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Reinforced plastics composites — Specifications for pultruded profiles — Part 2: Methods of test and general requirements

Verstärkte Kunststoffeverbundwerkstoffe — Spezifikationen für pultrudierte profile — Teil 2: Prüfverfahren und allgemeine Anforderungen

Composites en plastiques renforcés — Spécifications pour les profilés pultrudés — Partie 2 : Méthodes d'essai et exigences générales

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Contents

Foreword

This document has been prepared by CEN /TC 249, "Plastics".

This document is currently submitted to the Formal Vote.

EN 13706 consists of the following parts under the general title *Reinforced plastics composites - Specifications for pultruded profiles*.

— *Part 1 : Designation*

— *Part 2 : Methods of test and general requirements*

— *Part 3 : Specific requirements*

Annexes A to E of this Part are normative and annexes F to G are informative.

1 Scope

1.1 This Part 2 of EN 13706 defines the general requirements applicable to the specification of all types of pultruded profiles falling within the scope of this specification as defined in Part 1 of EN 13706.

1.2 This Part 2 of EN 13706 describes the procedures to be followed in the preparation of test specimens for the determination of mechanical properties required for the designation in Part 1 and the technical specification in Part 3 of EN 13706.

1.3 This Part 2 of EN 13706 also defines the test methods to be used to determine both the designated and the specified properties given in Parts 1 and 3 respectively of EN 13706.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN 10204, *Metallic products - Types of inspection documents*.

EN ISO 527-4, *Plastics - Determination of tensile properties - Part 4: Test condition for isotropic and anisotropic fibre-reinforced plastics composites*.

EN ISO 2818, *Plastics – Preparation of test specimens by machining*.

EN ISO 14125, *Plastic - Fibre reinforced plastics composites - Determination of flexural properties*.

EN ISO 14126, *Plastic - Fibre reinforced plastics composites - Determination of compressive properties in the in-plane direction.*

EN ISO 14130, *Plastic - Fibre reinforced plastics composites - Determination of apparent inter-laminar shear by short beam method.*

ISO 472, *Plastics- Vocabulary.*

ISO 1172, *Textile glass reinforced plastics - Determination of loss on ignition.*

ISO 1183, *Plastics- Methods for determining the density and relative density of non-cellular plastics.*

ISO 1268-6, *Fibre reinforced plastics – Methods for producing test plates - Part 6: Pultrusion moulding*.

ISO 5893, *Rubber and plastics test equipment tensile flexural and compression types (constante note of traverse) – Description.*

ISO 11359-2, *Plastics - Thermomechanical analysis (TMA) - Part 2: Determination of coefficient of linear expansion and glass transition temperature*.

ISO 15310, Plastic - Fibre reinforced plastics composites - Determination of in-plane shear modulus by plate-twist.

NOTE Other test methods in Tables F.1 to F.4 of Annex F are informative and the full titles are given in those Tables.

3 Terms and definitions

For the purposes of the present part 2 of EN 13706, the terms and definitions given in ISO 472 and the following apply.

3.1
pultrusion
continuous production process for the manufacture of composite profiles, by pulling layers of fibrous materials, impregnated with a synthetic resin, through a temperature controlled die, and by curing and/or cooling the resin, forming the final shape of the profile

3.2
pultruded profile
linear composite products, produced continuously by the pultrusion process and usually of constant cross section and characteristics

3.3
structural
area of application of pultruded profiles where the load bearing characteristic is the major criterion of design and where the product is part of a load bearing system. For the purposes of this standard the minimum mechanical properties for a profile to be classified as structural is one which meets the minimum properties of grade E17 as defined in Table 1 of clause 4.4 in Part 3 of EN 13706

3.4
reinforcement layer
a discrete layer of reinforcement comprising of one type of fibre format, such as unidirectional rovings, mat or fabric

3.5
transverse reinforcement
reinforcement included to provide the required level of properties in the direction transverse to the pultrusion axis (e.g. mat, fabric)

4 General requirements

4.1 Appearance

The pultrusion shall meet the requirements given in Annex A, “Visual Defects: Descriptions and Acceptance Levels”.

4.2 Dimensional tolerance

The pultrusion shall meet the requirements given in Annex B, “Dimensional Tolerances for Pultruded Profiles”.

4.3 Workmanship

The pultrusion shall meet the requirements given in Annex C, “Workmanship”.

5 Sampling

The properties of pultruded profiles shall be measured by the manufacturer in accordance with a recognised quality control scheme and documented in the form of a certificate of conformity.

5.1 Certificate of Conformity

Where required by the customer a certificate of conformity shall be issued identifying both the obligatory properties as defined in Part 3 of EN 13706, plus other optional tests as may be agreed between customer and supplier. The certificate shall comply with the requirements of EN 10204.

5.2 Resolution of quality issues

In the case when issues of quality arise between customer and supplier, re-testing of the material is necessary. The sampling and tests shall be undertaken as agreed between customer and supplier.

6 Preparation of plates and test specimens

Test specimens shall be cut from the profile where the dimensions of the profile permit (see clause 6.2.2). In other cases, a test plate can be used to simulate the pultrusion for the determination of the laminate properties for design or qualification purposes.

6.1 Manufacture of test plates

Test plates shall be manufactured in accordance with ISO 1268-6 using a flat strip die. For test specimens cut only in the direction of production, the flat strip shall be a minimum of 50 mm wide.

If properties perpendicular to the direction of production are required, the flat strip shall be a minimum of 250 mm wide.

The thickness of the flat strip shall be the same as the profile being simulated.

The raw materials used, the laminate construction and the production parameters (die temperature, pull speed, etc.) of the test plate shall match as closely as possible the intended production conditions of the profile being simulated.

6.2 Preparation of specimens

6.2.1 Dimensions

Test specimens shall be cut to the dimensions and tolerances given in the individual test methods.

6.2.2 Cutting of test specimens

Test specimens shall not be taken closer than 10 mm to the edges or change in section of a profile. The cutting of test specimens must be undertaken in such a way that any resultant edge defects do not adversely effect the test results. One of the following three procedures may be used.

6.2.2.1 Milling

Test specimens may be cut from the test plaque using a duplicating or CNC milling machine.

6.2.2.2 Sawing

Test specimens may be cut from the test plaque using a circular saw fitted with a hardened metal or diamond edged saw blade. Alternative techniques such as laser or water jet cutting are also acceptable if meeting the above quality requirements.

6.2.2.3 Pre-cutting

Test specimens may be cut by any convenient means to a minimum of 5 mm over the specified width of the test specimen. 5 or 10 test specimens may then be packed together and milled to size as a block.

