INTERNATIONAL STANDARD

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Plastics — Determination of dynamic mechanical properties —

Part 5:
Flexural vibration — Non-resonance method

Plastiques — Détermination des propriétés mécaniques dynamiques —

Partie 5: Vibration en flexion — Méthode hors résonance

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 6721-5 was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical properties*.

- *Part 1: General principles*
- *Part 2: Torsion-pendulum method*
- *Part 3: Flexural vibration — Resonance-curve method*
- *Part 4: Tensile vibration — Non-resonance method*
- *Part 5: Flexural vibration — Non-resonance method*
- *Part 6: Shear vibration — Non-resonance method*
- *Part 7: Torsional vibration — Non-resonance method*
- *Part 8: Longitudinal and shear vibration — Wave-propagation method*
- *Part 9: Tensile vibration — Sonic-pulse propagation method*
- *Part 10: Dynamic shear viscosity using a parallel-plate oscillatory rheometer*

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Plastics — Determination of dynamic mechanical properties —

Part 5:
Flexural vibration — Non-resonance method

1 Scope

This part of ISO 6721 describes a flexural, non-resonance method for determining the components of the Young's complex modulus E^* of polymers at frequencies typically in the range 0,01 Hz to 100 Hz. The method is suitable for measuring dynamic storage moduli in the range 10 MPa to 200 GPa. Although materials with moduli less than 10 MPa may be studied, more accurate measurements of their dynamic properties can be made using shear modes of deformation (see part 6 of ISO 6721).

This method is particularly suited to the measurement of loss factors greater than 0,1 and may therefore be conveniently used to study the variation of dynamic properties with temperature and frequency through most of the glass-rubber relaxation region (see ISO 6721-1:1994, subclause 9.4). The availability of data determined over wide ranges of both frequency and temperature enables master plots to be derived, using frequency/temperature shift procedures, which present dynamic properties over an extended frequency range at different temperatures.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of ISO 6721. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of ISO 6721 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 6721-1:1994, *Plastics — Determination of dynamic mechanical properties — Part 1: General principles.*

ISO 6721-6:1996, *Plastics — Determination of dynamic mechanical properties — Part 6: Shear vibration — Non-resonance method.*

3 Definitions

See ISO 6721-1:1994, clause 3.

4 Principle

A test specimen is subjected to a sinusoidal transverse force or displacement at a frequency significantly below the fundamental flexural resonance frequency (see 10.2.1). The amplitudes of the force and displacement cycles applied to the specimen and the phase angle between these cycles are measured. The storage and loss components of the Young's complex modulus and the loss factor are calculated using equations given in clause 10 of this part of ISO 6721.

5 Apparatus

5.1 Loading assembly

The requirements for the loading assembly are that it shall permit measurements of the amplitudes of, and phase angle between, the force and displacement cycles for a specimen subjected to a transverse sinusoidal force or displacement. Various designs of apparatus are possible, as illustrated schematically in figures 1 and 2. In figure 1a), a sinusoidal displacement is generated by the vibrator V and applied to the specimen S through moving clamps C_1 located close to the opposite ends of the specimen. The amplitude and frequency of the vibrator table displacement are variable and monitored by the transducer D. The specimen is held at its centre by a fixed clamp C_2 and thus undergoes sinusoidal flexural deformations. The sinusoidal force applied in deforming the specimen is

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monitored by a force transducer F connected to C_2. The members between the clamps C_1 and V, and between C_2 and F, shall be much stiffer than the specimen and shall have a low thermal conductance if the specimen is to be enclosed in a temperature-controlled cabinet.

NOTE 1 Whilst each member of the loading assembly may have a much higher stiffness than the specimen, the presence of clamped or bolted connections can significantly increase the apparatus compliance. It may then be necessary to apply a compliance correction as described in 10.2.3.

Various other loading assemblies may be employed as alternatives to that detailed above. For example, the specimen may be simply supported and deformed in three-point flexure, as illustrated in figure 1 b). Furthermore, the force on the specimen may be calculated from the current supplied to the vibrator, thus eliminating the need for a separate force transducer. With this method (see figure 2), it should be recognized that part of the force generated by the vibrator current is used to accelerate the drive shaft and to deform the drive-shaft suspension Su in parallel with the specimen. That part of the generated force used to deform the specimen must be determined with the aid of a separate calibration with the specimen absent.

5.1.1 Load stage

The clamps shall be capable of gripping the test specimen with a force which is sufficient to prevent the specimen from slipping during the flexural deformation, and to maintain the force at low temperatures.

