adhesion tests in general use, this method provides a measure of adhesive energy, via the critical energy release rate, and so is more useful for comparing adhesion of different specimen types; e.g. different materials, module or coupon samples, or materials before and after stress exposure.

This is a “weakest link” test, meaning that the weakest interface is the one most likely to fail in a given test. Adhesion of a specific layer may be difficult to intentionally measure if there is a weaker interface in the system.

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.

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

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*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 apply, as well as the following.

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

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
cantilevered beam
beam supported at only one end such that the slope and deflection of that end is ideally zero

3.2
mechanical compliance
measure of the extent of deformation due to the action of external forces (reciprocal of stiffness)

Note 1 to entry: Unit (preferred): m/N.

3.3
adhesive failure
de-bonding occurring between the adhesive and the adherent, to be differentiated from cohesive failure within the adhesive material

3.4
cohesive failure
crack propagating within the adhesive during adhesion test, e.g. peel test

3.5
adhesive energy
G
specific energy (in J/m^2) released during separation of two material layers

3.6
critical adhesive energy
G_c
critical strain energy release rate necessary to promote crack growth

3.7
debond length
a
measured length of specimen from the apex of the tapered beam to the end of the debonded area

3.8
load-line displacement
Δ
displacement measured along the loading axis of a load frame

3.9
unfixed beam length
L_b
length of the beam between the clamp and the tip, used to determine the compliance calibration of the beam

3.10
compliance calibration method
method used to calculate the debond length based on the measured compliance at various crack lengths for a specific beam

3.11
plastic deformation
permanent, non-recoverable deformation

3.12
cohesive zone
trailing area adjacent to the debond edge that may consist of cavitation, voids and ligaments within the adhesive

4 Apparatus

4.1 Load frame

A properly calibrated load frame shall be used that can be operated in a displacement control mode with a constant rate of 10,0 µm/s. A load cell with a capacity of 200 N is recommended. The load frame shall conform to the requirements of ISO 7500-1.

The load frame shall be equipped with the following:

- a clevis grip link that couples the load train to the loading tab attached to the specimen, Figure 1. The link should be ≥ 30 mm between the centres of the connection points, and each end of the link shall be able to rotate freely about the clevis pin orthogonal to the specimen plane. The clevis pin should be 1,0 mm steel or material of equal or greater elastic modulus.
- a platen opposite the loading grip to which the test specimen is secured, Figure 2a); or, the load frame may be modified to sit on the specimen (e.g., PV module) Figure 2b).
- a displacement indicator capable of monitoring and recording load-line displacement. The displacement indicator shall indicate the load-line displacement within an accuracy of 10 µm.
- a load-sensing device capable of monitoring and recording the total load carried by the specimen. This device shall indicate the load with an accuracy over the load range(s) of interest within 0,1 N.

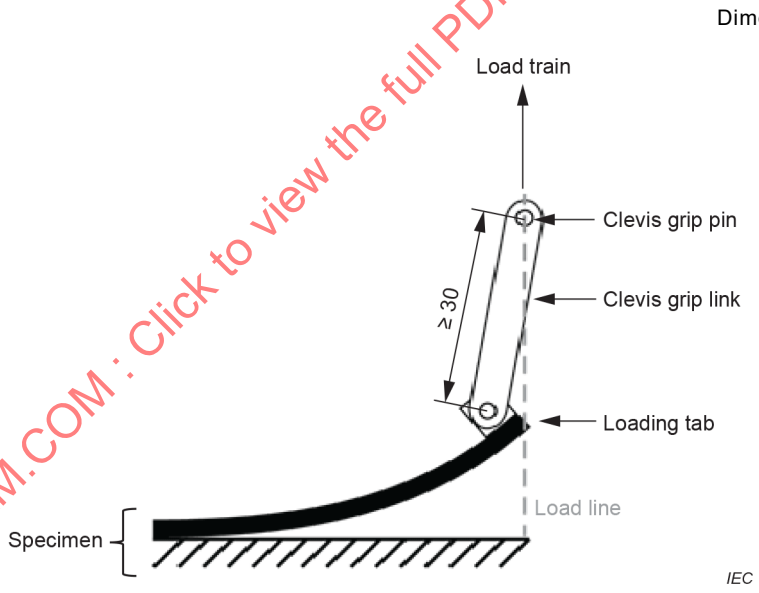


Figure 1 – Diagram of the loading connection using a clevis grip

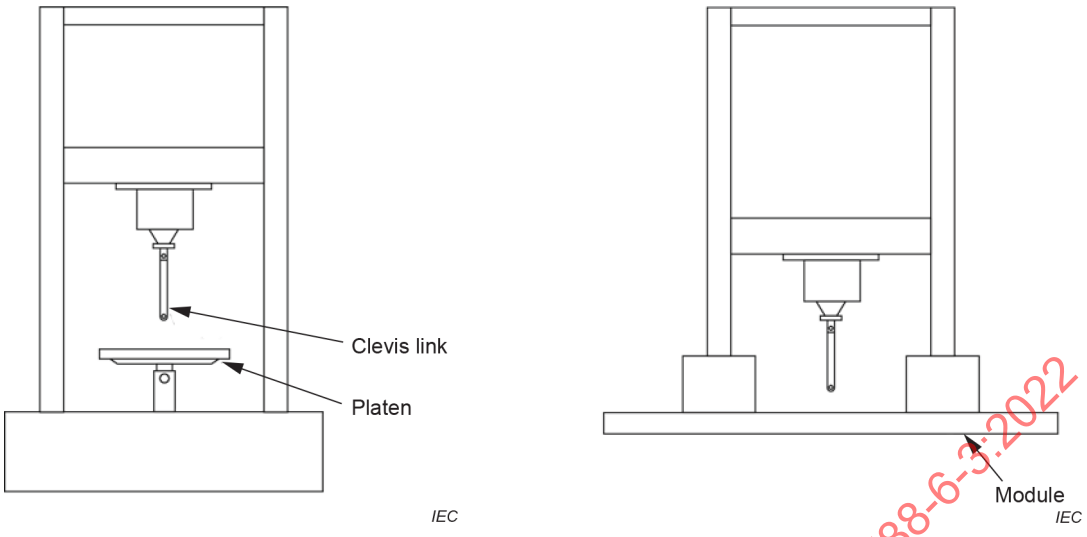


Figure 2 – Schematic of load frame with a) a platen for securing test coupon, and b) modified to sit on top of a PV module

4.2 Loading tab

The loading tab connects to the beam and to the loading pin of the Clevis joint. The preferred material for the loading tab is stainless steel, although aluminium may also be used. To provide a low friction surface, a sapphire jewel bearing is recommended for the contact with the loading pin. This should be inspected for damage prior to each test, and cracked bearings shall be replaced. Photos of a loading tab are shown in Figure 3. A reference engineering design is provided in Annex C.

