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English Version

Glass in building - Laminated glass and laminated safety glass - Determination of interlayer viscoelastic properties

Verre dans la construction - Verre feuilleté et verre feuilleté de sécurité - Détermination des propriétés viscoélastiques des intercalaires

Glas im Bauwesen - Verbundglas und Verbundsicherheitsglas - Bestimmung der viskoelastischen Eigenschaften von Zwischenschichten

This European Standard was approved by CEN on 7 April 2025.

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CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

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European foreword

This document (EN 16613:2025) has been prepared by Technical Committee CEN/TC 129 "Glass in building", the secretariat of which is held by NBN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2025, and conflicting national standards shall be withdrawn at the latest by November 2025.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

This document supersedes EN 16613:2019.

EN 16613:2025 includes the following significant technical changes with respect to EN 16613:2019:

a) The test procedure has been changed from tensile vibration to parallel-plate oscillation.

b) A more detailed description of the test procedure is provided comprising four subsequent steps.

c) Annex A has been reviewed and is used for non-isotropic and multilayer interlayer materials as well as Step 4 in the main test procedure. It provides the methods to calculate the effective thickness, shear transfer coefficient ω, the coupling factor η and the interlayer shear modulus G_{int}.

d) Annex C details the procedure to obtain the master curve and the Prony parameters.

e) The new Annex D will help determine mechanical properties used for calculation of noise reduction.

f) Annex E provides guidance for a precise geometrical assessment of a deflected specimen.

g) Interlayer stiffness family classification criteria have been removed.

Any feedback and questions on this document should be directed to the users' national standards body. A complete listing of these bodies can be found on the CEN website.

According to the CEN-CENELEC Internal Regulations, the national standards organisations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and the United Kingdom.

1 Scope

This document specifies a test method for determining the mechanical viscoelastic properties of interlayer materials. The interlayers under examination are those used in the production of laminated glass or laminated safety glass. The shear characteristics of interlayers are needed to design laminated glass in accordance with EN 16612:2019 and EN 19100 (all parts).

Parameters of the Prony series, widely used in numerical simulation, can be derived from the measurements in Annex C.

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.

EN 1288-3, *Glass in building — Determination of the bending strength of glass — Part 3: Test with specimen supported at two points (four point bending)*

EN ISO 6721-1:2019, *Plastics — Determination of dynamic mechanical properties — Part 1: General principles (ISO 6721-1:2019)*

ISO 6721-10, *Plastics — Determination of dynamic mechanical properties — Part 10: Complex shear viscosity using a parallel-plate oscillatory rheometer*

ISO 6721-11, *Plastics — Determination of dynamic mechanical properties — Part 11: Glass transition temperature*

EN 16612:2019, *Glass in building — Determination of the lateral load resistance of glass panes by calculation*

ISO 18437-6, *Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials — Part 6: Time-temperature superposition*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN ISO 6721-1:2019 and ISO 18437-6 and the following apply.

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

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

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

3.1
glass transition temperature
interval of temperature in which a material changes from a rubbery state to a solid state or vice versa

3.2
interlayer shear transfer coefficient
coefficient between 0 and 1 describing the ability of an interlayer material to transfer shear forces between the glass plies of a laminated glass pane when submitted to bending

3.3
relaxation modulus
ratio of the time-dependent stress to an imposed constant strain of the interlayer

3.4
complex modulus
ratio of dynamic stress and dynamic strain of a viscoelastic material that is subjected to a sinusoidal vibration

3.5
storage modulus
real part of the complex modulus

3.6
loss modulus
imaginary part of the complex modulus

3.7
phase angle
phase difference between the dynamic stress and the dynamic strain in a viscoelastic material subjected to a sinusoidal oscillation (δ)

Note 1 to entry: See Figure 2.

Note 2 to entry: The phase angle is expressed in radians (rad).

Note 3 to entry: In a dynamic experiment, it is the angle between the complex modulus G^* and the projection of its elastic part, the storage modulus part G'.

3.8
loss factor
tangent of the phase angle, also expressed as the ratio of the dynamic loss modulus G'' over the dynamic storage modulus G'

Note 1 to entry: See Figure 1.

Note 2 to entry: The loss factor is expressed as a dimensionless number.

3.9
shift factor
value (positive or negative) of the horizontal displacement of each DMTA curve along the frequency axis to form the master curve

3.10
master curve
curve obtained by shifting isothermal DMTA curves measured at different frequencies and at a selected reference temperature

3.11
time-temperature superposition
principle which enables prediction of material behaviour outside the testable range

3.12
Prony series
formula that allows calculation of the shear modulus based on Prony parameters

3.13
Prony parameters
parameters to evaluate the shear relaxation modulus from the Prony series, including the normalized moduli g_i, relaxation times τ_i and the initial shear modulus G_0

4 Symbols and abbreviations

$a(T)$	Temperature dependent, horizontal shift factor in the time-temperature superposition principle
b	Width of the test specimen
b_{ave}	Average width of the plate
l_{cor}	Corrected distance between supporting rollers in case of bent glass plate
l_{red}	Reduction of the span per each supporting roller
C_1, C_2	Empirical constants of the WLF-TTS visco-elastic formula
d	Distance of the mid-plane of the glass plies from the mid-plane of the laminated glass composed of two plies of the same thickness
d_1	Distance of the mid-plane of the glass ply 1 from the mid-plane of the laminated glass
d_2	Distance of the mid-plane of the glass ply 2 from the mid-plane of the laminated glass
d_3	Distance of the mid-plane of the glass ply 3 from the mid-plane of the laminated glass
D_{abs}	Flexural stiffness at "no shear" condition
D_{full}	Flexural limit at "full shear" condition
D_i	Flexural stiffness of the glass ply i
DMTA	Dynamic Mechanical Thermal Analysis (-TS: temperature sweep, -AS: amplitude sweep, -TFS: temperature-frequency sweep)
DSC	Differential Scanning Calorimetry
e_{dl} e_f	Deflection under self weight
EET	Deflection under applied load
E	Enhanced Effective Thickness method
E_a	Young's modulus of glass
E_{int}	Activation energy
f	Young's modulus of the interlayer material
F	Frequency
g_i	Four point bend test load
G^*, $\|G^*\|$	Normalized shear moduli
G'	Shear complex modulus
G''	Shear storage modulus
G_0	Shear loss modulus
G_∞	Initial shear modulus (at a time 0)
	Equilibrium modulus (at infinite time)

G_{int}	Shear relaxation modulus of the interlayer material
h h_1	Thickness of glass pane of laminated glass composed of n plies of the same thickness
h_2	Nominal thickness of pane 1 of an insulating glass unit or ply 1 of a laminated glass
h_3	Nominal thickness of pane 2 of an insulating glass unit or ply 2 of a laminated glass
$h_{\text{ef},\sigma}$	Nominal thickness of pane 3 of an insulating glass unit or ply 3 of a laminated glass
$h_{\text{ef,w}}$	Effective thickness of laminated glass for calculation of stress
$h_{\text{ef,wt}}$	Effective thickness of laminated glass for calculation of deflection
h_{i}	Effective thickness of laminated glass deflecting under load
h_{int}, $h_{\text{int,1}}$, $h_{\text{int,2}}$	Nominal thickness of pane i of an insulating glass unit or ply *i* of a laminated glass
l_{b}	Thickness of the interlayer
l	Distance between centre lines of bending rollers
l_{cor}	Distance between centre lines of supporting rollers
l_{red}	Distance between two original points of contact of the supporting rollers and the glass after deformation of the glass
n	Reduction of the span per each supporting roller
p	Number of plies (only in Annex A) and number of spring-damper elements (only in Annex C)
$P_{\text{r},j}$	Self weight of the plate
$P_{\text{s},j}$	is the polynomial coefficient of the shear storage modulus of degree *j*, with *j* ranging from 0 to 7;
r r_{r}	is the polynomial coefficient of the shear loss modulus of degree *j*, with *j* ranging from 0 to 7;
R t	Radius of the curved glass deflected under self weight
t_{r} T	Radius of the roller
T_{c}	Universal gas constant
T_{g}	Load duration
T_{k}	Time needed to apply load
T_{m}	Temperature in °C
T_{r}	Crystallization temperature
T_{ref}	Glass transition temperature
$T_{\text{k,r}}$	Temperature in Kelvin
TTS	Melting temperature
ν_{int}	Reference temperature
	Reference temperature
	Reference temperature in Kelvin
	Time-temperature superposition
	Poisson’s number of the interlayer material

ν	Poisson's number of glass material
WLF-TTS	Williams-Landel-Ferry TTS
x	Axis x illustrating the horizontal position of the test specimen
x_{F1}	Distance between the first supporting roller and the first bending roller
x_{F2}	Distance between the first supporting roller and the second bending roller
y	Axis y illustrating vertical displacement
$y_{c,g}$	Deflection under self weight
y'_{dl}	Angular deformation under self weight Angular
y'_{p}	deformation under two punctual loads Formula
y'_{r}	of the curvature of the support roller
y'_{t}	Total angular deformation under self weight and punctual loads
y_{tot}	Total deflection under self weight and applied load
$y_{tot,m}$	Total measured deflection under self weight and applied load
β	Scaling factor
$\delta\ \eta$	Phase angle
η_{v}	Coupling coefficient used in Annex A (EET)
η_{2}	Coefficient of viscosity used in Annex C (Maxwell model)
η_{3}	Coupling coefficient for laminated glass composed of two plies
η_{n}	Coupling coefficient for laminated glass composed of three plies
Ψ_{b}	Coupling coefficient for laminated glass composed of n plies with the same thickness
σ	Boundary coefficient for beam made of n plies
τ_{i}	Calculated stress
ω	Relaxation times
ω_{f}	Interlayer shear transfer coefficient
	Angular frequency (only in Annex C)

5 Test procedure

5.1 General

The general methodology of the test used is provided in EN ISO 6721-1. DMTA measurement is performed preferably following ISO 6721-10, parallel plate oscillation.