With the simply supported specimen [figure 1 b)], the supporting rollers shall contact the specimen along parallel lines and have radii sufficiently large to avoid significant indentation of the specimen and thereby minimize consequent errors in the measured moduli and loss factors.

The separation between the two outer clamps and between the outer supports shall be variable so that specimens of different length can be accommodated and length corrections may be determined for the clamped specimens (see 10.2.4). A facility to permit small variations in the clamp separation [figure 1 a)] would also allow for thermal expansion of the specimens and is necessary to avoid errors in the apparent moduli due to buckling of the specimens at high temperatures.

Any misalignment of the load stage with respect to the force transducer will produce a lateral component of the force applied to the transducer during loading of the specimen. The alignment of the loading assembly and test specimen shall be such that any lateral component recorded by the transducer is less than 1 % of the longitudinal force.

5.1.2 Transducers

The term transducer in this part of ISO 6721 refers to any device capable of measuring the applied force or displacement, or the ratio of these quantities, as a function of time. The calibration of the transducers shall be traceable to national standards for the measurement of force and length. The calibration shall be accurate to ± 2 % of the minimum force and displacement cycle amplitudes applied to the specimen for the purpose of determining dynamic properties.

5.2 Electronic data-processing equipment

Data-processing equipment shall be capable of recording the force and displacement cycle amplitudes to an accuracy of ± 1 %, the phase angle between the force and displacement cycles to an accuracy of ± 0,1° and the frequency to an accuracy of ± 10 %.

5.3 Temperature measurement and control

See ISO 6721-1:1994, subclauses 5.3 and 5.5.

5.4 Devices for measuring test specimen dimensions

See ISO 6721-1:1994, subclause 5.6.

6 Test specimens

See ISO 6721-1:1994, clause 6.

6.1 Shape and dimensions

Test specimens of rectangular cross-section are recommended to facilitate load introduction. The width and thickness shall not vary along the specimen length by more than 2 % of the mean value. The dimensions of the specimens are not critical although, for isotropic materials, values of $L_a/d > 16$ for clamped specimens and $L_a/d > 8$ for simply supported specimens would make corrections for shear deformation negligible (see 10.1 and 10.2). Also values of $L_a/b > 6$ for clamped specimens and $L_a/b > 3$ for simply supported specimens are recommended to avoid significant errors associated with constraints to deformations along the width direction (anticlastic curvature) near to the clamps or central support (see 10.1). For test conditions under which the storage moduli are high (⩾ 50 GPa), sufficiently long, thin specimens shall be employed so that displacements are generated that may be measured with high accuracy. Alternatively, when the storage moduli are low (< 100 MPa), relatively short, thick specimens may be required to achieve sufficient accuracy in the measurement of force.

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NOTE 2 A variation in dynamic properties may be observed between specimens of different thickness prepared by injection moulding owing to differences which may be present in the structure of the polymer in each specimen.

6.2 Preparation

See ISO 6721-1:1994, subclause 6.2.

7 Number of specimens

See ISO 6721-1:1994, clause 7.

8 Conditioning

See ISO 6721-1:1994, clause 8.

9 Procedure

9.1 Test atmosphere

See ISO 6721-1:1994, subclause 9.1.

9.2 Measuring the cross-section of the specimen

See ISO 6721-1:1994, subclause 9.2.

9.3 Clamping the specimen

Mount the specimen between the clamps, using a clamping force that is sufficient to prevent slip under all test conditions. If measurements are observed to depend upon clamp pressure, then a constant pressure shall be used for all measurements, especially when applying a length correction (see 10.2.4 and note 3).

NOTE 3 If measurements are observed to depend upon clamp pressure, then the clamped area of the specimen is probably too small. A larger clamp face or a wider specimen should eliminate this problem.

9.4 Varying the temperature

See ISO 6721-1:1994, subclause 9.4.

9.5 Performing the test

Apply, by means of the vibrator, a dynamic force which yields force and displacement signal amplitudes for the specimen that can be measured to the accuracy specified in 5.1.2. For simply supported specimens, also apply a static force that is sufficient to maintain the load under the decreasing part of the superimposed dynamic load.

NOTE 4 If the maximum tensile strain within the specimen exceeds the limit for linear behaviour, then the derived dynamic properties will depend on the magnitude of the applied displacement. The limiting strain varies with the composition of the polymer and the temperature, and is typically in the region of 0,2 % for glassy plastics.

Record the amplitudes of, the phase difference between and the frequency of the force and displacement signals, as well as the temperature of the test. Where measurements are to be made over ranges of frequency and temperature, it is recommended that the lowest temperature be selected first and measurements made with increasing frequency, keeping the temperature constant. The frequency range is then repeated at the next higher temperature (see ISO 6721-1:1994, subclause 9.4).