6.3 Full section test specimens

A full section test shall be used to determine the effective full section flexural modulus as required in clause 4 of Part 3 of EN 13706 using the test method described in Annex D.

Samples required for full section test shall be selected in accordance with the criteria given in clause 5 of this Part 2.

The samples selected shall be cut square at the ends and of sufficient length for the intended test (see Annex D of Part 2), and free from obvious production or other defects as listed in Annexes B and C.

7 List of Properties

Table 1 defines the list of material properties which shall be specified and the test methods which shall be used in each case to determine the property value.

Table 1 — List of properties which shall be specified and associated test methods

	Property	Unit	Test Method
1.1	Full Section test	GPa	Annex D, Part 2
1.2	Tension modulus-axial	GPa	EN ISO 527-4
1.3	Tension modulus-transverse	GPa	
1.4	Tension strength-axial	MPa	
1.5	Tension strength-transverse	MPa	
1.6	Pin bearing strength- axial	MPa	Annex E, Part 2
1.7	Pin bearing strength-transverse	MPa	
1.8	Flexural strength-axial	MPa	EN ISO 14125
1.9	Flexural strength- transverse	MPa	
1.10	Interlaminar shear strength-axial	MPa	EN ISO 14130

NOTE It should be noted that the stacking sequence of the different reinforcements formats (eg mat, rovings) produces a "sandwich type" layered structure, which results in different properties being obtained in flexural and tensile coupon tests. The position of the lay-up in the profile in webs and flanges will result in similar differences between these coupon tests and the full section test. It is not possible to predict any of the values from data obtained from a different test mode or test direction.

Table 2 defines the list of material properties which may be specified by agreement between customer and supplier and the test methods which shall be used in each case to determine the property value.

Table 2 — List of properties which may be specified and associated test methods

	Property	Units	Test Method
2.1	Compression strength -axial	MPa	EN ISO 14126
2.2	Compression strength - transverse	MPa	
2.3	Fibre content by weight	%	ISO 1172
2.4	Density	Kg/m^3	ISO 1183
2.5	Poisson's Ratio-axial		EN ISO 527-4
2.6	Poisson's Ratio-transverse		
2.7	Thermal expansion-axial	m/m °C	ISO 11359-2
2.8	Thermal expansion-transverse	m/m °C	
2.9	In-plane shear modulus	GPa	ISO 15310

Recommended methods for the determination of a number of mechanical, thermal, chemical, environmental and electrical properties are given in the Informative Annexes F and G. Unless otherwise agreed between interested parties, it is recommended that preference should be given to using these methods where applicable.

8 Labelling

Each package shall be clearly identified with:

8.1 Reference to the designation code.

8.2 Product type.

8.3 Section dimensions.

8.4 Number of sections or the total length in metres.

8.5 Gross and net weight of the pallet.

Annex A
(normative)

Visual Defects: Descriptions and Acceptance Levels
(see also annex C -Workmanship)

NOTE 1 These descriptions and levels are assessed by the unaided eye at a distance of 400 mm to 500 mm.

NOTE 2 Defect acceptable levels are on the basis that they cause no-adverse effect on mechanical performance of the pultruded profile.

NOTE 3 Some defects require examination of the cut end of a length of pultruded profile.

Table Error! Unknown switch argument.**.1**

Name	Definition	Acceptance Level
Blister	A rounded elevation of the pultruded surface with boundaries that may be more or less sharply defined. NOTE The rounded elevation somewhat resembles in shape a blister on the surface of human skin. Blisters may exist within the pultrusion as a hollow delaminated area (gas-filled) under a raised portion of the surface.	Permitted if formed between surfacing veil and next layer of reinforcement. Size not greater than 15 % of width and not greater than 10 mm in any direction. No more than 1 per 5 m of length. Product must meet test requirements and not exceed dimensional tolerances.
Crack	A visual separation that occurs internally or penetrates perpendicularly down from the pultruded surface to the equivalent of one full layer or more transverse to the reinforcement.	None
Crater	A small, shallow pultrusion surface imperfection, greater than 1 mm in diameter.	None greater than 5 mm diameter and 1 mm depth. No more than two per metre for craters between 1 mm and 5 mm diameter.
Delamination	The visible separation of two or more layers or plies of reinforcing material within a pultrusion.	None
Die Parting Line	A lengthwise flash or depression on the surface of a pultruded plastic part. NOTE The die-parting line is associated with the area where separate pieces of the die join together to form the cavity.	The line projection caused by the die-parting line shall not extend past the product's surface by more than 0,20 mm. It shall not create a sharp edge or have loose fibres. Repair if limits exceeded.
Internal Dry Fibre	A condition in which fibres are not fully impregnated by resin during pultrusion.	Permissible if area less than 0,5 mm diameter and not more than 2 % of the cross-section, including Internal Porosity (Void).
Dullness	A lack of normal pultruded surface gloss or shine. NOTE This condition can be caused by insufficient cure locally or in large areas, resulting in the dull band created on a pultruded part within the die when the pultrusion process is interrupted briefly (see Stop mark).	Permitted unless caused by insufficient cure.

"to be continued"

Table A.1 (*continued*)

Name	Definition	Acceptance Level
Exposed Underlayer	The underlying layer of mat or roving not covered by surface veil in a pultruded profile.	Permitted if surfacing material covers all but 5 mm from each free edge but not to exceed 20 % of the width of the surface being inspected
Fibre prominence	A visible and measurable pattern of the reinforcing material on the surface of a pultruded profile.	Permitted if reinforcing material is encapsulated by resin.
Folded Reinforcement	An unintentional or unspecified misalignment of mat or fabric reinforcing material in relation to the contour of a pultruded section. NOTE Such folds may or may not affect the surface appearance of the pultrusion and are chiefly visible in a cut cross section of the product. Such reinforcement irregularities are usually due to shifting and crowding of the reinforcing material during pultrusion.	Not permitted if fold causes a deviation in layer position greater than 20 % of thickness or 1,5 mm out of its plane.
Fracture	Cracks, crazing, or delamination, or a combination thereof, resulting from physical damage to the pultrusion.	None
Grooving	Long narrow grooves or depressions in a surface of a pultruded profile parallel to its length.	Permitted if material thickness reduction is not over 10 % and groove width is 3 mm or less. May be continuous in a length. Grooves on opposing surfaces are not permitted. Must satisfy dimensional and mechanical requirements.
Inclusion	Any foreign matter or particles greater than 1 mm in any dimension that are either encapsulated or imbedded in the pultruded profile.	None in excess of 5 mm in any dimension. No inclusion shall create a surface blemish above the resin. Not more than 1 per metre of length.
Under Cure	Insufficient crosslinking of the resin. NOTE Leads to lower mechanical performance and lower Barcol hardness (e.g. less than 30).	None
Internal Shrinkage Cracks	Longitudinal cracks in the pultrusion that are found within sections of roving reinforcement. NOTE This condition is caused by shrinkage strains during cure that show up in the roving portion of the pultruded profile where transverse strength is low.	Permitted if the crack does not penetrate an adjoining layer, reach the surface of the product or cause the product not to meets the test requirements.
Porosity, Internal (Void)	The presence of numerous voids beneath the pultruded profile surface, usually observable only in a cut cross section.	Sum of pinhole porosity area and void area shall be no more than 2 % of cross-sectional area, including Internal Dry Fibre
Porosity, Surface (Void)	The presence of numerous visible pits or pinholes at or near the pultruded profile surface, less than 1 mm diameter.	Permitted if pits are less than 0,4 mm in diameter and 0.4 mm deep. Maximum of 5 pits per 100 cm^2 of area and no more than one such area per 0,3 m of product.
Resin rich area	An area of pultruded profile that lacks sufficient reinforcement	Permitted if product meets test requirements (see also Folded Reinforcement).