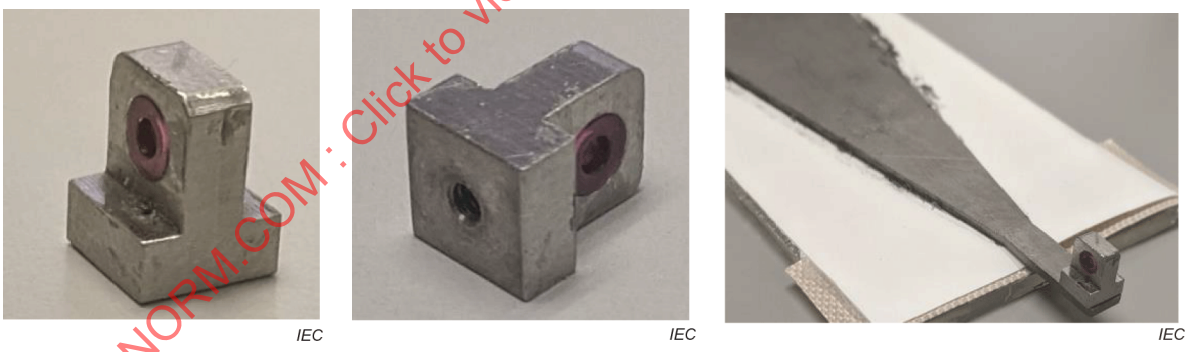


Figure 3 – Photos of the loading tab alone, and attached to the beam

5 Width-tapered cantilever beam

5.1 General

The beam is usually considered disposable and used only once. After cleaning, it may be reused if evaluated to ensure no permanent deformation has occurred. Recovering a deformed beam is not recommended.

Design parameters for the beam include both physical dimensions and material properties. Annex A describes a range of beams which may be used in the context of this document. Two specific designs are included in this specification, with the selection to be made based on the maximum expected adhesion energy, G_{max}, of the system to be measured.

5.2 Beam design

A variety of materials and beam designs can be used according to theory as described in Annex A. For simplicity, this document specifies a single material, Grade 5 Ti-6Al04V, and specific design parameters as given in Figure 4. Thickness shall be either 0,8 mm or 1,6 mm, as appropriate for different adhesion strengths (5.3).

A reference engineering diagram is provided in Figure C.1.

NOTE Annex A describes considerations for other materials, in particular for situations where very low adhesion energy measurements are targeted, or when adhesion to both beam and specimen is problematic with a titanium beam.

Dimensions in millimetres

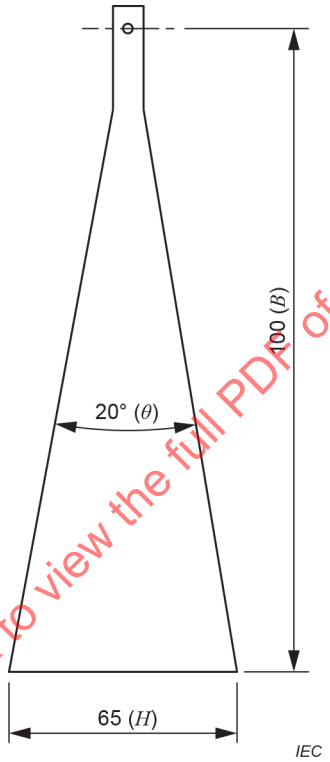


Figure 4 – Width-tapered beam

5.3 Beam selection

The optimum beam thickness is based on the expected adhesion strength value, with typical adhesion strengths for some PV interfaces shown in Table 1. The 0,8 mm titanium beam has been found useful for a range from ~20 J/m^2 to 1 200 J/m^2, and the 1,6 mm beam for a range from 100 J/m^2 to 2 500 J/m^2. For measurement of very low adhesion energies, a different beam material should be used; see Annex A.

Adhesion energy of an interface after environmental exposures can vary significantly, to near zero. For comparison of adhesion energy before and after environmental exposures, the same beam is recommended to be used for both, even for very low adhesion energies.

Highest sensitivity will be obtained with the most compliant beam which does not permanently deform during the measurement, so the titanium beam with thickness of 0,8 mm is a useful starting point. If the thin beam is used and visibly deformed after the test, the thicker beam should be used. If the thick beam is pulled off the substrate without elastically bending, this indicates a lower adhesion energy, and the thinner beam should be used.

Table 1 – Typical adhesion strengths

Interface	G_{max} J/m^2
Backsheet – encapsulant (initial)	200 to 800
Backsheet interlayers (initial)	200 to 2 300
Encapsulant glass (initial)	1 200 to 2 500
Encapsulant – cell (initial)	1 200 to 2 000

6 Test method

6.1 Specimen preparation

A general procedure is provided below, with examples for specific use cases provided in Annex B.

a) Prepare the test material

1) If the interface of interest is in the form of two different materials, laminate them in a manner which replicates the bonding in the application.

2) If a flexible substrate is used (e.g. for backsheet interlayer, or backsheet to-encapsulant), or a weak rigid substrate (e.g. a silicon cell) fix it to a strong rigid substrate (e.g. thick glass).