Alternatively, the non-resonance methods ISO 6721-6 (shear vibration), ISO 6721-4 (tensile vibration), ISO 6721-7 (torsional vibration) can be used.

NOTE 1 The commonly used interlayers are generally isotropic materials. Depending of the choice of measurement method, the interlayer shear or Young's modulus can be converted into each other using Formula (1).

$$G_{\mathrm{int}} = \frac{E_{\mathrm{int}}}{2\left(1 + \nu_{\mathrm{int}}\right)} \tag{1}$$

Where ν_{int} is the Poisson's number of the interlayer. ν_{int} can be approximated with 0,49, which leads to the approximation:

$$E_{int} \approx 3G_{int} \quad (2)$$

Scientifically, Poisson's number depends on the temperature, but for the purpose of structural design of laminated glass, this effect can be ignored.

There are some interlayers which cannot be formed into test pieces or which are not stable with exposed edges in such small sizes. For these interlayer materials, the relevant interlayer properties can be determined by calculation from the results of bending tests. Depending on the method of calculation used for design of laminated glass, the relevant shear characteristics may be determined according to Annex A.

DMTA measurements devices are limited in frequency range, with guidance provided in each part of the ISO 6721 series as cited above. In order to obtain modulus values at higher or lower frequencies, time-temperature superposition (TTS) analysis is applied. From a set of temperature-frequency curves, the time dependence of viscoelastic properties is calculated.

The here presented TTS is valid for thermo-rheologically simple materials. The material shall be linear viscoelastic under the deformations of interest, i.e. the deformation shall be expressed as a linear function of the stress by applying very small strains.

When applying WLF-TTS, shift factors should be used within the glass-transition temperature range. At a temperature below the glass-transition temperature, other TTS such as the Arrhenius model may be used.

The determination of the viscoelastic properties of interlayer materials implies generally the following steps:

— Step 1: DSC should be performed to determine thermomechanical phases (crystalline, amorphous) and characteristic temperatures (glass transition T_g, crystallization T_c and melting temperature T_m); additionally DMTA-TS to determine thermomechanical phases (crystalline, amorphous) and characteristic temperatures (glass transition T_g, crystallization T_c and melting temperature T_m).

— Step 2: DMTA-AS to check for linear viscoelasticity (linearity in stress-strain and time)

— Step 3: DMTA-TFS to acquire a set of curves depending on temperature and frequency. A subsequent TTS treatment with master curving is applied to deduce the time-temperature superposition law(s) and Prony series (if needed), see Annex C.

NOTE 2 The shear relaxation modulus values G_{int} used for finite-element calculations, or other advanced calculation methods, can be derived from the Prony series.

— Step 4: Conduction of large scale validation tests (bending creep).

For non-isotropic materials a direct measurement of the shear modulus shall be performed. This can be performed with DMTA or according to Annex A.

NOTE 3 For materials from which no small specimens can be produced, Step 4 can be considered as sufficient (see Annex A).

5.2 Test specimens

The test specimens shall be manufactured from samples representative of normal interlayer material production. The test specimens shall be processed under normal laminating conditions according to Annex B.

The thickness, h_{int}, of the test specimens should be not less than 0,50 mm thick and not more than 2,0 mm thick. The layering and stacking of the interlayer material to achieve an appropriate thickness shall be representative of normal production processes.

The test specimen size and tolerances on dimensions shall be determined according to the requirements of ISO 6721-10.

Two sets of test specimens are required. One set of three test specimens is used for determining the glass transition temperature, T_g, (see 5.3.1). The other set of one test specimens is used for the evaluation of the $G_{int}(T_r,t)$ curve (see 5.3.2).

Prior to testing, adequate hygrothermal conditioning of test samples is essential for a reproducible experimental examination. Important aspects for the conditioning are the level of cure and cross linking of the polymer and the polymer moisture content at the intended level. The manufacturer's storage instructions shall be followed.

The sample shall be first processed, stored for stabilization during a period according to the interlayer manufacturer and conditioned for a period of one week for all interlayer types in the laboratory.

5.3 Test method

5.3.1 Glass transition temperature T_g (Step 1)

Initial tests shall be conducted on at least three test specimens according to ISO 6721-11 to determine the glass transition temperature of the interlayer material. This is used to refine the temperatures assessed in 5.3.2. Alternatively, the DSC measurement performed following EN ISO 11357-2 can be used. Following the results of the measurement, the heating rate and temperature range of the DMTA-TFS (Step 3) can be decided.

NOTE 1 If the interlayer material is in a non-vitreous state, it might not be possible to determine a glass transition temperature.

NOTE 2 A rigorous TTS procedure is only valid for thermo-rheological simple material. Only one phase transition of the first order might be present, like vitreous transition or fusion.

NOTE 3 In the case of polymeric blends (mixture), block copolymers or other copolymers with specific monomer distributions, each polymeric component will have their specific rheological behaviour as a function of temperature. TTS does not apply to such blends or materials.

The temperature program is generally set between −40 °C and +100 °C with a heating rate of 3 K/min. The frequency should be set to 1 Hz and the amplitude should be in the linear-viscoelastic range. The temperature sweep experiment should typically be executed from the upper temperature to the lower temperature of the tested range. Following the results of the measurement, the heating rate and temperature range of the DMTA-TFS (Step 3) can be decided.

5.3.2 Determination of the temperature and time dependent shear modulus $G_{int}(T,t)$

5.3.2.1 General

A series of tests should be conducted according to ISO 6721-10 in combination with bending creep test to eventually evaluate $G_{int}(T,t)$ for a range of load durations t (or frequencies f), and a range of temperatures, T.

5.3.2.2 Amplitude sweeps measurement using DMTA-AS method (Step 2)

DMTA-AS measurement is performed to ensure that the testing regime (temperature, frequency) is within the linear viscoelastic region of mechanical behaviour.

Amplitude sweeps with testing frequency of f = 1 Hz are undertaken at different temperatures (T_g – 40 °C; T_g; T_g + 40 °C). These temperatures are between −40 °C and +80 °C. The amplitude may be set for most testing modes and interlayer materials in the region of 0,01 % to 0,3 %.

5.3.2.3 Temperature-frequency sweeps measurement using DMTA-TFS method (Step 3)

DMTA-TFS measurement is performed to determine the time and temperature dependent material behaviour. The test temperatures for the temperature-frequency sweeps shall be selected according to the thermo-mechanical regions of the polymer as found via Step 1.

The testing should start at high temperatures and go to low temperatures to minimize effects of physical ageing of the polymer below T_g. A holding phase of 5 min to 10 min will be applied before to decrease the temperature.

The frequency range evaluated should at least range from 0,1 Hz to 10 Hz (or the corresponding angular frequencies) and comprise 10-15 frequencies per temperature evaluated. Eigenfrequencies should be checked beforehand.

In the case of PVB material, general conditions are T between T_g – 40 °C and T_g + 40 °C. T_g is usually around 20 °C but depends on the plasticizer content. It is advised to conduct a temperature test program with temperature steps of 2 °C to 5 °C and a maximum cooling rate of 2 K/min.

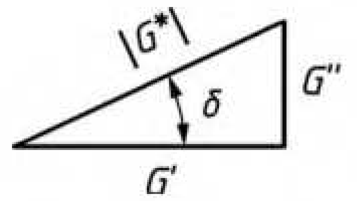
In the case of EVA material, general conditions are between T_g + 20 °C and T_g + 100 °C. T_g is usually around −40 °C but depends on the ratios of the compounds. It is advised to conduct a temperature test program with temperature steps of 2 °C to 5 °C and a maximum cooling rate of 2 K/min.

In the case of ionomer material, general conditions are T between T_g - 50 °C and T_g + 40 °C. It is advised to conduct a temperature test program with temperature steps of 2 °C to 5 °C and a maximum cooling rate of 2 K/min. For this material the testing may start from low temperatures and go to high temperatures.

The measurement procedure gives access to the storage modulus (G', elastic material component) and the loss modulus (G'', viscous material component). The ratio G''/G' gives the loss factor tanδ (δ, phase angle or mechanical damping factor).

NOTE 1 Loss factor is illustrated in Figure 1. Phase angle is illustrated in Figure 2.