"to be continued"

Table A.1 *(end)*

Name	Definition	Acceptance Level
Saw Burn	Blackening or carbonisation of a cut surface of a pultruded profile.	Permitted if product meets test requirements.
Scale	A condition wherein resin plates or particles are on the surface of a pultruded profile. NOTE Scales can often be readily removed, sometimes leaving surface voids or depressions.	Permitted if removal does not expose dry fibres and dimensional tolerances are met.
Stop Mark	A band, either dull or glossy, on the surface, approximately 12 to 100 mm long and extending around the periphery of a pultruded profile. NOTE This condition is the result of an interruption in the normal continuous pulling operation.	Permitted unless other associated defects (such as scale, craters, porosity, chips, and gouges) exceed their permitted levels.
Wrinkle Depression	An undulation or series of undulations or waves on the surface of the pultruded profile. NOTE This condition can occur in either the lengthwise or crosswise direction of the pultruded profile and is caused by reinforcement shifting and crowding (see Folded reinforcement). Wrinkles affect the flatness of the surface.	Permitted if the product is still within the dimensional tolerance limits.

Annex B
(normative)

Dimensional tolerances for pultruded profiles

Table Error! Unknown switch argument.**.1**

Property	Tolerance		
Wall thickness of open and closed profiles	Nominal dimensions (mm)		
	Thickness	T_1	T_2
	0 to 2	± 0,15	± 10 %
	2 to 5	± 0,20	with
	5 to 10	± 0,35	minimum
		± 0,45	of ± 0,30
Flatness in transverse direction	Tolerance F < 0,008 x B mm		
Profile height and width of flange	Nominal dimensions (mm) B and H: ± 0,5 % with minimum ± 0,20 mm and maximum ± 0,75 mm		
Size of angle	Tolerance Y ± 1,5 °		
Straightness	Tolerance (B and H are overall breadth and height dimensions) D < 0,002 x L^2 for sections with B or H < 50 mm D < 0,001 x L^2 for sections with B or H ≥ 50 and < 100 mm D < 0,0005 x L^2 for sections with B or H ≥ 100 mm		
Twist	Tolerance V < 1,5° per metre maximum for thickness < 5 mm V < 1,0 ° per metre maximum for thickness ≥ 5 mm		

Annex C
(normative)

Workmanship

C.1 Reinforcement geometry

C.1.1 Overlaps of mat: longitudinal

A minimum of 5 mm overlap should be used in closed sections.

Figure Error! Unknown switch argument.**.1**

C.1.2 Mat transverse splices

Splices shall not reduce the value of the minimum properties required for the grade in use.

Not more than one splice per laminate thickness shall be used, or 20 % of the mats for a laminate of more than five layers of transverse reinforcement, in a 1 m section of profile.

Figure Error! Unknown switch argument.**.2**

C.1.3 Mat positioning in section

The outer layer of transverse reinforcement shall follow the outside contours of the profile. Outer layers of transverse reinforcement are allowed to end in the extremities of a profile, but not at corners or T-junctions of a profile.

It is good practice, whenever possible, not to let inner layers of transverse reinforcement stop in a corner or T junctions.

Figure Error! Unknown switch argument.**.3**

C.2 Roving splices

Roving splices are allowed, but must be such that minimal mechanical properties are not affected. Not more than 20 % of rovings should be spliced in any metre of length.

Annex D
(normative)

Determination of effective flexural modulus

D.1 General

D.1.1 This annex specifies a method for determining the effective flexural modulus of full sections of a pultruded profiles.

D.1.2 The method is suitable for symmetrical thin walled pultruded profiles.

D.1.3 A pultruded profile of regular cross section is loaded as a simple beam in three-point flexure at a test span of 20 times the section depth with a tolerance of ± 10mm. From the slope of a plot of the load applied versus the resulting deflection the flexural stiffness is obtained.

NOTE The span to depth ratio is chosen to limit the reduction in the flexural modulus due to the unaccounted additional deflection due to the associated deformation in shear - see Figure D.1. The calculation in clause 7 includes a factor to correct, on average, for this effect.

D.1.4 This Normative Annex incorporates by undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. The latest edition of the publication referred to applies.

ISO 2818, *Plastics - Preparation of test specimens by machining.*

ISO 5893, *Rubber and plastics test equipment - Tensile, flexural and compression types (constant rate of traverse) - Description.*

D.2 Terms and definitions

For the purposes of this procedure, the following terms and definitions apply.

D.2.1
flexural stiffness, D
the flexural stiffness of a profile, expressed in Nmm^2

D.2.2
span, L
the distance between the two supports, expressed in millimetres, mm

D.2.3
mid-span deflection, s
distance over which the bottom surface of the profile at the midspan of the specimen deviated from its original position, expressed in millimetres, mm

D.2.4
speed of testing, v
rate of relative movement between the supports and the loading edge, expressed in millimetres per minute, mm/min

D.2.5
second moment of area, I
the second moment of area of the profile cross section. It is expressed in millimetres, mm^4

D.2.6
effective flexural modulus, E_{eff}
the modulus obtained by dividing the flexural stiffness by the second moment of area. It is expressed in GPa

D.2.7
profile coordinate axes
for the pultruded profile the direction along the production direction, or axis of the profile, is defined as the “axial" direction and the perpendicular direction is defined as the “transverse" direction

NOTE The "axial" direction is also referred to as the 0 degree (0^{o}), “1” or longitudinal direction, and the "transverse" direction as the 90 degree (90^{o}) or “2” direction.