For those test conditions under which the polymer exhibits medium or high loss (for example in the glass-rubber transition region), the energy dissipated by the polymer may raise its temperature sufficiently to give a significant change in dynamic properties. Any temperature rise will increase rapidly with increasing strain amplitude and frequency. If the data-processing electronics is capable of analysing the transducer outputs within the first few cycles, then the influence of any temperature rise will be minimized. Subsequent measurements will then change with time as the specimen temperature continues to rise, and such observations will indicate the need to exercise some caution in the presentation and interpretation of results.

10 Expression of results

10.1 Symbols

b specimen width, in metres

d specimen thickness, in metres

E'_a, E' apparent and corrected Young's storage modulus, in pascals

E'' Young's loss modulus, in pascals

f measurement frequency, in hertz

f_F resonance frequency, in hertz, of the force transducer

f_S resonance frequency, in hertz, of the specimen

G' shear storage modulus, in pascals

k_a, k measured and corrected magnitude, in newtons per metre, of the complex stiffness of the specimen

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k_F stiffness of the force transducer, in newtons per metre

k_∞ measured stiffness, in newtons per metre, of a steel test specimen whose cross-sectional dimensions and length are such that it is at least 100 times stiffer than the stiffest polymer specimen to be tested (see note 5)

l length correction term, in metres, to allow for clamping

L_a (for a clamped specimen) length, in metres, of specimen between the central clamp and each outer clamp

(for a simply supported specimen) length, in metres, of specimen between the central loading line and each outer clamp support

m_F mass, in kilograms, of that part of the loading assembly between the force transducer and the test specimen

s_A measured amplitude, in metres, of the dynamic displacement

$\tan \delta_{Ea}$, $\tan \delta_E$ apparent and corrected Young's loss factor

δ_{Ea}, δ_E measured and corrected phase difference, in degrees, between the force and displacement cycles

ΔF_A measured amplitude, in newtons, of the dynamic force applied to the specimen

NOTE 5 The magnitude of k_∞ will give an estimate of the stiffness of the loading assembly which is equivalent to a spring connected in series with the specimen and will enable a correction for apparatus compliance to be deduced (see 10.2.3).

10.2 Calculation of Young's storage modulus E'

An approximate value E'_a for the storage modulus is determined from the following equations:

Clamped specimen

$$E'_a = \frac{\Delta F_A}{s_A} \times \frac{L_a^3}{2bd^3} \times \left[1 + \frac{d^2}{L_a^2} \times \frac{E'}{G'}\right] \cos \delta_{Ea}$$

$$= k_a \times \frac{L_a^3}{2bd^3} \times \left[1 + \frac{d^2}{L_a^2} \times \frac{E'}{G'}\right] \cos \delta_{Ea} \qquad \text{... (1)}$$

Simply supported specimen

$$E'_a = \frac{\Delta F_A}{s_A} \times \frac{2L_a^3}{bd^3} \times \left[1 + \frac{d^2}{4L_a^2} \times \frac{E'}{G'}\right] \cos \delta_{Ea}$$

$$= k_a \times \frac{2L_a^3}{bd^3} \times \left[1 + \frac{d^2}{4L_a^2} \times \frac{E'}{G'}\right] \cos \delta_{Ea} \qquad \text{... (2)}$$

In these equations, the terms in square brackets account approximately for the effects of shear deformation during the flexure. Values for E'/G' typically range from 2,7 for isotropic glassy or semicrystalline polymers to 3,0 for rubbers. Higher values of E'/G' may be required for anisotropic materials and must be estimated from dynamic Young's and shear modulus data. It is recommended that the L_a/d ratios are chosen such that the magnitudes of the correction terms for shear deformation do not exceed 0,1.

NOTE 6 The shear correction terms $(d^2/L_a^2)(E'/G')$ and $(d^2/4L_a^2)(E'/G')$ in equations (1) and (2), respectively, are approximate since they omit a factor (the shear deflection coefficient) that accounts for the distribution of shear stress across the specimen thickness.

10.2.1 Avoidance of specimen resonance

Equations (1) and (2) become invalid as the drive frequency approaches the fundamental flexural resonance frequency f_s of the specimen given approximately by the following equations:

Clamped specimen

$$f_s = 1{,}03 \times \frac{d}{L_a^2} \times \left(\frac{E'_a}{\rho}\right)^{1/2} \qquad \text{... (3)}$$

Simply supported specimen

$$f_s = 0{,}71 \times \frac{d}{L_a^2} \times \left(\frac{E'_a}{\rho}\right)^{1/2} \qquad \text{... (4)}$$

where ρ is the polymer density in kilograms per cubic metre.