NOTE 2 A shift of the series is often observed near the T_g. It is due to an entropic contribution to the polymeric chain retraction force which adds to the free energy.



$$\delta = \arctan\frac{G''}{G'}$$

Key

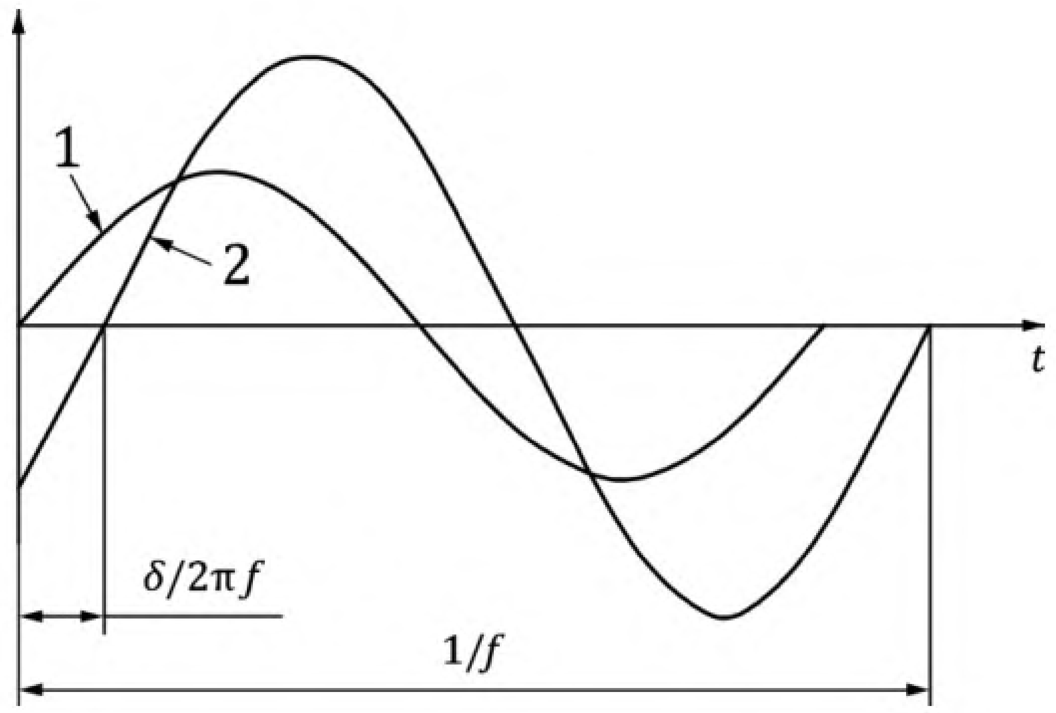
δ phase angle, rad

G' shear storage modulus, MPa

G'' shear loss modulus, MPa

$|G^*|$ shear complex modulus, MPa

Figure 1 — Loss factor



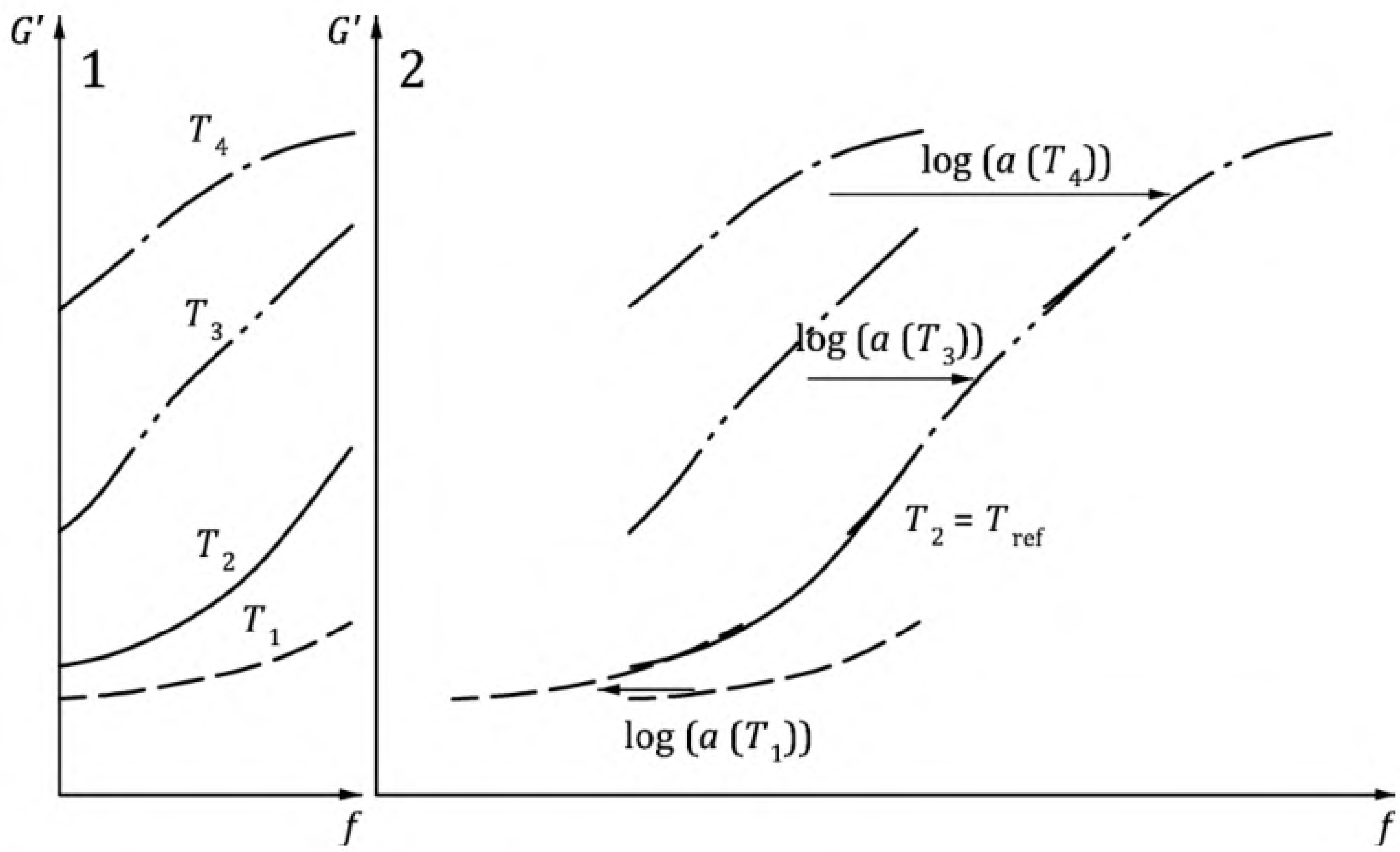
Key

t	time, s
1	dynamic stress, MPa
2	dynamic strain, dimensionless
δ	phase angle, rad
f	frequency, Hz

Figure 2 — Phase angle

From the temperature-frequency measurement sets, master curves for G' and G'' at the reference temperature T_r may be generated by only horizontally shifting the individual modulus curves. This is graphically illustrated in Figure 3 for G' and can also be applied to G''. If an angular frequency was specified or used for the measurements, it should be converted to a regular frequency for the test report and used with Annex D. Annex C describes the TTS models, which may be used to mathematically approximate the shift factors a(T).

NOTE 3 The sections of shifted measured $G'(\omega_f)$ and $G''(\omega_f)$ data that constitute the respective master curves can be used for the determination of the Prony parameters according to Clause C.2. The master curves for G' and G'' are part of the test report.



Key

1	results at different test temperatures
2	transformations to the reference temperature (T_2) give the master curve
G'	shear storage modulus, MPa
T_1 to T_4	temperatures during the test, °C
$a(T)$	temperature dependent, horizontal shift factor
f	frequency, Hz

Figure 3 — Determination of the master curve

The reference temperature, T_r (labelled T_{ref} in Figure 3), shall be chosen.

NOTE 4 The reference temperature is typically chosen in relation to the glass transition of the interlayer, see Clause C.1 for further guidance.

The master curve can also be used to determine the shear modulus used in acoustic software (see Annex D).

5.3.2.4 Bending creep tests (Step 4)

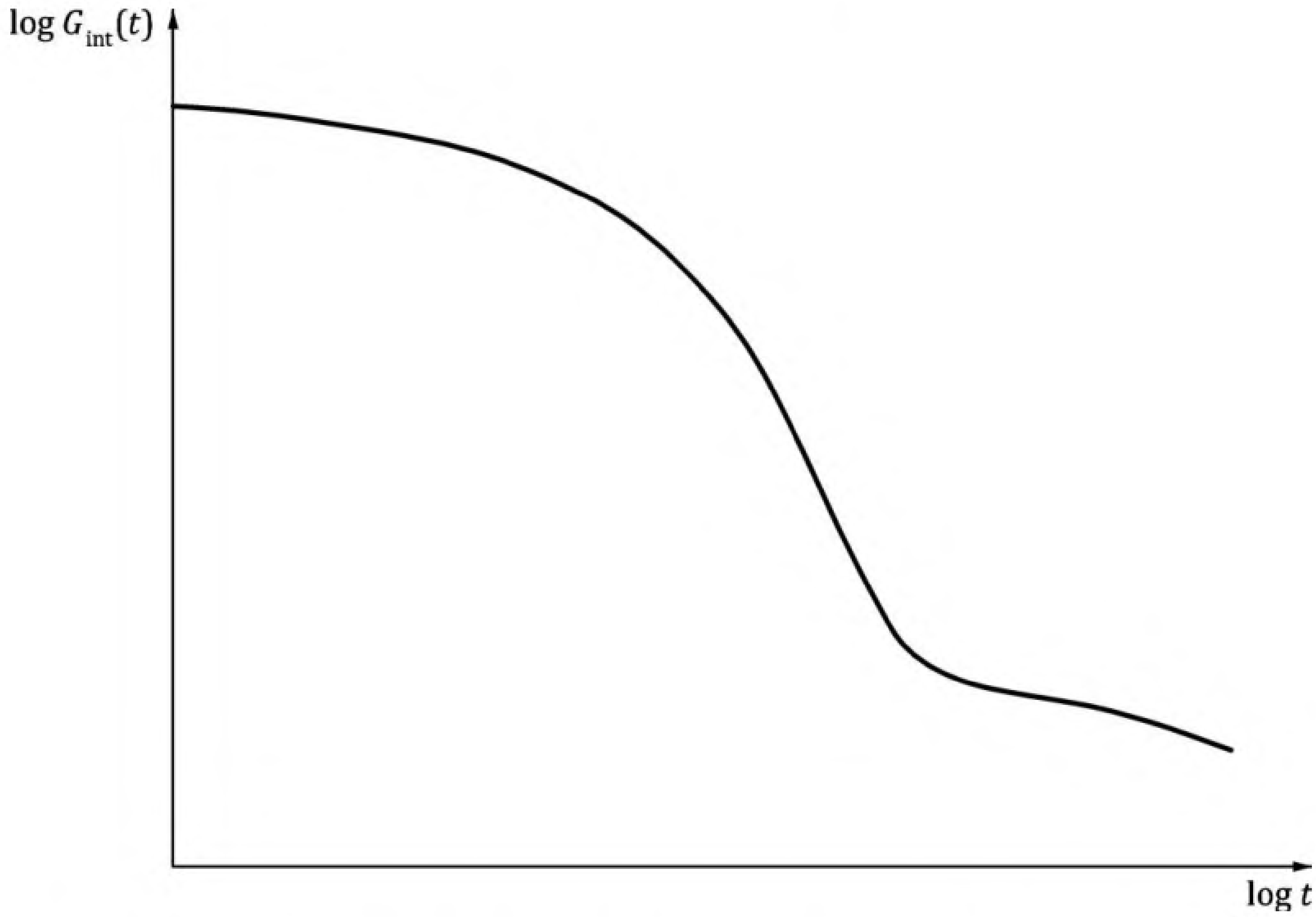
Bending creep tests on the laminates shall be conducted according to Annex A to validate the DMTA-based Prony-series and TTS. The objective is to measure deflection for a range of temperatures T and a range of load durations t sufficient to define the interlayer shear modulus.