D.3 Apparatus

D.3.1 Test machine

D.3.1.1 General, the machine shall conform to ISO 5893 as appropriate to the requirements given in D.3.1.2 and D.3.1.3.

D.3.1.2 Speed of testing, v, shall be kept constant according to ISO 5893.

D.3.1.3 Indicator for load, such that the error shall not exceed ± 1 % of the full scale (see ISO 5893).

D.3.1.4 Apparatus for measurement of mid-span deflection, s, the mid-span deflection shall be measured to a precision of ± 1 % of the indicated value using, for example, a Linear Variable Differential Transducer (LVDT).

D.3.2 Loading member and supports, the radius of the loading member and supports, R1 and R2 respectively, shall be 100 mm and 50 mm minimum; They shall be circular in cross section to within 2 % of their diameter and shall be straight to within 1 % of their length.

The length of the loading member and supports shall be greater than the test specimen width, b. The loading member shall apply the load mid-way between the supports. The span distance between the supports shall be adjustable.

D.3.3 Micrometer, or equivalent, capable of reading to 0,01 mm, or less, for measuring the wall thickness, t, of the profile. The micrometer shall have contact faces appropriate to the surface being measured (i.e. flat faces for parallel, flat surfaces and hemispherical faces for other surfaces).

D.3.4 Rulers and Vernier callipers or equivalent, accurate to within 0,1 % of the distance being measured for determining the span length, L; and specimen height, h, and width, b.

D.4 Test specimens

D.4.1 Shape and dimensions

The specimen length shall be 1,2 times the test span, L.

An angle should be tested so that it does not twist, by testing two angles **(**bolted**)** back-to-back (⌋⌊) or by ensuring that the bending occurs in a plane of symmetry (eg $<$ or $\wedge$).

D.4.2 Preparation of test pieces

Cut the test specimens to the required length from a pultruded profile.

D.4.3 Checking the test specimens

The specimens shall be straight and free of twist within the requirements detailed in Annex B of Part 2 of this standard.

D.5 Number of test specimens

Three test specimens shall be used.

D.6 Procedure

D.6.1 Test atmosphere

Conduct the test at ambient temperature (i.e. between 15 °C and 30°) unless otherwise agreed by the interested parties (e.g. for testing at elevated or reduced temperatures).

D.6.2 Setting the test span

Measure, at four approximately equidistant points along the test specimen, the depth of the pultruded profile to the nearest ± 0,5 %. Use the average depth to set the test span according to clause D.1.3.

D.6.3 Conduct of the test

D.6.3.1 Speed of testing

Set the speed of testing so that the maximum deflection is achieved in 30 s to 90 s.

D.6.3.2 Specimen testing

Set the loading apparatus to the test span and place the test specimen symmetrically across the two parallel supports. Apply the force uniformly across the width of the test piece by means of the loading member, parallel with and midway between the supports. Loading should continue until the specimen has been deflected to the required level.

D.6.3.3 Data collection

Record the force and midspan deflection throughout each test, using, if practicable, an automatic recording system that yields a load/displacement curve for this operation.

D.6.4 Determine the second moment of inertia

After testing, cut the profile into three equal portions and measure all dimensions of the cut section. Using mean values for each dimension calculate the second moment of inertia.

D.7 Calculation and expression of results

Calculate the effective flexural modulus, E_{eff}, from the slope of the straight line fit through the data points of P against s (Figure 1.2) between s_1 = L/500 and s_2 = L/200 using the following equation:

E_{eff} = 1,05 D/l = 1,05 $(P_2 - P_1)L^3/48(s_2 - s_1)$

where

I is the second moment of area of the profile in mm^4;

D is the flexural rigidity in Nmm^2;

P_1, P_2 are the load in newtons, N_1, at s_1 and N_2 at s_2;

s is the mid-point deflection, mm; and

E_{eff} is expressed in gigapascals, GPa.

NOTE The factor of 1,05 is a mean correction factor to allow for the uncorrected deflections due to the transverse shear stresses that occur in flexure loading in addition to the in-plane stresses.

The test result is the mean of the three values.

D.8 Test report

The test report shall include the following information:

a) a reference to Annex D of EN 13706;

b) a complete identification of the material tested, including type, source, manufacturer's code number, form;

c) the date of measurement;

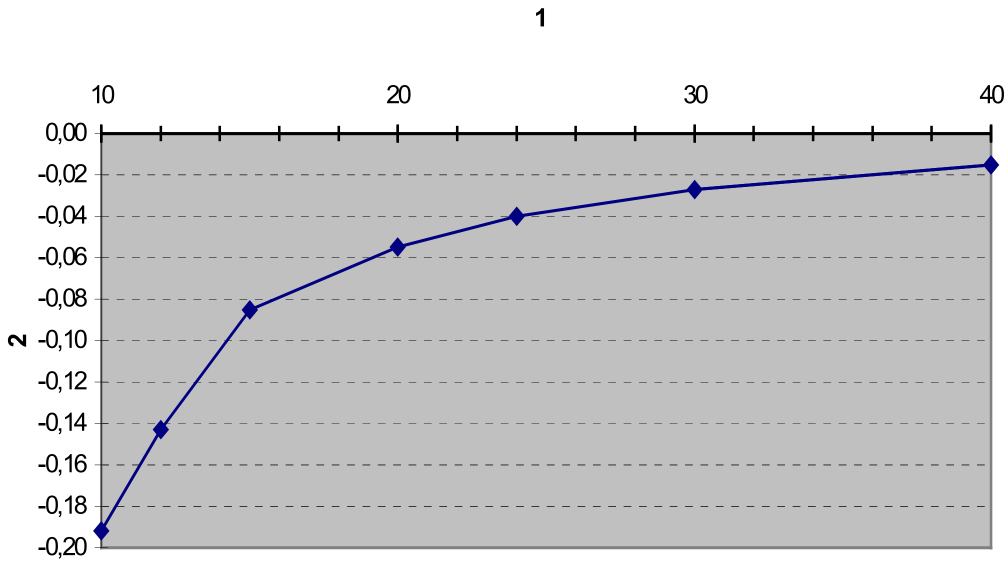
d) the dimensions of the test specimens;

e) the test span used;

f) the mean effective flexural modulus in GPa;

g) any operation not specified in this Annex, as well as any incident likely to have affected the results.