- The size shall be large enough to completely hold the beam, with width greater than h, and length greater than b.
- It may improve beam-specimen adhesion if the surface to be attached to the beam is abraded. Then, clean the surface with isopropyl alcohol and allow to dry.

b) Abrade the surface of the selected beam to be bonded with a 150 grit sandpaper or similar, and clean with isopropyl alcohol.

c) Adhere the tapered-width portion of beam to the top layer of the test specimen using a thin layer of adhesive, leaving the rectangular portion unattached. A two-part structural adhesive is recommended, using manufacturer's instructions for mixing and shelf life. A weight (1 kg to 5 kg) should be placed on top of each beam specimen to ensure even adhesive coverage and a thin bond line. Care should be taken to ensure uniform weight distribution along the length of the beam. Use of silica spheres in the epoxy can help to assure a minimum thickness across the interface. Remove any excess adhesive from around the beam while tacky but before it is fully cured.

NOTE 1 One example is 3M DP4M epoxy adhesive. This information is provided for the convenience of users of this document and does not constitute an endorsement by IEC of this products.

d) Once the adhesive is fully cured, cut through the material around the beam down to the rigid substrate using a sharp razor blade or scalpel (e.g. for a backsheet), or a sharp carbide or diamond scribe (e.g. for a silicon cell). A leading-edge laser cutting device may also be useful.

e) Condition the specimen at 23 °C ± 2 °C and 50 % ± 10 % RH for at least 24 h prior to test.

NOTE 2 Achieving equilibrium at standard conditions may take longer and can affect the results.

NOTE 3 Adhesive curing and sample conditioning can take place at the same time.

6.2 Measurement procedure

a) Attach the loading tab to the beam.

b) Attach the clevis link to the loading tab and clamp the sample to the platen. Orient the sample so that the clevis link is vertical and in-line with the loading direction, and the centre of the beam is aligned with the loading direction.

c) With zero applied load on the sample, initiate the test at a constant displacement rate of 10 µm/s and continue until the debond has propagated approximately 1/3 to 1/2 of the sample length.

NOTE 1 With a constant displacement rate of 10 µm/s, test time may range between 5 min and 15 min depending on the amount of deflection required to achieve an adequate debond length.

d) Check the beam and sample; the following conditions shall be met to result in a valid measurement:

- The width-tapered beam shall not show any indication that it has plastically deformed during the measurement. If the beam demonstrates any indication of permanent deformation following the measurement, e.g. does not lie flat, the measurement is not valid. If this occurs, repeat the measurement with a stiffer or thicker beam.
- In the sample, debonding shall exist at only one interface. If the debond switches interfaces during the measurement or propagates at more than one interface simultaneously, the measurement is not valid.

NOTE 2 Analysis for mixed mode debonding is beyond the current scope of this document.

e) Define the portion of the curve where the load, P, is reasonably stable as shown in Figure 5, and note the average and standard deviation over that range. Some software will do this automatically.

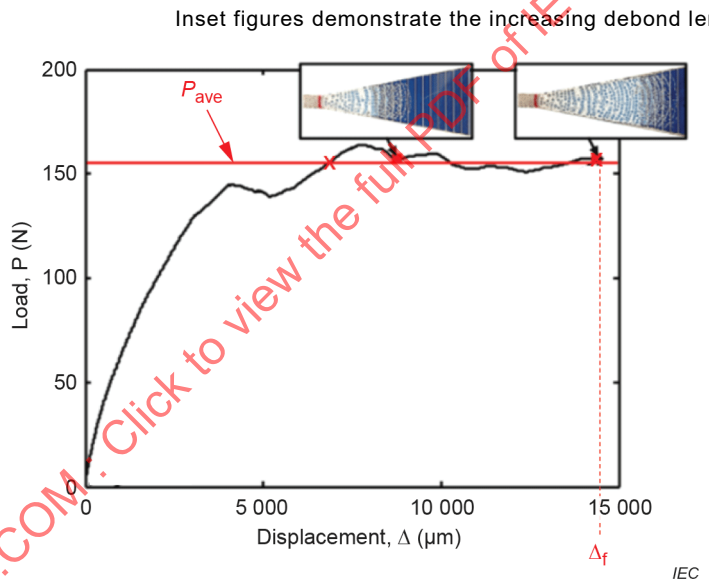


Figure 5 – Typical width-tapered cantilever beam load/displacement curve

f) If using Method 2 (6.3) to calculate the critical adhesion energy G_c:

- Note the final load line displacement, Δ_f, as shown in Figure 5.
- Measure the final debond length a_f from the centre of the loading tab's pin axis to the debond edge (Figure 6). Tips for measurement of opaque samples are provided in Annex E.

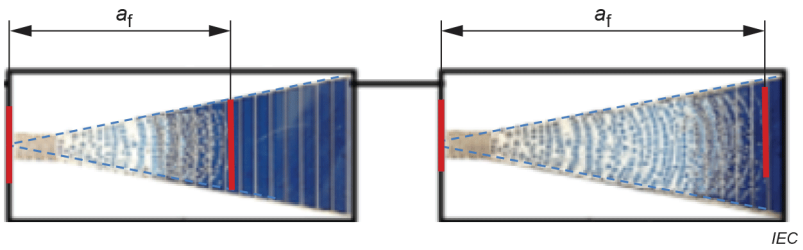


Figure 6 – Example of an a_f measurement on glass/encapsulant/cell specimens

6.3 Analysis

6.3.1 Critical adhesion energy, G_c

6.3.1.1 General

Two different methods may be used to calculate G_c, with both providing similar results. Method 2 may be easier for initial or occasional use. Method 1 will take more time initially to generate the reference compliance curve and set up the calculation spreadsheet, but may be easier for repeated studies.

For opaque samples, the location of the crack tip may be difficult to define and user-dependent (see Annex B); Method 1 will be easier and more repeatable.