With respect to the evaluation of the creep and relaxation tests, the interlayer shear modulus can be computed for times $t > 10\ t_r$ (where t_r is the time needed to apply the load). This method is applicable for a G_{int} value between 0,5 and 10 MPa.

6 Evaluation of the shear transfer characteristics

6.1 Determination of the temperature and time dependent shear modulus $G_{int}(T,t)$

The determination of the interlayer shear relaxation modulus $G_{int}(t)$ from the G' and G'' master curves is described in C.1. For any given temperature T, a graph plotting $G_{int}(t)$ can be generated. An example of this is shown in Figure 4.



Key

$G_{int}(t)$ time dependent shear relaxation modulus of the interlayer material, MPa

t time, s

Figure 4 — Example of a plot of interlayer shear relaxation modulus against time at a given temperature

6.2 Load durations and temperature ranges

Indicative durations and temperature ranges for different load cases can be found in Table D.2 of EN 16612:2019. However, for wind load, the duration 3 s shall be used for interlayer stiffness properties.

7 Test report

The obtained results from Step 1 to 4 shall be recorded in a report according to ISO 6721 series and this document. The following information should be included:

— Reference to the relevant dated part of the ISO 6721 series and this document;

— A full description of the interlayer material including chemical type, thickness for sheets, tradename or manufacturer's code number, previous history where these are known;

— Date of the test;

— The shape and dimensions of the specimen (eventually with a drawn section or pictures);

— The number of specimens tested;

— A description of the apparatus used for the test (trademark, model);

— The temperature program used for the test, including the initial and final temperatures as well as the rate of linear change in temperature or the size and duration of the temperature steps, dynamic strain amplitude and frequency range;

— Characteristic temperatures T_g, T_m, T_c and description of the evaluation method;

— Graphical representation of the master curve of the storage (G') and loss modulus (G'') at the reference temperature T_r;

— Tables containing shear relaxation modulus G_{int} for specified load scenarios according to Table D.2 of EN 16612:2019;

— Prony parameters as well as the parameters for the temperature shift function;

— Description and results of the creep tests;

— Optionally, polynomial coefficients for shear storage modulus (G') and shear loss modulus (G'') that can be used for the Annex D.

Annex A
(normative)

Bending creep method for the determination of the interlayer properties

A.1 General

This method can be used to determine the shear transfer of:

— non-isotropic interlayers and interlayers which cannot be formed into small test pieces or

— used in Step 4 (see 5.3.2.3).

For validation of the interlayer properties and the Prony series, two different options can be used:

a) The shear modulus values from DMTA can be compared to those from the creep test;

b) The modulus values derived from the Prony series is used to calculate the deflection, and the deflection is compared to that of the creep test.

This annex provides only additional information regarding option a).

Based on measurement of deflections of a specimen under load, the following quantities are determined:

— The effective thickness of the laminate under the loading conditions applied, see Formula (A.6);

— The shear transfer coefficient ω as occurs in this document and EN 16612, see Formula (A.5);

— The coupling factor η as occurs in CEN/TS 19100-2 based on the effective thickness of the laminate, see Formulae (A.8) and (A.9);

— The interlayer modulus as calculated from coupling factor η, see Formulae (A.10), (A.11) and (A.12);

— The coupling factor η as occurs in CEN/TS 19100-2 based on a known modulus of the interlayer, see Formulae (A.14), (A.15) and (A.16).

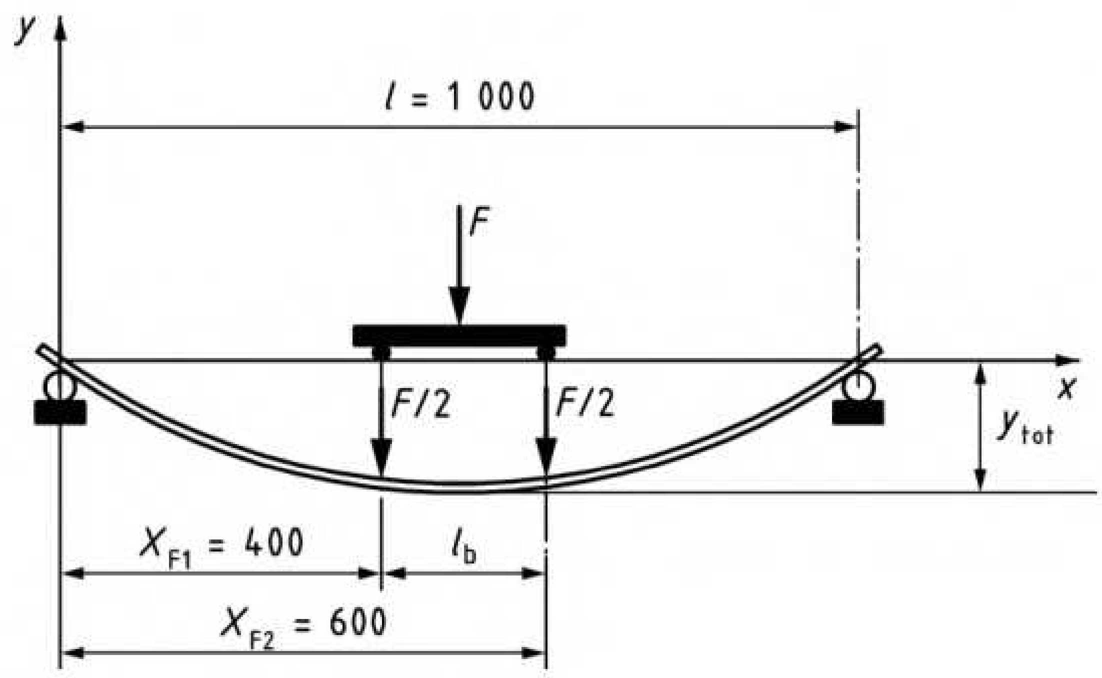
A.2 Method

Test specimens shall be manufactured from samples representative of normal interlayer material production. Test specimens shall be processed under normal laminating conditions.

A series of tests shall be conducted according to the principles of EN 1288-3 (see Figure A.1) and without breaking the test specimens.

The objective is to measure deflection for a range of temperatures, T, and a range of load durations, t, sufficient to define the interlayer shear relaxation modulus G_{int} for durations and temperatures as provided in Table D.2 of EN 16612:2019, while taking into account the specifications of 5.3.2.3.

dimensions in millimetres



Key

x	x-axis illustrating the horizontal position, m
x_{F1}	distance between the first supporting roller and the first bending roller, mm
x_{F2}	distance between the first supporting roller and the second bending roller, mm
y	y-axis, illustrating vertical displacement, mm
y_{tot}	total deflection under self weight and punctual loads, mm
l	distance between centre lines of supporting rollers, m
l_b	distance between centre lines of bending rollers, mm
F	four point bend test load, kN

Figure A.1 — Structural model of the bending test according to EN 1288-3

A.3 Test specimen

The sample shall consist of three test specimens, 1 100 mm x 360 mm of laminated glass with two float glass plies. The total thickness of the pane should be chosen in order to minimize the deformation due to the dead load.

The test specimen shall be such that:

— The stress under long term loading should not exceed 10 MPa;

— The stress under short term loading should not exceed 25 MPa;

The accuracy of the deflection measurement of 5 % should be considered. The width, b, of the samples is measured in the mid-span and above the supporting rollers. The average value of the three measurements, b_{ave}, is used in the determination of the effective thickness, $h_{ef,wt}$. The precision of the measurement is of ± 1 mm.

Due to the viscoelasticity of the materials this strongly depends on the temperature regime that is tested. Especially for temperatures above the glass transition temperature the initial deflection can already contain viscous parts depending on the dead load and thus this part cannot be distinguished from the purely elastic response. Waiting for a stabilization can be influenced exactly from this delayed viscous response. It is recommended to check by a calculation beforehand and depending on the test‘s boundary conditions and temperature if neglecting this effect is possible.