The error in effective flexural modulus (i.e. the degree of under estimation due to the unaccounted shear deformation) as a function of test span is given in the following graph, for an average pultrusion.



Key

1 % error flexure modulus

2 Test span/profile depth ratio

Figure Error! Unknown switch argument.**.1 — Error due to unaccounted shear deflection as a function of the ratio of test spar/profile depth**

Annex E
(normative)

Determination of the pin bearing strength

E.1 Scope

E.1.1 This annex specifies a procedure for determining the pin bearing strength of fibre-reinforced plastic composites, with both thermoset and thermoplastic matrices.

E.1.2 A test specimen consisting of a strip of rectangular cross-section with a plain hole, centrally positioned, is loaded in double shear by a close fitting metallic pin. The maximum load sustained by the specimen is used to determine the pin bearing strength based on the projected area of the pin in contact with the specimen.

E.1.3 This Normative Annex incorporates by undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. The latest edition of the publication referred to applies.

ISO 527, *Plastics - Determination of tensile properties*.

EN ISO 1268-6, *Fibre reinforced plastics - Test plate manufacturing methods - Part 6: Pultrusion.*

ISO 5893, *Rubber and plastics test equipment - Tensile, flexural and compression types (constant rate of traverse) - Description*.

NOTE This method uses the maximum load to define the pin bearing strength. This has been shown to be at a similar level to the initial failure in the similar "torqued bolt" tests. The characterisation of "bolted" joints is very dependent on the actual conditions involved. This includes initial bolt torque (including any load lost in bolt threads), effect of relaxation due to visco-elastic effects, effect of hot/wet conditioning, washer size/over-size, bolt material, rivet details, chamfer depth and plate thickness. Therefore, it is suggested that additional tests to the plain pin test be conducted for the actual joint conditions.

E.2 Terms and definitions

For the purposes of this Annex, the following terms and definitions apply.

E.2.1
pin bearing strength, σ_p
the stress obtained by dividing the maximum load by the projected cross-sectional area of the pin contact area with the specimen. The result is expressed in megapascals, MPa

E.2.2
specimen coordinate axes
the direction parallel with the production process is the axial direction and the direction perpendicular to the axial direction is the transverse direction

NOTE The "axial" direction is also referred to as the “1”, 0 degree (0^o) or longitudinal direction, and the "transverse" direction as the “2” or 90 degree (90^o).

E.3 Apparatus

E.3.1 Test machine

E.3.1.1 General, test machine conforming to ISO 5893 as appropriate to the requirements given in 3.1.2 and 3.1.3.

E.3.1.2 **Speed of testing**, v, shall be kept constant according to ISO 5893.

E.3.1.3 **Indicator for load**, such that the error in the indicated force is less than ± 1 % of the full scale (see ISO 5893).

E.3.2 **Micrometer**, or equivalent, capable of reading to 0,01 mm, or less, and suitable for measuring the thickness h of the test specimen; and the hole diameter. The micrometer shall have contact faces appropriate to the surface being measured (i.e. flat faces for parallel, flat surfaces and hemispherical surfaces for other surfaces).

E.3.3 **Calipers,** or equivalent, capable of reading to 0,1 mm for measuring the width b of the test specimen and the hole position.

E.3.4 **Loading jig**: The pin is loaded by a double-shear metal plate assembly as shown in Figure 3. There plates shall allow a gap of 0,5 mm on either side of the specimen and shall not distort under the applied load. The loading pin shall similarly not distort during the test and should be an interference fit unless specified otherwise.

E.4 Test specimens

E.4.1 Shape and dimensions

E.4.1.1 Specimen thickness less than or equal to 4 mm.

The specimen shall have a width of (36 ± 0,5) mm and a length of 180 mm. The width of individual specimens shall be parallel to within 0,2 mm. The dimensions of the specimen are shown in Figure E.1.

A hole (6 ± 0,2) mm in diameter is machined within 0,1 mm of the specimen centreline and a distance of check 36 mm (i.e. 6 x hole diameter) from the end of the coupon.

E.4.1.2 Specimen thickness greater than 4 mm.

Alternative specimens shall maintain a specimen thickness/hole diameter ratio of 1,5, and a specimen width/hole diameter and end distance/hole diameter ratios of 6.

E.4.2 Preparation of specimens

E.4.2.1 General

The test specimens shall either be cut from a section of the profile or from a panel prepared in accordance with ISO 1268-6.

E.4.2.2 End tab material (if required)

Providing failure does not occur at or within the grip, specimens can be tested with unbonded tabs or no tabs. Guidance on tabbing, if required, is given in Annex A of ISO 527-4 and ISO 527-5.

E.4.2.3 Machining the specimens

The test specimen shall be cut and drilled without causing damage.

E.4.3 Checking the test specimens

The specimens shall conform to the dimensional tolerances and visual aspects specified in this annex.

E.5 Number of test specimens

E.5.1 Five test specimens shall be tested.

E.5.2 The results from test specimens that do not fail by compressive bearing beneath the bolt contact area shall be discarded and new specimens tested in their place. The number of unacceptable failures and their types shall be recorded.

E.6 Procedure

E.6.1 Test atmosphere: Conduct the test at ambient temperature (i.e. between 15 °C and 30°) unless otherwise agreed by the interested parties (e.g. for testing at elevated or reduced temperatures).

E.6.2 Specimen dimensions: Measure the thickness of the test piece to the nearest 0,02 mm at the mid-point of the specimen. Measure the hole diameter to ensure within the required tolerance.

E.6.3 Testing speed: The speed of testing, v, shall be 1 mm/min.

E.6.4 Test conduct: Assemble the specimen and loading jig as shown in Figure E.2. Load the specimen to failure.

E.6.5 Data collection: Record the load throughout the test.

E.6.6 Maximum load: Record the failure load.

E.6.7 Failure mode: Check and record the mode of failure (see clause E.5.2).

E.7 Calculation and expression of results

E.7.1 Interference fitting pins: Calculate the pin bearing strength σ_p, expressed in megapascals, using the following equation, h

$$\sigma_p = \frac{F}{hd}$$

where

F is the maximum load, in newtons;

d is the diameter of the loading pin, in millimetres;

h is the thickness of the test specimen, in millimetres.

E.7.2 Calculate the arithmetic mean of the individual determinations to three significant figures.