6.3.1.2 Method 1

a) Calculate the debond length a_i for every data point as in Formula (D.3), using the parameters established for the reference compliance curve for that beam type as in Annex D.

b) Using the pull force and displacement at each of N measurement points (P_i, Δ_i, and N respectively), calculate $G_{c,ave}$ as in Formula (1).

$$G_{c,ave} = \frac{1}{N}\sum_{i=1}^{N} G_{ci} = \frac{1}{N}\sum_{i=1}^{N} \frac{P_i}{2\tan\left(\frac{\theta}{2}\right)}\frac{\Delta_i}{a_i^2} \tag{1}$$

c) Calculate σ_{Gc} as in Formula (2).

$$\sigma_{Gc} = G_{c,ave}\sqrt{\left(\frac{\sigma_P}{P_{ave}}\right)^2 + \frac{2}{N-1}\sum_{i=1}^{N}\left(\frac{1{,}5\ \text{mm}}{a_i}\right)^2} \tag{2}$$

NOTE The uncertainty of Method 1 is largely due to variability in the method (compression of the polymer behind the crack tip, expansion under the head deviation of up to 10 % can occur due to effects of the polymeric materials), and in part from the measurement. To simplify error propagation, a constant value of 1,5 mm is used for the uncertainty in all the individual debond length estimates, σ_{ai}.

6.3.1.3 Method 2

a) Calculate G_c, as in Formula (3).

$$G_c = \frac{P_{ave}}{2\tan\left(\theta/2\right)}\frac{\Delta_f}{a_f^2} \tag{3}$$

b) Calculate σ_G as in Formula (4).

$$\sigma_G = G_{c,ave}\sqrt{\left(\frac{\sigma_P}{P_{ave}}\right)^2 + 2\left(\frac{0{,}002\ \text{m}}{a_f}\right)^2} \quad (4)$$

where

P_{ave} is the average load from point a to b [N];

θ is the included beam angle (20°);

Δ_f is the final load line displacement [m];

a_f is the final debond length [m].

NOTE The uncertainty of a_f comes from the physical measurement, a qualitative determination of the fracture line, and the size of the cohesive zone. To simplify error propagation, a constant value of 2 mm is used for the final debond length uncertainty, σ_{af}.

7 Report

Each test report should include at least the following information:

a) a title;

b) the name and address of the laboratory, and the location where the tests were carried out, if different from the address of the laboratory (such as on-site location);

c) unique identification of the test report (such as the serial number), and on each page an identification to ensure that the page is recognized as a part of the test report, and a clear identification of the end of the test report;

d) name and address of the client, where appropriate;

e) description and identification of the item tested;

f) characterization and condition of the test item;

g) date of receipt of test item and date(s) of the test, where appropriate;

h) reference to sampling procedure, where relevant;

i) whether the test is performed on fresh material, or after a specified stress exposure;

j) method and duration of sample conditioning;

k) characterization of the beam used, including material, thickness;

l) any deviations from, additions to, or exclusions from the test method, and any other information relevant for a specific test, such as sample temperature and environmental conditions;

m) the method used to calculate G_c;

n) the adhesion energy, and one standard deviation of the measurement as $G_c \pm \sigma_G$;

o) the debond interface;

p) failure mode (cohesive or adhesive) at interface and indicate if significant slip/stick behaviour is observed;

q) for Method 2, the manner of measuring the final debond length, a_f;

r) if the beam deforms during the measurement, report the beam thickness used, and “not valid – beam deformation”.

Annex A
(informative)

Summary of background theory, and how this method can be generalized

A.1 Background theory

Adhesion energy is defined as the energy required to create a unit of area of fracture surface, G [J/m^2], and can be quantified by a critical value of the energy release rate, G_c, given by Formula (A.1).

$$G = \frac{P^2}{2}\frac{dC}{da} \tag{A.1}$$

where

P is the applied force [N];

C is the mechanical compliance of the cantilever beam [1/N];

a is the debond length [m].

In the cantilever beam method of measuring this quantity, the cantilever beam is an elastic beam, adhered to the laminate structure of interest, which stores strain energy when it is deflected. Once the stored strain energy overcomes the adhesion energy of the system, a debond will propagate. In the width-tapered embodiment of this specimen configuration under the assumptions of simple beam theory, the geometry of the beam dictates that the change in compliance per unit area of debond growth (dC/da) is constant, which permits a direct evaluation of G from measurement of the applied force, given by Formula (A.2).

$$G \approx P^2 \tag{A.2}$$

In terms of geometric properties of the beam, the critical value of Formula (A.1) becomes:

$$G_c = \frac{P_c}{2\tan\left(\frac{\theta}{2}\right)}\frac{\Delta}{a^2} \tag{A.3}$$

where

P_c is the critical load [N];

θ is the included beam angle;

Δ is the load line displacement [m];

a is the debond length [m].

However, the assumptions of small deflections in simple beam theory are not always valid. For an elastic beam, the radius of curvature, R, is related to the bending moment, M, as a function of the distance along the beam from the tip, a', by Formula (A.4).

$$\frac{1}{R} = \frac{M(a')}{EI(a')} = \frac{P \times a'}{E\frac{2tan\left(\frac{\theta}{2}\right)a' \times t^3}{12}} = \frac{P}{E}\frac{12}{2tan\left(\frac{\theta}{2}\right)t^3} \tag{A.4}$$

Here, it is assumed that the component of P parallel to the beam surface causes negligible elongation of the beam, and that it is normal to the surface at the beam tip. The bending moment, $M(a')$ is the product of the component of force, P, multiplied by the distance from the point of application, $M = P \times a'$. For the tapered beam, the bending moment of inertia, $I(a')$, is given by the product of the beam width, w, multiplied by the beam thickness, t, to the third power: $I = wt^3/12$. Noting that the beam width, w, varies with the wedge angle (Θ) as $w = 2\tan(\theta/2)\, a'$, yields the result that the curvature of the beam, K, is constant, independent of distance from the end of the beam. However, this ignores the fact that that the free end does not come to a point, the applied force is not normal to the surface, the fixed is not a true cantilever, and no strain is occurring in the direction of the plane of the beam. Nonetheless, if simple beam theory is taken to be valid then, Formula (A.5) holds true:

$$\frac{1}{R} = \frac{\frac{d^2y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \cong \frac{d^2y}{dx^2} \sim \frac{\Delta}{a^2} \tag{A.5}$$

where

Δ is the displacement of the beam tip in the y direction normal to the plate [m];

a is the crack length as measured along the surface of the beam in the direction x [m].