NOTE Some products are manufactured on thin glass substrate. In order to be representative, a non-symmetric composition can be used, e.g. 3 mm / interlayer / 6 mm laminated glass.

A.4 Test procedure

The tests shall be performed in climatic chamber where the temperature is controlled to ± 1 °C.

In order to avoid deflection under self weight, the test sample shall be heated to the test temperature in a vertical position. A new test sample shall be used for each condition.

The conditioned sample is installed on the test rig. In order to stabilize the specimen, an initial pre-loading as given in Table A.1 shall be applied for 10 s and released. The zero reference for the deflection measurement shall be then set. The test shall not begin if the zero reference is not stable.

It is recommended that the bending creep test cover different test durations and temperatures as provided in Table D.2 of EN 16612:2019, while taking into account provisions of 5.3.2.3.

If the DMTA is not possible, a master curve can be created by using several bending tests, fixing a test duration and repeating the test at a defined set of temperatures. The long term data can then be obtained using procedures defined in the Annex C. Here it shall be verified that the individual shear modulus curves have an overlap.

If tests are conducted at different temperatures, one can use a step of 10 °C between −20 °C and 60 °C. In cases where temperatures below 20 °C are not possible, the tests shall be conducted at different temperatures using a step of 10 °C between 20 °C and 60 °C. In this case, the result of the 20 °C test shall be used for temperatures between −20 °C and 10 °C.

Producer shall provide one specimen of monolithic glass panes used for lamination for accurate measurement of its thickness.

The applied load and the deflection shall be monitored while the load is applied. The load shall be applied until the above-mentioned test durations are reached. The test can be stopped early, if the deflection remains constant. The deflection shall be considered to remain constant when the difference between two measurements taken four hours apart is less than 1 %. For annealed glass, in order to avoid breakage, it is recommended to set the load to a value such that approximately 10 MPa stress is reached for the assumption of no shear transfer. Table A.1 contains the force to apply depending on the glass thickness that is valid for the measurement according to the EN 1288-3.

Table A.1 — Recommended force for bending test in case of annealed glass

Laminated glass	Nominal thickness mm	$h_{ef;w}$ mm	$h_{ef;\sigma 1}$ mm	Preloading N	F N	σ MPa
33,2	6,8	3,52	3,96	8 to 15	15	10,25
44,2	8,8	4,78	5,37	19 to 37	37	10,26
55,2	10,8	6,04	6,79	25 to 65	65	10,00
66,2	12,8	7,30	8,20	25 to 105	105	10,12

NOTE 1 The forces were calculated using the minimum thickness of the glass according to EN 572-2.

For any type of glass, the test conditions should result in a deflection that can be measured with sufficient accuracy, especially in case of 30 days testing.

NOTE 2 The annotation 33,2, in the first column, represents nominal thicknesses of the glass panes in millimetres (both glass panes are 3 mm thick) and the number of interlayers (ex. for PVB laminates, the digit 2 would represent two 0,38 mm thick PVB interlayers).

A.5 Determination of effective thickness

Using EN 16612:2019, 9.2 the effective thickness for deformation, $h_{ef,wt}$, shall be calculated for the bending condition based on the measured glass thickness.

The value of deflection in the centre of the pane, e_F, under applied load shall be recorded until the test has been completed.

In order to calculate the effective thickness in deformation, the deflection calculated at the centre of the pane under dead load p and the applied load, F, shall be given by the following formulas:

Deflection under dead load (see also NOTE 1):

$$e_{dl} = \frac{-5pl^4}{384EI} \quad (A.1)$$

Deflection under applied load:

$$e_F = -\frac{F}{96EI}\left(3l^2\left(x_{F1} + x_{F2}\right) - 4\left(x_{F1}^3 + x_{F2}^3\right)\right) \quad (A.2)$$

Total deflection:

$$y_{tot,m} = e_{dl} + e_F \quad (A.3)$$

The effective thickness, $h_{ef,wt}$, of the laminated glass pane is given by the following formula:

$$h_{ef,wt} = \sqrt[3]{\frac{12}{b_{ave} y_{tot,m}}\left[\frac{5pl^4}{384E} + \frac{F}{96E}\left(3l^2\left(x_{F1} + x_{F2}\right) - 4\left(x_{F1}^3 + x_{F2}^3\right)\right)\right]} \quad (A.4)$$

NOTE 1 In case the test is performed with the sample in horizontal position, the displacement gauge is set to "0" once the pane is in place on the supporting rollers. The deflection due to the dead load has then already taken place, before the application of the load F. As a consequence, $P = 0$ in Formula (A.1).

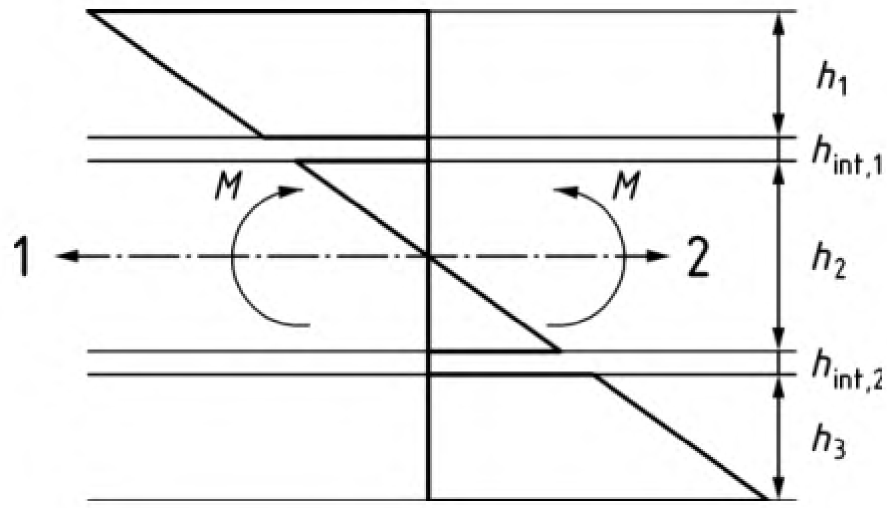
NOTE 2 For a more accurate treatment of the results, the exact span of the sample can be calculated following Annex E.

A.6 Determination of shear transfer coefficient ω

Using the formula of effective thickness according to EN 16612, the interlayer shear transfer coefficient, ω, is calculated from $h_{ef,wt}$:

$$\omega = \frac{h_{ef,wt}^3 - \sum_{i=1}^{n} h_i^3}{12\sum_{i=1}^{n}\left(h_i d_i^2\right)} \quad (A.5)$$

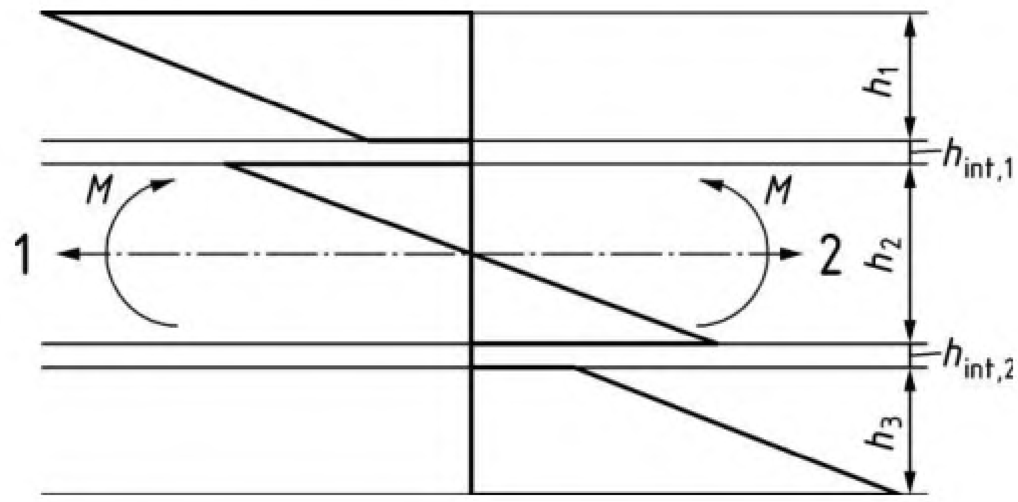
When the effective thickness of laminated glass is equal to its nominal thickness, the shear transfer coefficient ω will have the magnitude 1,0. This condition is also known as "full shear", generally occurring at low temperature and for short load durations. The opposite condition, when the interlayer becomes soft due to a higher temperature and/or long load duration, is called "no shear" and it occurs when the shear transfer coefficient ω is equal to zero. In most of the cases, the value is between 0 and 1 ("partial shear"). Figures A.2, A.3 and A.4 illustrates these conditions based on stress distribution diagrams.