E.8 Test report

The test report shall include the following information:

a) reference to Annex E of EN 13706;

b) complete identification of the material tested, including type, source, manufacturer's code number, form;

c) the date of measurement;

d) the dimensions of the test specimens, including the hole;

e) the size and grade of the loading pin, including the projected contact area;

f) the pin bearing strength expressed in megapascals;

g) the numbers and type(s) of failure obtained on rejected test specimens;

h) any operation not specified in this Annex, as well as any incident likely to have affected the results.

Key

1 Region for end-tabbing/alignment hole
2 Pin hole
3 End tabs (optional)

Figure E.1 — Fibre-reinforced plastic composite specimens showing hole position

Key

1 Spacer plate (thickness = h + 1 mm)
2 Hardened steel side plate
3 Hardened steel bushes, sliding fit in side plates (optional)
4 Plain pin
5 Test specimen (h)

Figure E.2 — Loading plates and test arrangement

Annex F
(informative)

Recommended test methods for particular requirements

In the absence of other test methods covering additional requirements (e.g. chemical, fire resistance), the test methods given in the following tables are recommended.

Table Error! Unknown switch argument.**.1 — List of test methods for other mechanical properties**

	Property	Test method
F.1.1	Impact Resistance-Flexed plate and/or Charpy	ISO 6603-2, *Plastics -- Determination of puncture impact behaviour of rigid plastics -- Part 2: Instrumented impact test.* ISO 179, *Plastics -- Determination of Charpy impact strength.*
F.1.2	Creep behaviour	ISO 899-1, *Plastics -- Determination of creep behaviour -- Part 1: Tensile creep.* ISO 899-2, *Plastics -- Determination of creep behaviour -- Part 2: Flexural creep by three-point loading.*
F.1.3	Fatigue behaviour	ISO 13003, *Fibre reinforced plastics – Determination of fatigue properties under cyclic conditions.*
F.1.4	Wear resistance	ISO 6601, *Plastics -- Friction and wear by sliding -- Identification of test parameters.* ISO 9352, *Plastics -- Determination of resistance to wear by abrasive wheels.*
F.1.5	Barcol hardness	EN 59, *Measurement of hardness by means of a Barcol impressor.*

Table Error! Unknown switch argument.**.2 — List of test methods for thermal, chemical and environmental properties**

	Property	Test method
F.2.1	Temperature of deflection under load. (TDUL/ HDT)	ISO 75-3, *Plastics - Determination of temperature of deflection under load - Part 3: High-strength thermosetting laminates and long-fibre-reinforced plastics.*
F.2.2	Heat ageing	IEC 60216-1, *Guide for the determination of thermal endurance properties of electrical insulating materials. Part 1: General guidelines for ageing procedures and evaluation of test results.*
F.2.3	Water absorption.	ISO 62, *Plastics -- Determination of water absorption.*
F.2.4	Chemical resistance	ISO 175, *Plastics -- Determination of the effects of liquid chemicals, including water.*
F.2.5	Exposure to damp heat, water spray and salt mist.	ISO 4611, *Plastics -- Determination of the effects of exposure to damp heat, water spray and salt mist.*
F.2.6	Exposure to laboratory light source.	ISO 4892-1, *Plastics -- Methods of exposure to laboratory light sources. -- Part 1: General guidanc*e. ISO 4892-2, *Plastics -- Methods of exposure to laboratory light sources -- Part 2: Xenon-arc sources.*

Table Error! Unknown switch argument.**.3 — List of test methods for fire properties**

	Description	Standard
F.3.1	Non-combustibility test	EN ISO 1182, *Fire tests -- Building materials -- Non-combustibility test.*
F.3.2	Reaction to fire - ignitability	ISO 5657, *Reaction to fire tests -- Ignitability of building products using a radiant heat source.*
F.3.3	Rate of heat release from building products (calorimeter)	ISO 5660-1, *Fire tests -- Reaction to fire -- Part 1: Rate of heat release from building products -- (Cone calorimeter method).*
F.3.4	Fire resistance tests	ISO 834, *Fire-resistance tests -- Elements of building construction.*
F.3.5	Full-scale room test	ISO 9705, *Fire tests -- Full-scale room test for surface products.*
F.3.6	Burning behaviour- guidance for development and use of fire tests	ISO/TR 10840, *Plastics -- Burning behaviour -- Guidance for development and use of fire tests.*
F.3.7	Determination of burning behaviour	ISO 9773, *Plastics -- Determination of burning behaviour of thin flexible vertical specimens in contact with a small-flame ignition source.*
F.3.8	Combustibility of specimens using 125mm flame source	ISO 10351, *Plastics -- Determination of the combustibility of specimens using a 125 mm flame source.*
F.3.9	Plastics- Determination of flammability of oxygen index	ISO 4589-1, *Plastics -- Determination of burning behaviour by oxygen index -- Part 1: Guidance.*
F.3.10	Building materials - Determination of calorific potential	EN ISO 1716, *Building materials -- Determination of calorific potential.*
F.3.11	Reaction to fire tests	EN ISO 11925-2, *Reaction to fire tests -- Ignitability of building products subjected to direct impingement of flame -- Part 2: Single flame source test.*
F.3.12	Single burning item test	prEN 12823, *Reaction to fire tests for building products — Building products excluding floorings exposed to the thermal attack by a single burning item.*

Several of these tests are included in EU standards for "fire classification for construction products and building elements" with associated criteria for each class. Further details are given in :

prEN 13501-1, *Fire classification of construction products and building elements - Part 1: Classification using test data from reaction to fire tests*.

prEN 13501-2, *Fire classification of construction products and building elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services*.

NOTE The test methods given in Tables F.1 and F.2, and some in Table F.3 are general test methods for all plastic materials. In practice other test methods (possibly national standards or industrially accepted methods) may be more suitable for assessing the performance of a profile under given service conditions. Alternatively there may be national legal, contractual or insurance industry requirements to use specific test methods. In these cases, test methods other than those listed in these tables may be used.

Table Error! Unknown switch argument.**.4 — List of test methods for electrical properties**

	Property	Test method
F.4.1	Arc resistance	ASTM D495, *Standard Test Method for High-Voltage, Low-Current, Dry Arc Resistance of Solid Electrical Insulation.*
F.4.2	Loss factor	IEC 60250, *Recommended methods for the determination of the permittivity and dielectric dissipation factor of electrical insulating materials at power, audio and radio frequencies including metre wavelengths.*
F.4.3	Tracking resistance	IEC 60112, *Method for determining the comparative and the proof tracking indices of solid insulating materials under moist conditions.*
F.4.4	Dielectric strength	IEC 60243-1, *Electrical strength of insulating materials - Test methods - Part 1: Tests at power frequencies.* IEC 60243-2, *Methods of test for electric strength of solid insulating materials. Part 2: Additional requirements for tests using direct voltage.* IEC 60243-3, *Methods of test for electric strength of solid insulating materials - Part 3: Additional requirements. for impulse tests.*
F.4.5	Thermal insulation class	IEC 60085, *Thermal evaluation and classification of electrical insulation.*
F.4.7	Volume and surface resistivity	IEC 60093, *Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials*.