Combination and rearrangement of Formulae (A.2) and (A.3) yield Formula (A.6):

$$\frac{\Delta}{Pa^2} = \frac{12}{E \times 2tan\left(\frac{\theta}{2}\right) t^3} \tag{A.6}$$

Here, the factor $\frac{\Delta}{Pa^2}$ is predicted, in the context of simple beam theory, to be a constant, dependent only on geometric and material parameters of the beam. In practice, however, $\frac{\Delta}{Pa^2}$ decreases as a function of displacement, Δ, and increases as a function of crack length, a. For the sample beam configuration, the nonlinearities in the response curve have been shown to vary as $\frac{\Delta E t^3}{Pa^2}$, [5]. This allows for variations in beam design, including material and physical parameters to be used to scale the relationships for the calculation of crack tip length as shown in Annex D.

A.2 Beam materials

Based on the ratio of Young's modulus to yield strength and compatibility with backsheet-compatible adhesive systems [1], [2], [5], acrylic and titanium have been found useful. This document has been developed with a focus on titanium beams, and care should be taken if generalizing for other materials.

For some applications, resistance to corrosion or transparency may be important, and other materials may be useful. Titanium has high resistance to corrosion, acrylic and other polymers are transparent, allowing for a simple visual measurement of a_f.

Polymethylmethacrylate (PMMA) may be useful for systems with very low adhesion energy, or where finding an adhesive with good adhesion to both the substrate and a titanium beam is difficult. As a warning, PMMA beams are more susceptible to deformation, so should be carefully checked after the test. A thickness of 6,4 mm has been found useful for 10 J/m^2 to 1 600 J/m^2.

Changing the beam (materials, thickness, etc.) may impact the results, so comparative tests should only be done with the same beam design.

Annex B
(informative)

Guidance for specific use cases

B.1 General

This Annex provides additional details beyond 6.1 for specific use cases. As this is a “weakest link test”, when testing coupons with more than two layers the adhesion strength of the weakest interface will be measured. The test should not be relied upon to define adhesion of a specific layer in the multilayer coupon, e.g., for purposes of comparing before and after a stress exposure.

B.2 Adhesion test coupons

B.2.1 Backsheet / encapsulant adhesion

This model coupon structure consists of a rigid substrate such as thick glass, plus encapsulant and backsheet as in Figure B.1a and Figure B.2a. One layer of encapsulant is sufficient.

- Cut the materials to be larger than the beam and laminate the stack according to manufacturer’s recommendations.
- When laying up the sample prior to lamination, a 1 cm wide strip of release liner can be placed between the encapsulant and backsheet layers at the edge of the sample. Then the beam can be placed with the handle over this non-adhered area providing a crack initiation at this interface.
- Adhere the tapered-width portion of beam to the air side (environment facing surface of the backsheet using a thin layer of adhesive, leaving the rectangular portion unattached). A two-part epoxy-based structural adhesive is recommended. A weight should be placed on top of the beam to ensure even adhesive coverage and a thin bond line. Care should be taken to ensure uniform weight distribution along the length of the beam. Remove any excess adhesive from around the beam before it is fully cured.
- Once the adhesive is fully cured, cut through the material around the beam, down to the rigid substrate using a sharp razor blade or scalpel. A rough cut is sufficient.

Often the 3,175 mm glass typically used in the PV industry will break during the test. To fix this problem, use a thicker piece of glass to build the sample or adhere the glass to another rigid substrate prior to testing.

If the epoxy fails during test, alternative epoxy formulations and/or beam materials should be evaluated.

B.2.2 Backsheet interlayer adhesion

This model coupon structure consists of a rigid substrate such as thick glass, plus backsheet as in Figure B.1a and Figure B.2b.

- Cut the backsheet sample to be larger than the beam. Adhere the backsheet directly to the glass using an epoxy adhesive,
- Heat-treat the sample according to the backsheet manufacturer’s recommended lamination conditions.

- Adhere the tapered-width portion of beam to the top layer of the backsheet using a thin layer of adhesive, leaving the rectangular portion unattached. A two-part epoxy-based structural adhesive is recommended. A weight should be placed on top of the beam to ensure even adhesive coverage and a thin bond line. Care should be taken to ensure uniform weight distribution along the length of the beam. Remove any excess adhesive from around the beam before it is fully cured.
- Once the adhesive is fully cured, cut through the material around the beam, down to the rigid substrate using a sharp razor blade or scalpel. A rough cut is sufficient.
- A debond at the interface of interest can be started prior to adhering the beam. To accomplish this, cut a ~3 cm long, open strip in the backsheet and peel back the layer of interest. A heat gun may be useful to soften materials so that they may be more easily separated. Once cool, tape this peeled tab back down to the backsheet and adhere the beam so that the handle is over this debonded portion.
- Often the 3,175 mm glass typically used in the PV industry will break during the test. To fix this problem, use a thicker piece of glass to build the sample or adhere the glass to another rigid substrate prior to testing.

If the epoxy fails during test, alternative epoxy formulations and/or beam materials should be evaluated.

B.2.3 Glass/encapsulant adhesion

This model coupon structure consists of a rigid substrate such as thick glass, plus encapsulant and a thin glass slide as in Figure B.1b and Figure B.2c. One layer of encapsulant is sufficient.

- Laminate the thick glass, encapsulant, and thin glass according to the encapsulant manufacturer's recommended conditions. For the thin glass slide, use a cover slip for microscopy (typically 1 mm thick) or thinner glass if available. The encapsulant/thin glass slide shall be larger than the beam.

NOTE Corning® Eagle XT® Glass and Precision Glass and Optics D263 are two examples of suppliers of glass with thickness less than 1 mm. Reference to these materials is given for the convenience of users of this document and does not constitute an endorsement by IEC of these products.

- Adhere the tapered-width portion of the beam to the glass slide using a thin layer of adhesive, leaving the rectangular portion unattached. A two-part epoxy structural adhesive is recommended. A weight should be placed on top of the beam to ensure even adhesive coverage and a thin bond line. Care should be taken to ensure uniform weight distribution along the length of the beam. Remove any excess adhesive from around the beam before it is fully cured.
- Once the adhesive is fully cured, cut through the material around the beam, down to the rigid substrate using a sharp carbide or diamond scribe. A rough cut is sufficient.