Key

1	compressive stress, MPa
2	tensile stress, MPa
h_1, h_2, h_3	thicknesses of glass layers, mm
$h_{int,1}$, $h_{int,2}$	thicknesses of interlayers, mm
M	bending moments, Nmm

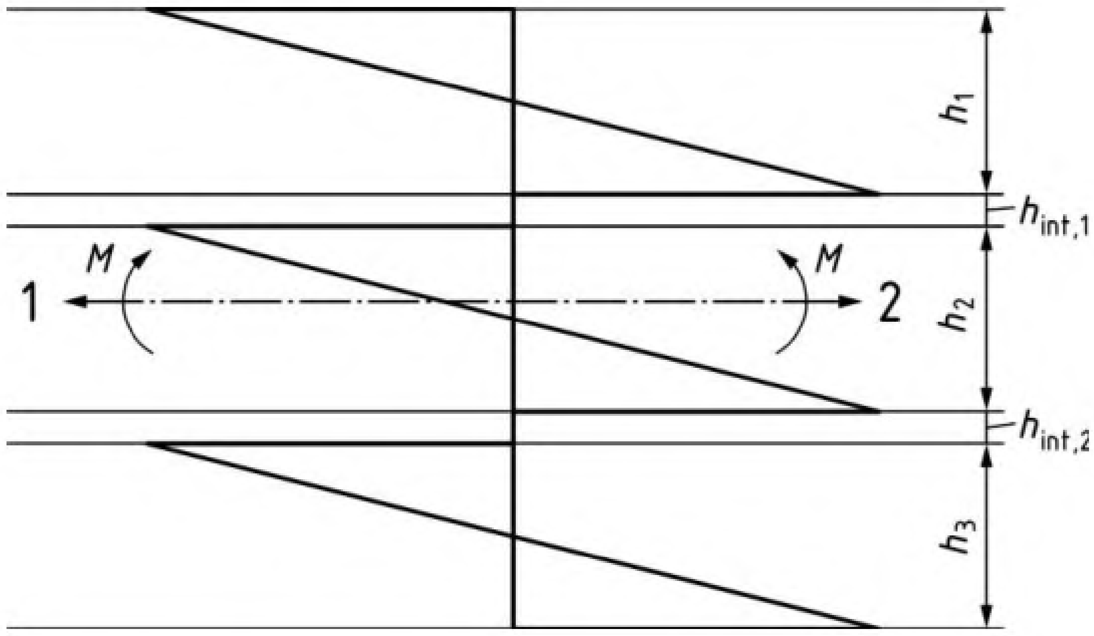
Figure A.2 — Full shear coupling (ω = 1)



Key

1	compressive stress, MPa
2	tensile stress, MPa
h_1, h_2, h_3	thicknesses of glass layers, mm
$h_{int,1}$, $h_{int,2}$	thicknesses of interlayers, mm
M	bending moments, Nmm

Figure A.3 — Partial shear coupling (ω≈0,5)



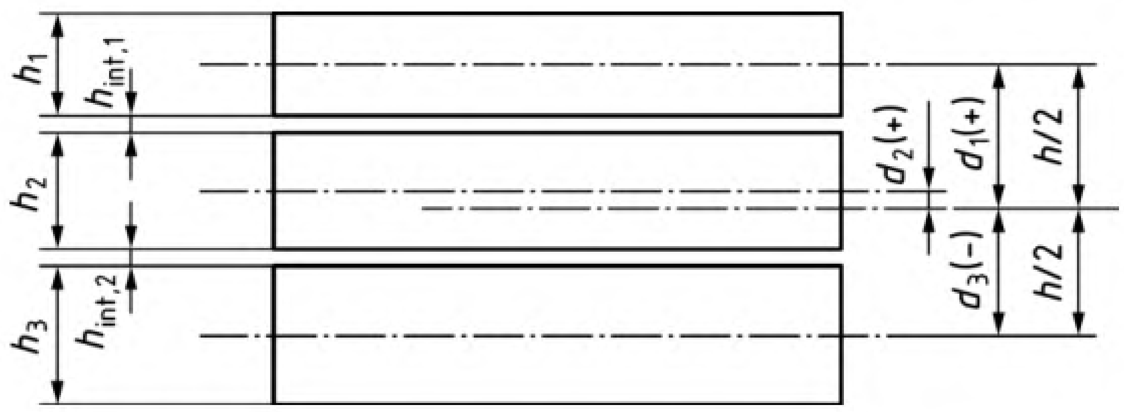
Key

1	compressive stress, MPa
2	tensile stress, MPa
h_1, h_2, h_3	thicknesses of glass layers, mm
$h_{int,1}$, $h_{int,2}$	thicknesses of interlayers, mm
M	bending moments, Nmm

Figure A.4 — No shear coupling (ω = 0)

A.7 Determination of the coupling factor η

In order to calculate the interlayer shear modulus G_{int} using the EET method, the coupling factor η shall be determined. The geometric cross section characteristics of the laminated glass are illustrated in Figure A.5.



Key

1	the mid-plane of the cross section
d_1, d_2, d_3	distances of the mid-plane of the glass plies 1, 2 and 3 from the mid-plane of the laminated glass
h_1, h_2, h_3	thicknesses of glass layers, mm
$h_{int,1}$, $h_{int,2}$	thicknesses of interlayers, mm

Figure A.5 — Geometry of a laminated glass element (cross-sectional view)

The effective thickness $h_{ef,wt}$ for deflection calculation is given in EN 19100-2:—[1], Formula (A.1), as follows:

$$h_{ef,w} = \sqrt[3]{\frac{1}{\frac{\eta}{\sum_{i=1}^{n} h_i^3 + 12\sum_{i=1}^{n}\left(h_i d_i^2\right)} + \frac{1-\eta}{\sum_{i=1}^{n} h_i^3}}} \quad \text{(A.6)}$$

and

$$h_{ef,wt} = h_{ef,w} \quad \text{(A.7)}$$

The coupling factor η for n plies laminated glass of different thickness h_1, h_2, h_3 and the different interlayer thickness $h_{int,1}$, $h_{int,2}$ can be expressed from the previous formula as follows:

$$\eta = \frac{-\left(\sum_{i=1}^{n} h_i^3 + 12\sum_{i=1}^{n}\left(h_i d_i^2\right)\right)\left(\sum_{i=1}^{n} h_i^3 - h_{ef,wt}^3\right)}{12 h_{ef,wt}^3 \sum_{i=1}^{n}\left(h_i d_i^2\right)} \quad \text{(A.8)}$$

The coupling factor for two plies laminated glass having both glass components of the same thickness can be calculated according to the following formula:

$$\eta = \frac{-2h^3\left(h^2 + 12d^2\right) + h_{ef,wt}^3\left(h^2 + 12d^2\right)}{12d^2 h_{ef,wt}^3} \quad \text{(A.9)}$$

The coupling factor for two plies laminated glass with different thickness can be calculated according to the following formula:

$$\eta_2 = \frac{1}{1 + \frac{h_{int}E}{G_{int}\left(1-\nu^2\right)}\frac{D_{abs}}{D_{full}}\frac{h_1 h_2}{\left(h_1 + h_2\right)^2}\psi_p} \quad \text{(A.10)}$$

where

$$D_{abs} = \sum_{i=1}^{n} D_i = \frac{E\sum_{i=1}^{n} h_i^3}{12\left(1-\nu^2\right)} \quad \text{(A.11)}$$

$$D_{full} = D_{abs} + \frac{E\sum_{i=1}^{n}\left(h_i d_i^2\right)}{\left(1-\nu^2\right)} \quad \text{(A.12)}$$

[1] Under preparation. Stage at the time of publication: prEN 19100-2:2024

A.8 Determination of the shear modulus G_{int}

For laminated glass composed of n plies having all the same thickness *h*, the shear modulus G_{int} can be expressed from Formula (A.17) as follows:

$$G_{int} = \frac{E h_{int}}{12\left(\frac{1}{\eta}-1\right)\left(\frac{h^2+(h+h_{int})^2(n^2-1)}{n h^3 (n+1)\Psi_b}\right)} \quad \text{(A.13)}$$

For two plies laminated glass having both the same thickness *h*, the shear modulus G_{int} can be expressed from Formula (A.18) as follows:

$$G_{int} = \frac{E h_{int}}{\left(\frac{1}{\eta_2}-1\right)12\left(\frac{h^2+3(h+h_{int})^2}{6h^3\Psi_b}\right)} \quad \text{(A.14)}$$

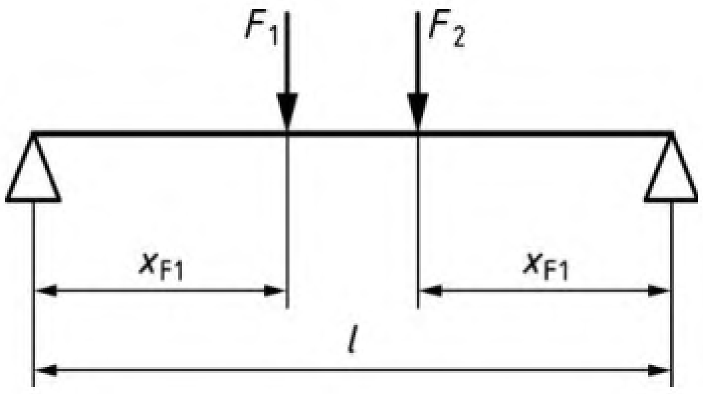
For laminated glass made of three plies of different thickness h_1, h_2, h_3 and the different interlayer thickness $h_{int,1}$ $h_{int,2}$ the shear modulus G_{int} can be expressed from Formula (A.19) as follows:

$$G_{int} = \frac{E\sum_{i=1}^{3} h_i^3 \sum_{i=1}^{3}\left(h_i d_i^2\right)\Psi_b}{\left(\frac{1}{\eta_3}-1\right)\left(\sum_{i=1}^{3} h_i^3 + 12\sum_{i=1}^{3}\left(h_i d_i^2\right)\right)\left(\frac{(d_1-d_2)^2}{h_{int,1}}+\frac{(d_2-d_3)^2}{h_{int,2}}\right)} \quad \text{(A.15)}$$

WARNING — Parameter d_1 is always positive, d_3 is always negative, d_2 can be positive or negative depending on its position compared to the mid-plane of the cross section, see Figure A.5.