Table Error! Unknown switch argument.**.5 — Test methods for exact values of profile stiffness properties**

	Profile property	Unit	Test method
F.5.1	Flexural stiffness (D)	$N.m^2$	Annex G Part 2 of EN 13706
F.5.2	Shear stiffness (Q)	N	
F.5.3	Torsion stiffness (T)	$N.m^2$	

Annex G
(informative)

Determination of flexural, shear and torsional stiffness properties

G.1 Scope

G.1.1 This annex specifies two methods for determining accurate values of the flexural, shear and torsional stiffness properties of pultruded profiles.

G.1.2 The methods are suitable for symmetrical thin walled pultruded profiles but not angle profiles.

G.1.3 A pultruded profile of regular cross section is repeatedly loaded (elastically) as a simple beam:

Method A in three-point flexure at a number of different spans lengths (*at a set strain rate and to a set strain level)*. The shear and bending contributions to the overall beam deflection vary with test span. Plotting the results for each span as L^2 vs s/PL and $1/L^2$ vs s/PL^3, yields the flexural and shear stiffness.

NOTE The method is iterative, so that initial values must be estimated or known from similar profiles.

Method B in torsion at a number of offset loads. The torsional and bending contributions to the overall beam deflection vary with loading off-set. Plotting the results for each off-set yields the torsional stiffness.

During the procedure the force applied to the specimen and the resulting deflection are measured.

G.1.4 This Informative Annex incorporates by undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. The latest edition of the publication referred to applies.

ISO 5893, *Rubber and plastics test equipment - Tensile, flexural and compression types (constant rate of traverse) - Description.*

G.2 Terms and definitions

For the purposes of this procedure, the following terms and definitions apply.

G.2.1
flexural stiffness, D
the flexural stiffness of a profile. It is expressed in N.m^2

G.2.2
shear stiffness, Q
the shear stiffness of a profile. It is expressed in newtons, N

G.2.3
torsional stiffness, T
the torsional stiffness of a profile. It is expressed in N.m^2

G.2.4
span, L
the distance between the two supports for Method A, and the distance between the centre-line edge of the clamp and the centre-line of the drilled hole for Method B. They are expressed in millimetres, mm

G.2.5
critical length, l_c
the critical length at which shear deformation contributes about 12 % of the total mid-point deflection under flexure. It is calculated according to the relationship given in clause in G 7.1.4. It is expressed in millimetres, mm

G.2.6
beam deflection, s
distance over which the bottom surface of the profile in Method A deviates from its original position at the midspan of the specimen, It is expressed in millimetres, mm

G.2.7
loading point deflection, w
distance over which the loading point in Method B deviated from its original position. It is expressed in millimetres, mm

G.2.8
offset loading distance, S
distance from the profile centreline to the loading point on offset arm (see Figure G.5). It is expressed in millimetres, mm

G.2.9
speed of testing, v
rate of relative movement between the supports and the striking edge, expressed in millimetres per minute, mm/min

G.2.10
second moment of area, I
the second moment of area of the profile cross section. It is expressed in millimetres, mm^4

G.2.11
profile coordinate axes:
for the pultruded profile the direction along the production direction, or axis of the profile, is defined as the "axial" direction and the perpendicular direction is defined as the "transverse" direction

NOTE The "axial" direction is also referred to as the 0 degree (0^o), "1" or longitudinal direction, and the "transverse" direction as the 90 degree (90^o) or "2" direction.

G.3 Apparatus

G.3.1 Test machine

G.3.1.1 **General**, the machine shall conform to ISO 5893 as appropriate to the requirements given in G.3.1.2 and G.3.1.3. Alternatively, a dead-weight loading system can be used.

G.3.1.2 **Speed of testing**, v, shall be kept constant according to ISO 5893. If used, the dead-weight load shall be applied smoothly over a short period or in small uniform steps.

G.3.1.3 **Indicator for load**, such that the error shall not exceed ± 1 % of the full scale (see ISO 5893). For dead-weights loads no indicator is required but the loads should be known to within 1 %.

G.3.1.4 **Apparatus for measurement of deflection,** the mid-span deflecion, s, and loading point deflection, w shall be measured to a precision of ± 1 % of the indicated value, using a **dial gauge**, Linear Variable Differential Transducer (LVDT) or equivalents.

G.3.2 Loading member and supports for Method A

The radius of the loading member and supports, R_1 and R_2 respectively, shall be - 100 mm and 50 mm minimum. They shall be circular in cross section to within 2 % of their diameter and shall be straight to within 1 % of their length (see Figure G.1).

The length of the loading member and supports shall be greater than the test specimen width, b. The loading member shall apply the load mid-way between the supports. The span distance between the supports shall be adjustable.

G.3.3 Clamp and loading bar for Method B, where the clamp prevents any lateral or torsional movement of the profile. For thin-walled sections, it may be necessary to fill the section within the clamp region only, to avoid collapse of the section.

A light, stiff rod of sufficient length, with an end stop, as shown in Figure G.2, is required. There should be no free movement at the fixing point when the test loads are applied.

G.3.4 Micrometer, or equivalent, capable of reading to 0,01 mm, or less, for measuring the wall thickness h of the profile. The micrometer shall have contact faces. appropriate to the surface being measured (i.e. flat faces for parallel, flat faces and hemispherical faces for other surfaces).

G.3.5 Rulers and vernier callipers or equivalent, accurate to within 0,1 % of the distances being measured for determining the span length, L; and specimen height, h, and width, b.

G.4 Test specimens

G.4.1 Shape and dimensions

Method A. The specimen length shall be 1.2 x the test initial test span.

Method B. The specimen shall have a total length-sufficient for the required gauge length (approximately 20 x profile widest dimension) together with the length within the clamp and for the loading lever positioning.

G.4.2 Cut the test specimens to the required length from a pultruded profile. For Method B machine a hole through the section at a point sufficiently away from the free end to avoid failure (e.g. 1 x profile widest dimension), midway between the top and bottom surface, to take the loading rod.

G.4.3 Checking the test specimens

The specimens shall be flat and free of twist within the requirements of the standard.

G.5 Number of test specimens

Two test specimens shall be tested for each method. For results differing by more than 5 % from each other, a third specimen shall be tested.

