INTERNATIONAL STANDARD

ISO 18437-5

First edition
2011-04-15

Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials —

Part 5: Poisson ratio based on comparison between measurements and finite element analysis

Vibrations et chocs mécaniques — Caractérisation des propriétés mécaniques dynamiques des matériaux visco-élastiques —

Partie 5: Nombre de Poisson obtenu par comparaison entre les mesures et l'analyse par éléments finis

Reference number
ISO 18437-5:2011(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. 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.

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

ISO 18437-5 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*.

ISO 18437 consists of the following parts, under the general title *Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials*:

— *Part 2: Resonance method*

— *Part 3: Cantilever shear beam method*

— *Part 4: Dynamic stiffness method*

— *Part 5: Poisson ratio based on comparison between measurements and finite element analysis*

The following part is under preparation:

— *Part 1: Principles and guidelines*

Introduction

Visco-elastic materials are used extensively to reduce vibrations in structural systems through dissipation of energy (damping) or isolation of components and noise levels in acoustical applications through modification of reflection, transmission, or absorption of acoustic energy. It is often required to have specific dynamic mechanical properties in order for such materials to function in an optimum manner. Energy dissipation is due to interactions on the molecular scale and can be measured in terms of the lag between stress and strain in the material. The dynamic mechanical properties, such as Young modulus, loss factor and Poisson ratio, of most visco-elastic materials depend on frequency, temperature, pre-strain and strain amplitude. The choice of a specific material for a given application determines the system performance. The goal of this part of ISO 18437 is to provide brief descriptions of several methods, the details in construction of each apparatus, measurement range, and the limitations of each apparatus. This part of ISO 18437 applies to the linear behaviour observed at small strain amplitudes.

Mechanical vibration and shock — Characterization of the dynamic mechanical properties of visco-elastic materials —

Part 5:
Poisson ratio based on comparison between measurements and finite element analysis

1 Scope

This part of ISO 18437 specifies two methods for estimating Poisson ratio or/and elastic modulus for isotropic visco-elastic or porous-elastic materials for use in linear finite element method (FEM) computer programs or other numerical approaches to vibrational or acoustic problems in visco-elastic structures of complicated geometry. The method is based on comparison between measurements of force-deflection or stiffness characteristics for disc-shaped specimens, with bonded boundary conditions at both ends, and FEM calculations of those conditions as a function of Poisson ratio. The choice of the single-sample or two-sample measurement method depends on whether the Poisson ratio is to be determined alone or together with the elastic modulus. Sometimes these materials are considered to be incompressible and behave non-linearly especially in large static deformations. Many commercial codes are available to solve such problems. This is not the case in this part of ISO 18437, where only small deformations observed in typical vibration problems are considered and, hence, linear FEM codes are adequate and more convenient.

For the purposes of this part of ISO 18437, and within the framework of ISO/TC 108, the term dynamic mechanical properties refers to the determination of the fundamental elastic properties, e.g. the complex Young modulus and Poisson ratio, as a function of temperature and frequency.

This part of ISO 18437 is applicable to resilient materials that are used in vibration isolators in order to reduce:

a) transmission of audio frequency vibrations to a structure, e.g. radiating fluid-borne sound (airborne, structure-borne, or other);

b) transmission of low-frequency vibrations which can, for example, act upon humans or cause damage to structures or equipment when the vibration is too severe.

The data obtained with the measurement methods that are outlined in this part of ISO 18437 and further detailed in ISO 18437-2 to ISO 18437-4 can be used for:

— design of efficient vibration isolators;

— selection of an optimum resilient material for a given design;

— theoretical computation of the transfer of vibrations through isolators;

— information during product development;

— product information provided by manufacturers and suppliers;

— quality control.

2 Normative references

The following referenced documents are indispensable for the application 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.

ISO 472, *Plastics — Vocabulary*

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 4664-1, *Rubber, vulcanized or thermoplastic — Determination of dynamic properties — Part 1: General guidance*

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

ISO 10846-1, *Acoustics and vibration — Laboratory measurement of vibro-acoustic transfer properties of resilient elements — Part 1: Principles and guidelines*

ISO 23529, *Rubber — General procedures for preparing and conditioning test pieces for physical test methods*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 472, ISO 2041, ISO 4664-1, ISO 6721-1, ISO 10846-1, and ISO 23529 and the following apply.

3.1
dynamic mechanical properties
fundamental elastic properties of a visco-elastic material, i.e. elastic modulus, shear modulus, bulk modulus and loss factor

3.2
resilient material
visco-elastic material intended to reduce the transmission of vibration, shock or noise

3.3
Young modulus
quotient of normal stress (tensile or compressive) to resulting normal strain or fractional change in length for a long specimen of resilient material

NOTE 1 The Young modulus is expressed in pascals.