B.2.4 Adhesion between different encapsulants

The model coupon structure consists of a rigid substrate such a thick glass, plus encapsulant (encapsulant 1, the front encapsulant), plus encapsulant (encapsulant 2, the back encapsulant), and a thin glass slide as in Figure B.1b and Figure B.2e.

- Laminate the thick glass, encapsulant, and thin glass according to the encapsulant manufacturer's recommended conditions. For the thin glass slide, use a cover slip for microscopy (typically 1 mm thick) or thinner glass if available. The encapsulant/thin glass slide shall be larger than the beam.

NOTE Corning® Willow® Glass and Precision Glass and Optics D263 are two examples of suppliers of glass with thickness less than 1 mm. Reference to these materials is given for the convenience of users of this document and does not constitute an endorsement by IEC of these products.

- A removable release layer may be inserted at the edge of the specimen between the encapsulant layers to provide an initial separation between the two encapsulant layers to aid the test. The release layer would be inserted prior to specimen lamination and removed prior to weathering (in the case of aging) or testing (in the case of unaged specimens).

- Adhere the tapered-width portion of beam to the glass slide using a thin layer of adhesive, leaving the rectangular portion unattached. A two-part epoxy structural adhesive is recommended. A weight should be placed on top of the beam to ensure even adhesive coverage and a thin bond line. Care should be taken to ensure uniform weight distribution along the length of the beam. Remove any excess adhesive from around the beam before it is fully cured.
- Once the adhesive is fully cured, cut through the material around the beam, down to the rigid substrate using a sharp carbide or diamond scribe. A rough cut is sufficient.

B.2.5 Cell/encapsulant (coupons)

This model coupon structure consists of a rigid substrate, such a thick glass, plus encapsulant and a portion of a cell as in Figure B.1c and Figure B.2d. Either the front or back of the cell may be tested in this way. One layer of encapsulant is sufficient.

- Identify the “A” and “B” sides of the cell, with the intended test defined as the “A” side.
- Cut the materials (including the cell) to be larger than the beam, and laminate the stack according to manufacturer’s recommendations.
- Adhere the tapered-width portion of beam to the “B” side of the cell using a thin layer of adhesive, leaving the rectangular portion unattached. A two-part epoxy structural adhesive is recommended. A weight should be placed on top of the beam to ensure even adhesive coverage and a thin bond line. Care should be taken to ensure uniform weight distribution along the length of the beam. Remove any excess adhesive from around the beam before it is fully cured.
- Once the adhesive is fully cured, cut around the beam, through the cell and encapsulant, to the glass using a sharp carbide or diamond scribe. A rough cut is sufficient.
- The cell will break during the test – this will not substantively affect the result.

B.3 Modules

B.3.1 General

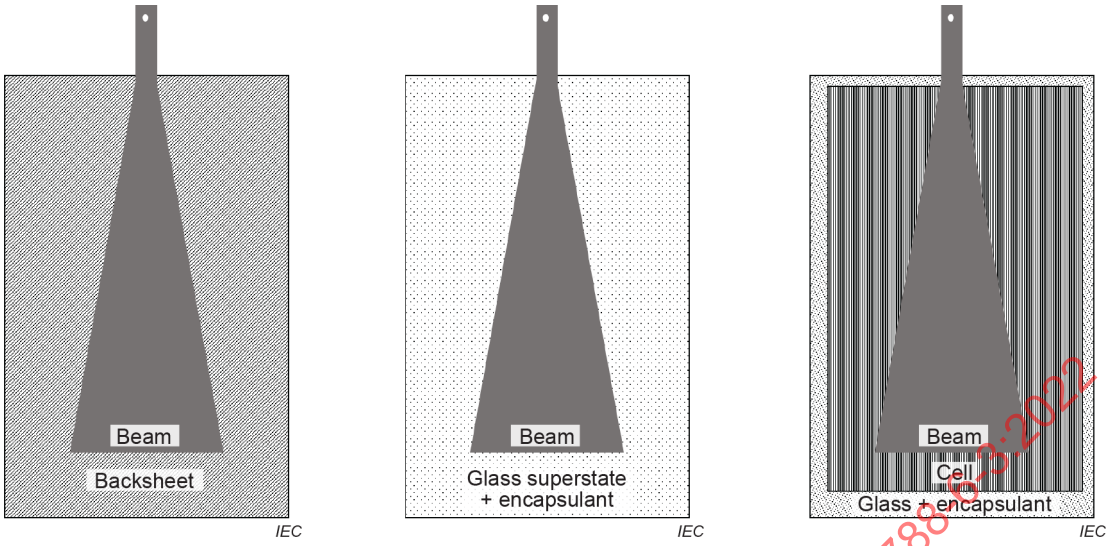
For modules, the beam is adhered directly to the module with the beam centred on a cell. The result will give the adhesion energy of the “weakest link” in the laminate structure.

B.3.2 Targeting a specific interface in a module

A specific interface can be targeted by initiating a crack between two layers, but it is not guaranteed that this interface will be the one to debond during the test.

For evaluation of the backsheet interlayer, backsheet / encapsulant, or backside / encapsulant / cell, cut a ~3 cm long, open strip in the backsheet and peel back the layer of interest. Use of a heat gun is often required to soften a thermoplastic backsheet adhesive such that it may be easily peeled.

To target the cell / encapsulant (front side) of a module with a polymeric backsheet, the backsheet and back encapsulant shall be removed to expose the back of the cell, and then grind off the back metallization of the cell to optimize bonding of the beam to the cell and avoid unwanted debonding of the metallization. This may be accomplished via wet polishing with metallography paper and isopropyl alcohol.