In which the boundary coefficient, Ψ_b, according to Figure A.6, is given by Formula (A.16):

$$\Psi_b = -\frac{20(4x_{F1}-3l)}{16x_{F1}^3-20x_{F1}^2 l+5l^3} \quad \text{(A.16)}$$



Key

x_{F1} distance between the first supporting roller and the first bending roller (equal to the distance between the second supporting roller and the second bending roller), mm

l distance between centre lines of supporting rollers, m

F four point bend test load, kN

Figure A.6 — Loading and boundary conditions

A.9 Determination of coupling factor for a known interlayer shear modulus

For laminated glass composed of n plies having all the same thickness h, the shear modulus G_{int} can be expressed from Formula (A.18) as follows:

For two plies laminated panes having all the same thickness h, and the same interlayer thickness h_{int}, the coupling factor is given in EN 19100-2:—[1], Formula (A.7), as follows:

$$\eta_2 = \frac{1}{1 + \left(\frac{h_{int} E}{12 G_{int}}\right)\left(\frac{6h^3}{h^2 + 3\left(h + h_{int}\right)^2}\right)\Psi_b} \quad \text{(A.17)}$$

For a n plies laminated panes having all the same thickness h, and the same interlayer thickness h_{int}, the coupling factor is given by in EN 19100-2:—[1], Formula (A.7), as follows:

$$\eta_n = \frac{1}{1 + \left(\frac{h_{int} E}{12 G_{int}}\right)\left(\frac{nh^3\left(n+1\right)}{h^2 + \left(h + h_{int}\right)^2 \left(n^2 - 1\right)}\right)\Psi_b} \quad \text{(A.18)}$$

For laminated glass made of three plies of different thickness h_1, h_2, h_3 and different interlayer thicknesses $h_{int,1}$ $h_{int,2}$, the coupling factor η_3 is given by in EN 19100-2:—[1], Formula (A.8), as follows:

$$\eta_3 = \frac{1}{1 + \frac{E\sum_{i=1}^{3} h_i \sum_{i=1}^{3}\left(h_i d_i\right)^2 \Psi_b}{G_{int}\left(\sum_{i=1}^{3} h_i^3 + 12\sum_{i=1}^{3}\left(h_i d_i^2\right)\right)\left(\frac{\left(d_1 - d_2\right)^2}{h_{int,1}} + \frac{\left(d_2 - d_3\right)^2}{h_{int,2}}\right)}} \quad \text{(A.19)}$$

Annex B
(normative)

Preparation of test specimens

B.1 Folio interlayers

The test specimens should be produced under normal manufacturing conditions. The adhesion of the interlayer to the glass can be prevented by using a suitable film, e.g. a PTFE or PET film, between the glass and the interlayer material.

B.2 Cast in place interlayers

These interlayers require to be manufactured as if they were a laminated glass, i.e. with glass and edge closure tape/spacer. The adhesion of the interlayer to the glass should be prevented.

B.3 Intumescent interlayers

If the interlayer can be produced as folios that can be added together to get the required test thickness, then the test specimens should be manufactured as for a folio interlayer.

In the case that the interlayer cannot be produced as a folio then it should be treated as a cast in place interlayer (see B.2).

Annex C
(informative)

Time-temperature-superposition principle and Prony series

C.1 Creation of the Master curve

From the temperature-frequency measurement sets, master curves for G' and G'' may be generated for a reference temperature T_r by only horizontally shifting the individual modulus curves. The shift factors can be approximated using the time-temperature superposition principle (TTS).

NOTE 1 The following reference temperature (T_r) are commonly used:

— For PVB: 20 °C and,

— For EVA: −20 °C

The a_T factors shall be determined in such a way that continuous master curves are produced for each G^* component (G' and G'').

Different TTS models exist:

— Williams-Landel-Ferry (WLF-TTS) Formula (3) shall be used in the glass transition range of temperatures and above:

$$\log \alpha_T = -\frac{C_1 (T - T_r)}{C_2 + T - T_r} \quad (C.1)$$

This formula contains two empirical constants (C_1 and C_2). These constants depend on the reference temperature T_r.

NOTE 2 C_1 and C_2 can be determined with a least squares algorithm or with a linear regression of $-1/\log a_T$ versus $1/(T-T_r)$:

$$-\frac{1}{\log \alpha_T} = \frac{1}{C_1} + \frac{C_2}{C_1} \frac{1}{T - T_r} \quad (C.2)$$

— Arrhenius formula shall be used below the glass transition range:

$$\log \alpha_T = -0{,}434 \frac{E_a}{R} \left(\frac{1}{T_k} - \frac{1}{T_{kr}} \right) \quad (C.3)$$

where

R	is the universal gas constant;
E_a	is the activation energy.

NOTE 3 E_a can be determined with a least squares algorithm or with the slope of log a_T versus $\left(\frac{1}{T_k} - \frac{1}{T_{kr}} \right)$

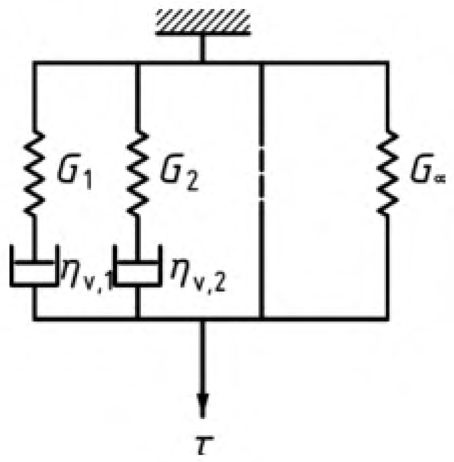
— Polynomial formula.

DMTA-TFS test is run to deliver Storage and Loss moduli data such that the master curve generation using an incremental shifting procedure is possible. The incremental shift procedure is independent of a functional form of one or more TTS principles (strictly, one TTS should be assigned to one transition phase).

It is necessary to check the convexity of a chosen TTS principle, especially if polynomial TTS principle is assumed to ensure physically sensible shifting behaviour. There exist temperature ranges, where the shift is unphysical, hence convexity of the polynomial TTS principle shall be enforced. The boundary conditions of the TTS shall be defined.

C.2 Determination of the Prony series

The complex dynamic modulus is linked to a spectrum of relaxation times [6, 7, 8]. A good description is given by a generalized Maxwell model (see Figure C.1).



Key

G_i, τ_i Prony parameters

G_∞ equilibrium modulus

$\eta_{v,1}$, $\eta_{v,2}$ coefficient of viscosity

Figure C.1 — Generalized Maxwell model representation

The expression:

$$G_{\text{int}}(t) = G_\infty + \sum_{i=1}^{n} G_i \exp\left(-\frac{t}{\tau_i}\right) \qquad \text{(C.4)}$$

is called Prony series wherein G_i, τ_i and G_∞ are called Prony parameters. G_∞ tends to zero when the material shows flowing (e.g. thermoplastics) or to a finite positive limit (e.g. elastomers). For each measurement the time dependent modulus can then be generated.

Using normalized parameters $g_i = G_i / G_0$, $\tau_i = \frac{\eta_{v,i}}{G_i}$ where G_0 is the modulus at time t = 0, the storage and loss moduli become:

$$G'(\omega_f) = G_\infty + \sum_{i=1}^{n} \frac{G_i \omega_f^2 \tau_i^2}{1 + \omega_f^2 \tau_i^2} = G_0 \left[1 - \sum_{i=1}^{n} g_i + \sum_{i=1}^{n} \frac{g_i \omega_f^2 \tau_i^2}{1 + \omega_f^2 \tau_i^2} \right] \tag{C.5}$$

$$G''(\omega_f) = \sum_{i=1}^{n} \frac{G_i \omega_f \tau_i}{1 + \omega_f^2 \tau_i^2} = G_0 \sum_{i=1}^{n} \frac{g_i \omega_f \tau_i}{1 + \omega_f^2 \tau_i^2} \tag{C.6}$$

Where g_i and τ_i are the Prony parameters (respectively normalized moduli and relaxation times) and ω_f the angular frequency. Parameter n is equal to the number of Maxwell-elements (spring-damper elements) in the generalized Maxwell model. The Prony parameters can be determined by simultaneously fitting the above presented equations for the storage modulus $G'(\omega_f)$ and loss modulus $G''(\omega_f)$ to the respective mastercurves.

NOTE The number n of spring-damper elements can be set to the number of investigated time decades. Less Maxwell elements cannot describe the relaxation function $G_{int}(t)$ adequately over the whole frequency range of the master curve and a higher number of elements delivers no significant improvement. The additional parallel spring ensures that the relaxation function $G_{int}(t)$ tends to a finite positive limit G_∞. This is fulfilled for viscoelastic behaviour without flowing. If flowing occurs, $G_{int}(t)$ achieves after a long time zero and the parallel spring can be omitted ($G_\infty = 0$).

It is possible to determine a reduced Prony series with less elements (e.g. n = 10). For most engineering applications, a shear modulus value > 10 MPa leads to full shear transfer [6], and hence, a reduced Prony series could be determined in the range of $0 < G_{int} \leq 10$ MPa.