G.6 Procedure

G.6.1 Test atmosphere: Conduct the test in the same atmosphere as used for conditioning unless otherwise agreed by the interested parties (e.g. for testing at elevated or reduced temperatures).

G.6.2 Determine the second moment of inertia: Measure all dimensions of the section and calculate the second moment of inertia and cross-sectional area of the section.

G.6.3 Method A

G.6.3.1 Span: Choose the range of span lengths to cover values larger and smaller than the estimated critical length, l_c, of the profile being tested or to cover the range of the 3-point bend apparatus used. Spans should be fairly evenly spaced over the selected range and a minimum of 5 spans shall be tested.

G.6.3.2 Speed of testing: Load the specimen over a constant time period chosen in the range 30 s to 90 s. Use the same time period for each re-loading of the beam.

G.6.3.3 Displacement limit: The beam should be deflected to a displacement equal to L/200 (i.e. test span divided by 200).

G.6.3.4 Specimen testing: Set the loading apparatus to the largest span of the chosen range and place the test specimen symmetrically across the two parallel supports. Apply the force uniformly across the width of the test piece by means of the loading member, parallel with and midway between the supports. Loading should continue until the specimen has been deflected to the required level for each particular span. The specimen should then be unloaded.

This procedure should be repeated for each of the spans in the chosen range starting with the largest and finishing with the smallest, adjusting the specimen length at each span to ensure that the specimen to span length ratio is kept at 1,2:1 (see Figure G.1). When adjusting the specimen length, equal lengths of material should be removed from both ends of the specimen so as to keep the same mid-span position.

G.6.3.5 Data collection, record the force and midspan deflection throughout each test, using, if practicable, an automatic recording system that yields a load/displacement curve for this operation.

G.6.4 Method B

G.6.4.1 Offset lengths: Choose a range of off-set lengths, s, which should be fairly evenly spaced over the selected range and a minimum of 5 spans shall be tested.

G.6.4.2 Specimen testing: Set the profile in a rigid clamp. Place the loading bar through the profile. Apply the force at the different off-set positions and at the zero offset (i.e. on the pultrusion axis). Loading should continue until the loading point has been deflected a distance equal to L/200 (i.e. the beam gauge length divided by 200). The specimen should then be unloaded.

This loading procedure is then repeated for each of the offsets in the chosen range.

G.6.4.3 Data collection, record the force and loading point deflection throughout each test for each offset length, using, if practicable, an automatic recording system that yields a load/displacement curve for this operation.

G.7 Calculation and expression of results

The test result is the mean of the two, or three (see clause G.5) values.

G.7.1 Method A

G.7.1.1 At each span, from a graph of deflection (s) (on the x-axis) against load (P) (on the y-axis) measure the slope (P/s in Newton per millimetre, N/mm) of the linear section of the plot.

Plot L^2 (x-axis) against s/PL (y-axis) (see Figure G.2) and $1/L^2$ (x-axis) against s/PL^3 (y-axis) (see Figure G.3) for all of the span lengths, L, tested. In addition individual values of L^2, s/PL, $1/L^2$ and s/PL^3 shall be tabulated.

G.7.1.2 Calculate the Flexural Stiffness, D, from the slope of the straight line through the data points of L^2 vs.s/PL (Figure G.2).

where

D is the flexural rigidity in Nmm^2;

P is the load in newtons, N;

s is the mid-point deflection, mm ;

L is the test span, mm.

E_{eff}, expressed in gigapascals, is obtained using the following equation:

$$E_{eff} = D/I$$

where I is the second moment of area of the profile in mm^4.

G.7.1.3 Calculate the Shear stiffness, Q, from the slope of the straight line through the data points of $1/L^2$ vs. s/PL^3.

where

Q is the shear stiffness in N;

P is the load in newtons, N;

s is the mid-point deflection, mm ;

L is the test span, mm.

The effective shear modulus, G_{eff}, expressed in gigapascals, can be calculated using the following equation:

$$G_{eff} = Q/A$$

where

A is the area of the profile cross section in mm^2.

NOTE As a cross-check, the slope of L^2 vs s/PL should agree with the intercept of $1/L^2$ vs s/PL^3 and the intercept of L^2 vs s/PL should agree with the slope of $1/L^2$ vs s/PL^2.

G.7.1.4 Calculate the critical length of the pultruded profile material from the following equation:

$$l_c = (100D/Q)^{½}$$

The critical length is shown for a the case where the shear deflection contributes 12 % to the total deflection. A critical length value can also be calculated for other values of shear deflection if required. The test spans used should be larger and smaller than l_c for the best analysis.

G.7.2 Method B

G.7.2.1 At each off-set length, from a graph of deflection (w) (on the x-axis) against load (P) (on the y-axis) measure the slope (w/P in millimetres per Newton, mm/N) of the linear section of the plot.

G.7.2.2 Calculate the Torsional Stiffness, T, from the slope of the straight line through the data points of S^2 vs. w/PL (Figure G.5) where the slope equals L/T.

where

T is the torsional rigidity in Nmm^2;

P is the load in newtons, N;

w is the loading point deflection, mm;

L is the beam length, mm;

S is the beam offset length. mm.

G.8 Test report

The test report shall include the following information:

a) a reference to Annex G of EN 13706;

b) a complete identification of the material tested, including type, source, manufacturer's code number, form;

c) the date of measurement;

d) the dimensions of the test specimens;

e) the radii of the loading member and the supports;

f) the test spans used (Method A);

g) the gauge length and offset spans used (Method B);

h) the number of specimens tested;

i) the mean flexural, shear and torsional stiffness values; as appropriate depending on whether Methods A and/or B were used;

j) any operation not specified in this Annex, as well as any incident likely to have affected the results.

Figure Error! Unknown switch argument.**.1 — Loading configuration for method A**

Key

1 Clamp

Figure Error! Unknown switch argument.**.2 — Loading configuration for method B**

Key

1 Slope = 1/48 D

2 Intercept = ¼ D

3 s/PL (x 10^{-3} N^{-1})

4 L^2 (x10^6 mm^2)

Figure G.3 — Plot of L^2 (x-axis) against s/PL (y-axis)

Key

1 Slope = 1/48 D

2 Intercept = ¼ Q

3 s/PL^3 (x 10^{-9} N^{-1} mm^{-2})

4 1/L^2 (x10^{-6} mm^{-2})

Figure G.4 — Plot of 1/L^2 (x-axis) against s/PL^3 (y-axis)

Key

1

2

Figure G.5 —