a) **Backsheet test coupon**

b) **Glass/encapsulant test coupon**
Encapsulant 1/encapsulant 2 test coupon

c) **Cell/encapsulant test coupon**

Figure B.1 – Top view of backsheet and encapsulant beam coupons

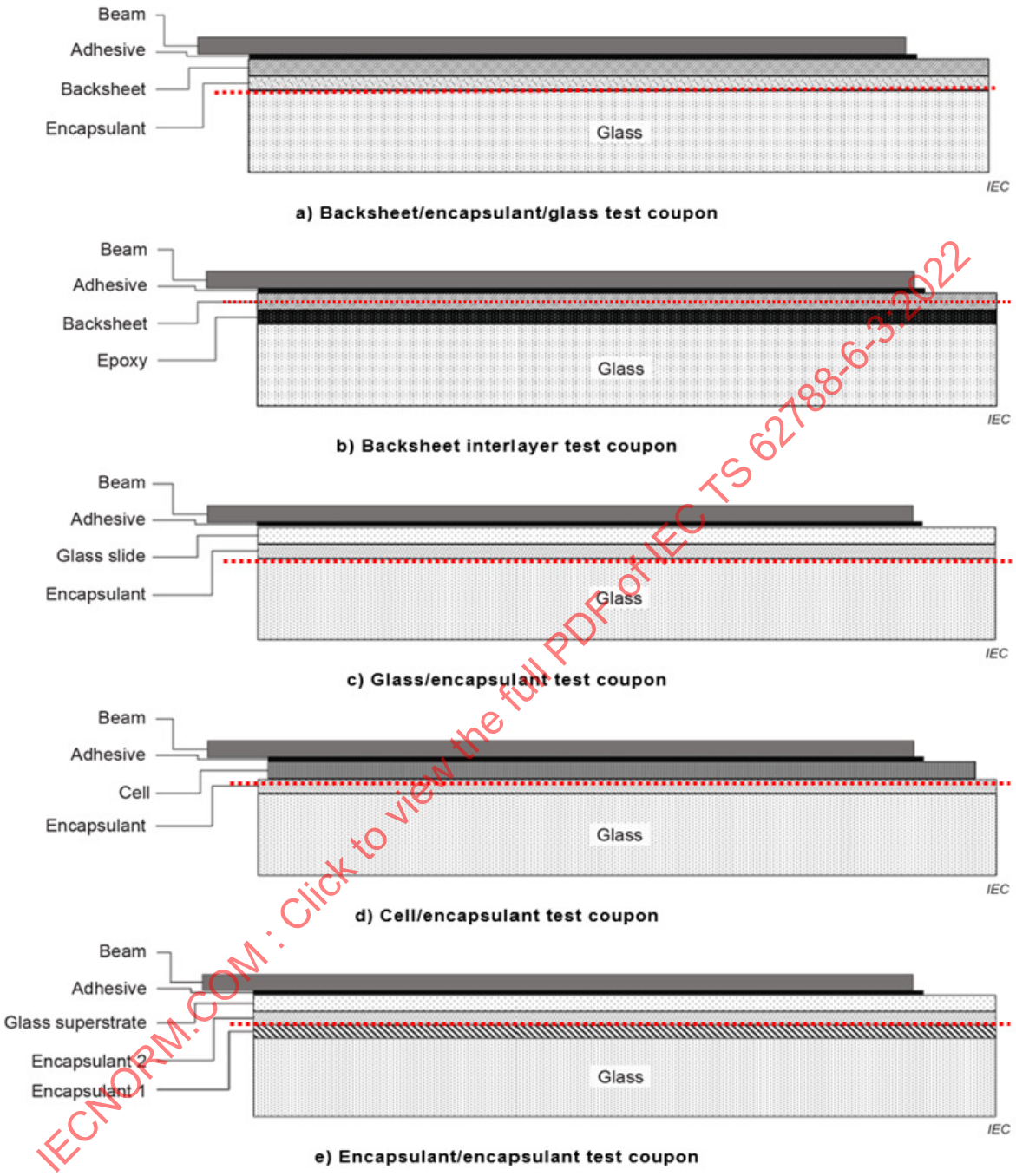


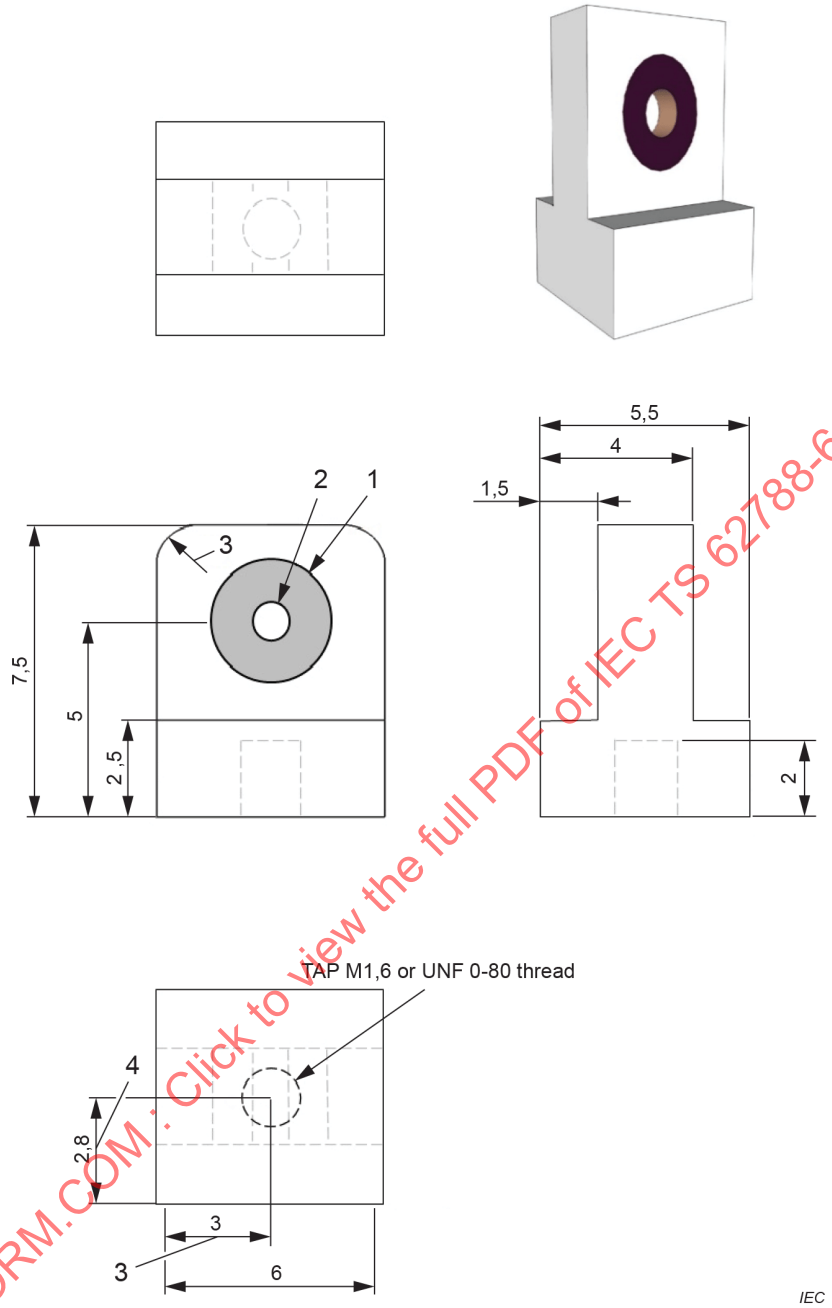
Figure B.2 – Cross-sectional view of backsheet and encapsulant beam coupons