Errors in the use of equations (1) and (2) become significant at applied frequencies such that

$$f \geqslant 0{,}08 f_s \qquad \text{... (5)}$$

Calculations of dynamic properties shall therefore be confined to frequencies below $0{,}08 f_s$.

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10.2.2 Correction for transducer resonance

At sufficiently high frequencies, the applied deformation will excite the force transducer into resonance. The resonance frequency f_F is given by

$$f_F = \frac{1}{2\pi}\left(\frac{k_F}{m_F}\right)^{1/2} \qquad \text{... (6)}$$

The transducer output will have a significant error for all applied frequencies

$$f > 0{,}1 f_F \qquad \text{... (7)}$$

The resonance frequency f_F of the force transducer and supported mass m_F can be determined directly by recording the natural frequency of the transducer output after striking the attached clamp without the specimen.

The specimen stiffness corrected for transducer resonance is given to a good approximation by the equation

$$k = k_a\left(1 - \frac{4\pi^2 m_F f^2}{k_F}\right) = k_a\left(1 - \frac{f^2}{f_F^2}\right) \qquad \text{... (8)}$$

It is recommended that equations (6) and (7) be used to select a force transducer whose resonance frequency is above the frequency range for which a correction to the force measurement is necessary.

10.2.3 Correction for apparatus compliance

If k_a is greater than 0,02 k_∞, then the compliance of the test assembly is not negligible and the measured displacement differs significantly from that of the specimen. The following correction shall then be applied:

$$k \cos \delta_E = \frac{k_a(\cos \delta_{Ea} - k_a/k_\infty)}{1 - 2(k_a/k_\infty)\cos \delta_{Ea}} \qquad \text{... (9)}$$

where δ_E is given by equation (11).

The value of $k \cos \delta_E$ obtained from equation (9) shall be used in place of $k_a \cos \delta_{Ea}$ in equation (1) or (2) to give a more accurate estimate for E'_a.

NOTE 7 The compliance correction is unnecessary if the displacement transducer is located so as to measure the relative displacement of central and outer clamps or supports.

10.2.4 Application of a length correction

Using the measured clamp separation L_a for the specimen length in equation (1) takes no account of some distortion of the specimen within and around the clamps. Applying a small correction to L_a such that the effective length is $L_a + l$, and assuming l is independent of L_a, yields from equation (1)

$$E' = \frac{k(L_a + l)^3}{2bd^3} \times \left(1 + \frac{d^2}{L_a^2} \times \frac{E'}{G'}\right) \cos \delta_{Ea}$$

$$= E'_a \times \frac{(L_a + l)^3}{L_a^3} \qquad \text{... (10)}$$

where E'_a is the apparent storage modulus corrected for apparatus compliance, if necessary, and the length correction has been ignored in the small shear-correction term.

A value for l may be determined from measurements of E'_a for a series of clamp separations L_a. From equation (10), a plot of $L_a/E'_a{}^{1/3}$ against L_a enables l to be determined from the intercept at $L_a/E'_a{}^{1/3} = 0$ and E' to be determined from the gradient.

NOTE 8 The value of l will vary with the cross-sectional dimensions of the specimen and with temperature if this causes significant changes in dynamic modulus.

10.3 Calculation of the Young's loss factor tan δ_E

An approximate value for the Young's loss factor is tan δ_{Ea}.

If k_a is greater than 0,02 k_∞ then the compliance of the loading assembly will influence the accuracy of the phase angle measurement. The loss factor shall then be obtained using the equation

$$\tan \delta_E = \frac{\tan \delta_{Ea}}{1 - (k_a/k_\infty \cos \delta_{Ea})} \qquad \text{... (11)}$$

NOTE 9 If the origin of the source of compliance in the loading assembly arises through clamped or bolted connections, there may be a contribution from friction to the measured phase angle δ_{Ea}. The magnitude of the resulting error increases with the ratio k_a/k_∞. This source of error can be avoided by locating the displacement transducer so that the relative displacement of the central and outer clamps or supports is measured.

10.4 Calculation of the Young's loss modulus

Calculate the loss modulus E'' from the equation

$$E'' = E' \tan \delta_E \qquad \text{... (12)}$$

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10.5 Presentation of data as a function of temperature

See ISO 6721-1:1994, subclause 9.4.