The optimization problem can lead to problem related to a non-proper scaling of the loss modulus G''. It can be suggested to use the following scaling function [6, 7, 8]:

$$f = \sum_{i=1}^{m} \left[\left(\log\left(G'(\omega_{fi})\right) - \log\left(\overline{G'}(\omega_{fi})\right) \right)^2 + \beta \left(\log\left(G''(\omega_{fi})\right) - \log\left(\overline{G''}(\omega_{fi})\right) \right)^2 \right] \tag{C.7}$$

Where $\overline{G'}(\omega_{fi})$ and $\overline{G''}(\omega_{fi})$ are the storage and loss moduli out of measurement, $G'(\omega_{fi})$ and $G''(\omega_{fi})$ are the storage and loss moduli calculated with the Prony series and β is the scaling factor. The scaling factor β depends on the order of magnitude of the ratio G''/G'. In many cases, $\beta = 10$ can be used.

The shear relaxation modulus $G_{int}(t)$, as calculated from the Prony series in the frequency domain, should not exceed the measured shear storage modulus G' values under the same condition.

The result is a table giving the Prony parameters g_i (or G_i), τ_i and G_0 (or G_∞). In addition to the Prony parameters, a table containing the shear relaxation modulus G_{int} values evaluated for the load cases in Table D.2 of EN 16612:2019 will be provided.

Annex D
(informative)

Interlayer mechanical properties at different frequencies for a chosen temperature

D.1 Purpose of this annex

In order to calculate the sound reduction of laminated glass containing viscoelastic interlayers, shear storage modulus (G') and shear loss modulus (G'') shall be both determined for a chosen temperature T at different frequencies (f).

NOTE The temperature during acoustic measurement according to EN ISO 10140-1 is given in its Annex D. For calculation of acoustic properties, the temperature 20 °C is generally used.

Shear storage modulus (G') and shear loss modulus (G'') are both measured according to 5.3.2.3 and master curves shall be generated for these properties in the frequency domain.

D.2 Calculation of shear storage modulus (G') and shear loss modulus (G'') at different frequencies for a chosen temperature (T)

Shear storage modulus G' at the chosen temperature T can be obtained from Formula (D.1) and shear loss modulus G'' at the chosen temperature T from Formula (D.2).

$$\log G' = \sum_{j=0}^{7} P_{\mathrm{r},j} \cdot \log\left(f \cdot 10^{\frac{-C_1 \left(T - T_\mathrm{r} \right)}{C_2 + T - T_\mathrm{r}}} \right)^j \qquad \text{(D.1)}$$

$$\log G'' = \sum_{j=0}^{7} P_{\mathrm{s},j} \cdot \log\left(f \cdot 10^{\frac{-C_1 \left(T - T_\mathrm{r} \right)}{C_2 + T - T_\mathrm{r}}} \right)^j \qquad \text{(D.2)}$$

where

$P_{\mathrm{r},j}$	is the polynomial coefficient of the shear storage modulus of degree j, with j ranging from 0 to 7;
$P_{\mathrm{s},j}$	is the polynomial coefficient of the shear loss modulus of degree j, with j ranging from 0 to 7;
T_r	is the reference temperature in °C;
T	is the chosen temperature in °C;
f	is the frequency in Hz;
C_1 and C_2	are empirical constants of the WLF-TTS visco-elastic formula, see C.1.

Polynomial coefficients $P_{\mathrm{r},j}$ and $P_{\mathrm{s},j}$ are obtained from a regression model using the method of least squares respectively from the measurement of G' and G'' (see C.1).

NOTE The common frequency range currently used is 50 – 5 000 Hz. An extension to lower frequency can be required for certain applications.

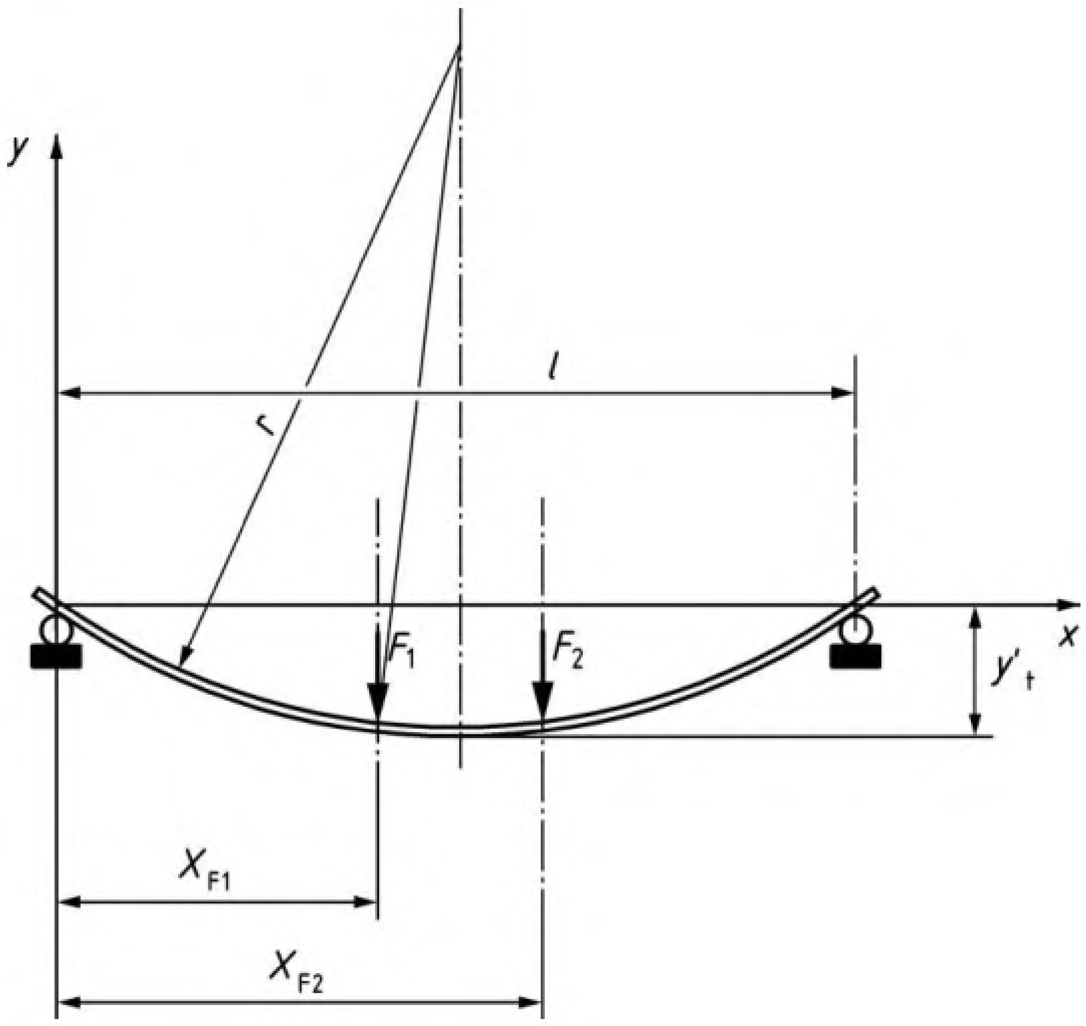
Annex E
(informative)

Determination of the displacement of the point of contact between the support rollers and the plate

E.1 Introduction

The more the plate is subjected to bending, the more the original point of contact between the pane and the roller moves towards the interior of the sample. Therefore, the distance between these two original points of contact, l_{corr}, decreases and can be calculated (see Figure E.1).

E.2 Calculation of l_{corr}



Key

x	x-axis illustrating the horizontal position, mm
x_{F1}	distance between the first supporting roller and the first bending roller, mm x_{F2}
	distance between the first supporting roller and the second bending roller, mm
y	y-axis, illustrating vertical displacement, mm
y'_t	total angular deformation under self weight and punctual loads, mm
l	distance between centre lines of supporting rollers, mm
r	radius of the glass deflected under self weight, mm
F	four point bend test load, kN

Figure E.1 — Structural model

The angular deformation of the glass plate under two punctual loads:

$$y'_{\mathrm{p}} = \frac{-F}{12EIl}\left\{x_{\mathrm{F1}}\left(l^2 - x_{\mathrm{F1}}{}^2 - 3x^2\right) + x_{\mathrm{F2}}\left(l^2 - x_{\mathrm{F2}}{}^2 - 3x^2\right)\right\} \quad \text{(E.1)}$$

$$F = F_1 + F_2 \quad \text{(E.2)}$$

The angular deformation of the glass plate under dead load:

$$y'_{\mathrm{dl}} = \frac{-p}{24EI}\left(l^3 - 6lx^2 - 4x^3\right) \quad \text{(E.3)}$$

The total angular deformation:

$$y'_{\mathrm{t}} = y'_{\mathrm{p}} + y'_{\mathrm{dl}} \quad \text{(E.4)}$$

The derived curvature of support roller is:

$$y'_{\mathrm{r}} = \frac{-x}{\sqrt{r_{\mathrm{r}}^2 - x^2}} \quad \text{(E.5)}$$

The derived formula of the glass at initial state (unloaded):

$$y'_{\mathrm{cg}} = \frac{-0{,}5\left(-2x + l\right)}{\sqrt{r^2 - \left(x - 0{,}5l\right)^2}} \quad \text{(E.6)}$$

If the glass is not deflected, $r = \infty$ and $y'_{\mathrm{cg}} = 0$.

The contact point between the bent plate and the roller is given by the following operations:

For $0 \le x < r_r$, determine $x = l_{red}$ by intercepting “*x*” for which the expression $y'_{\mathrm{t}} + y'_{\mathrm{cg}} - y'_{\mathrm{r}}$ changes of sign and $l_{\mathrm{cor}} = l - 2 \cdot l_{\mathrm{red}}$.

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