Annex C
(informative)

Reference engineering diagrams for loading tab and beam

A reference schematic for the loading tab dimensions is shown in Figure C.1. The bearing here is an olive hole ring jewel, OD: (3,040 ± 0,006) mm, ID: (1,270 ± 0,003) mm and (0,902 ± 0,013) mm thick. The base of the loading tab is threaded for a flathead screw to affix the tab to the beam.

Dimensions in millimetres



Key

1 Press fit for jewel bearing, OD 3 mm

2 ID defined by separate purchased component

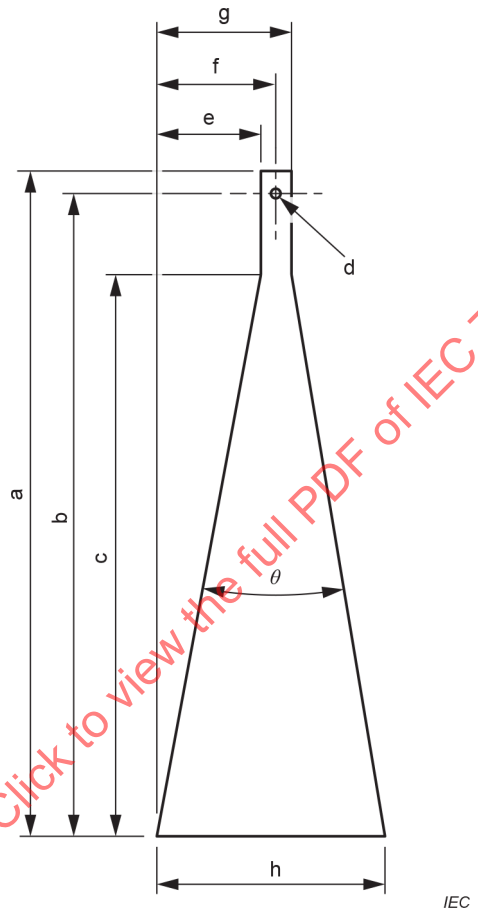
3 Option to grind or file to approximately R 1 mm or chamfer similarly to prevent contact between loading tab and clevis grip link

4 Centre mounting screw in middle of loading tab

Figure C.1 – Schematics of loading tab

A reference engineering diagram and dimensions for a beam is provided in Figure C.2.

- A rectangular handle portion shall provide a hole for mounting the loading tab positioned at the apex of the beam's included angle, θ:
  - width = 5,0 mm ± 0,5 mm with distance from centre of hole to end of tab ~2,5 mm;
  - hole is sized for M2 flat head screw (or similar).
- Beam material: Grade 5 Ti-6Al04V
- Beam thickness:



dimension	mm
a	103
b	100
c	85,6
d(iameter)	1,6
e	15,1
f	17,6
g	20,2
h	35,6

Figure C.2 – Schematics of beam

Annex D
(normative)

Using a reference compliance curve to calculate G_c

D.1 General

The crack length, a, can be calculated from the load and displacement values in the experiment on a point-by-point basis by generating a beam specific compliance curve and fitting an equation to this curve. This curve will be valid for beams of the same material, shape, and thickness if using the same load frame and clevis joint. As explained in Annex A, the response curve has been shown to vary as $\frac{\Delta E t^3}{P a^2}$, [5] which can aid in the application to different beams using the same experimental setup. Because titanium grades and machining practices can vary, each "lot" of beams shall be validated prior to use.

The set of a_i values is calculated according to Formula (D.3) after empirical parameters α, β and γ have been determined. These parameters shall be derived for each specific combination of apparatus and beam type. A set of reference parameters are provided in Table D.1 and can be used if validated. If they cannot be validated, they may prove useful as a starting point for identifying a new set of parameters based on an empirical fit of the beam compliance curve.

D.2 Procedure

D.2.1 Beam compliance measurement

a) Clamp a holding bar over the beam with the front edge at distance of about (60 ± 5) mm from loading tab at the point of the beam. This is the unfixed beam length, L_b (Figure D.1).

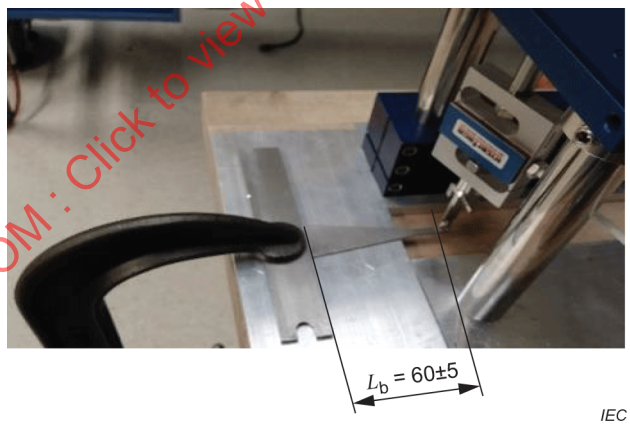


Figure D.1 – Photo of a beam prior to start of the calibration measurement

b) Initiate the test and pull to a displacement of 20 mm to 25 mm as in Figure D.2 for a 0,8 mm beam and 15 mm to 18 mm for a 1,6 mm beam. Record the pull force and displacement during the pull.