11 Precision

The precision of this test method is not known because interlaboratory data are not available. When interlaboratory data are obtained, a precision statement will be added at the following revision.

12 Test report

The test report shall contain the following information:

a) a reference to this part of ISO 6721;

b) to m) see ISO 6721-1:1994, clause 12;

n) the maximum dynamic strain amplitude, given approximately by $3ds_A/L_a^2$ for clamped specimens and by $3ds_A/2L_a^2$ for simply supported specimens.

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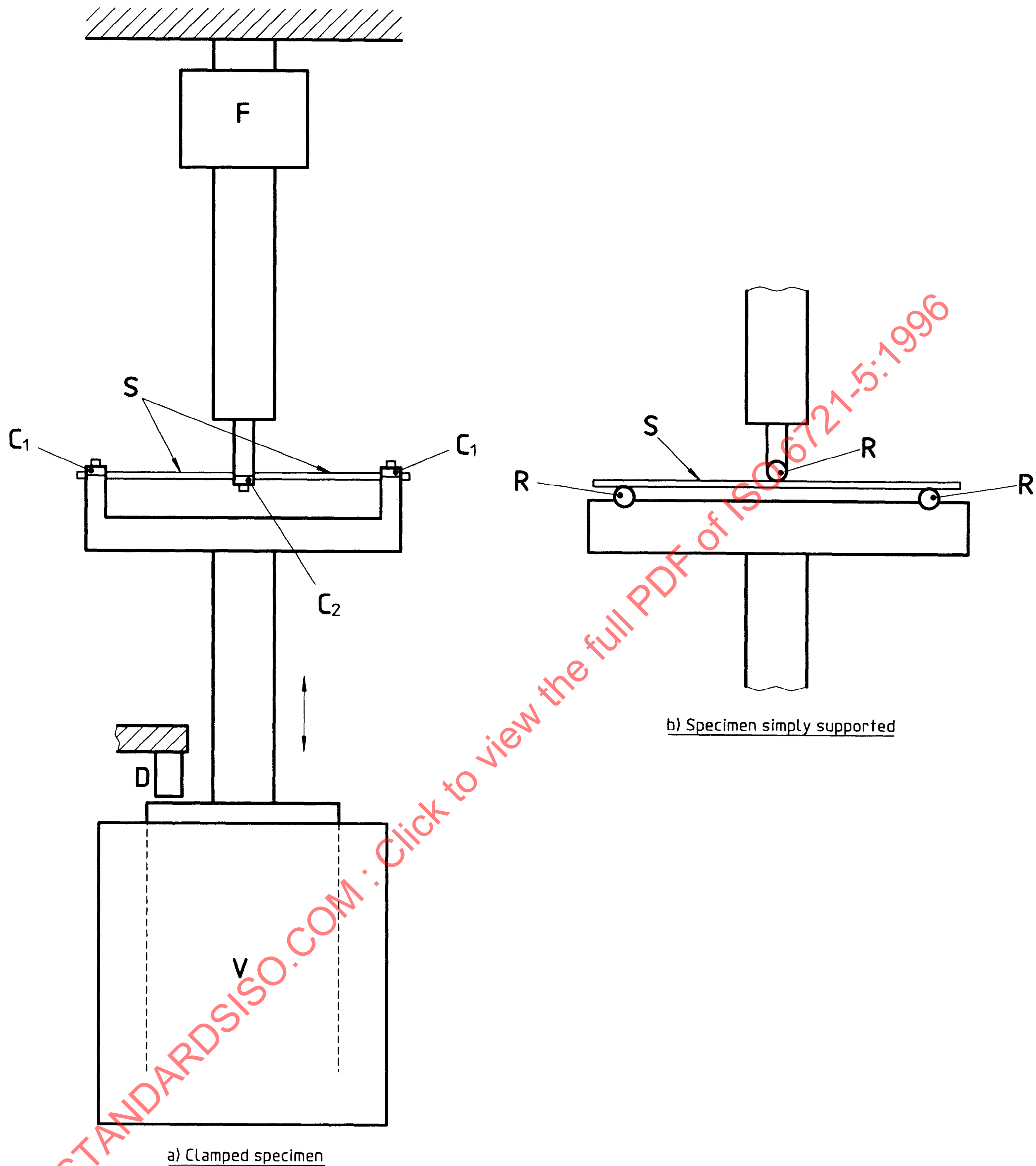

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Key:

C_1, C_2	Clamps	R	Rollers
D	Displacement transducer	S	Test specimen
F	Force transducer	V	Vibrator

Figure 1 — Schematic diagrams of suitable loading assemblies for determining dynamic moduli under flexure