NOTE 2 The Young modulus for visco-elastic materials which are isotropic is a complex quantity with symbol E^*, having a real part E' and an imaginary part E''.

NOTE 3 Physically, the real component of the Young modulus is related to the stored mechanical energy. The imaginary component is a measure of mechanical energy loss.

3.4
loss factor
ratio of the imaginary part of the Young modulus of a material to the real part of the Young modulus (the tangent of the argument of the complex Young modulus)

NOTE When there is energy loss in a material, the strain lags the stress by a phase angle, δ. The loss factor is equal to tan δ.

[ISO 18437-2, 3.2]

3.5
linearity
property of the dynamic behaviour of a resilient material if it satisfies the principle of superposition

NOTE 1 The principle of superposition can be stated as follows: if an input $x_1(t)$ produces an output $y_1(t)$ and in a separate test an input $x_2(t)$ produces an output $y_2(t)$, superposition holds if the input $\alpha x_1(t) + \beta x_2(t)$ produces the output $\alpha y_1(t) + \beta y_2(t)$. This holds for all values of α, β and $x_1(t)$, $x_2(t)$; α and β are arbitrary constants.

NOTE 2 In practice the above test for linearity is impractical and measuring the dynamic modulus for a range of input levels does a limited check of linearity. For a specific preload, if the dynamic transfer modulus is nominally invariant, the system measurement can be considered linear. In effect this procedure checks for a proportional relationship between the response and the excitation.

[ISO 18437-2, 3.7]

3.6
Poisson ratio
ratio of transverse strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material

[ISO 17561:2002[11], 3.1.1]

3.7
shape factor
ratio of the area of one loaded surface to the total force-free area in a sample for compression or tension test with bonded ends

4 Background and measurement principles

It is very difficult for numerical analysts to select the Poisson ratio properly in linear FEM analysis. The reason is that the Poisson ratio of visco-elastic materials, which is known to be close to 0,5, is rarely provided by the material manufacturers while the computation results are extremely sensitive to the Poisson ratio at values neighbouring 0,5. This part of ISO 18437 uses a quasi-static method for determining the Poisson ratio of a visco-elastic material or a porous-elastic material. The method is based on the relationship between the compressional stiffness, Young modulus, Poisson ratio, and shape factor obtained from axisymmetrical finite element calculations on a disc-shaped sample under static compression. The relationship accounts for the fact that the disc sample bulges sideways when compressed between two rigid plates on which it is bonded. A compression test is used to measure the stiffness of the sample.

The conditions for the validity of the estimation methods are:

a) linearity of the vibrational behaviour of the isolator;

NOTE 1 This includes elastic elements with non-linear static load-deflection characteristics where the elements show approximate linearity in vibration behaviour at a given static preload.

b) interfaces of the vibration isolator with the adjacent source and receiver structures can be considered as surface contacts;

c) no interaction between the isolator and the surrounding fluid (usually air) medium.

NOTE 2 This condition is typically fulfilled at frequencies less than 100 Hz for isolators made from open-cell porous-elastic materials (e.g. foams).

The Poisson ratio may also be determined by measuring other elastic constants such as complex bulk and shear modulus[7]. However, experimental difficulties may exist. Alternatively, a direct measurement of Poisson ratio may be possible using a laser vibrometer to measure the lateral displacement.

5 Single-sample measurement method[8]

5.1 Introduction

In this method it is assumed that the Young modulus for the material of interest is determined using other techniques, such as those specified in ISO 18437-2 to ISO 18437-4. The key idea and practice of this method is simply to prepare a chart of dimensionless stiffness versus Poisson ratio for a disc-shaped specimen by FEM computations, to measure the stiffness from an excitation test using a test rig and measurement equipment such as those in ISO 18437-4, and to select a value of Poisson ratio from the chart corresponding to the measured stiffness. In this method, the size of the sample is not specified, but a large shape factor is required.

5.2 Basic theory

Let a circular cylindrical visco-elastic or porous-elastic specimen of thickness, T, cross-sectional area, $A = \pi D^2/4$, and Young modulus, E, with bonded boundary conditions at both ends, as shown in Figure 1, be subject to an axial load, F, and for which a corresponding deflection, Δ, occurs. Then, a factor defined by

$$R = \frac{FT}{AE\Delta} \tag{1}$$

that may be called dimensionless stiffness, is known to be ideally 1,0 for thick specimens. Numerical computations for three sample specimens of different geometric shapes, but of one given material in Figure 2[2] show that the factor, R, depends on the Poisson ratio, ν, and on the shape factor as a parameter. For a disc-shaped sample the shape factor, S, is given by

$$S = \frac{D}{4T} \tag{2}$$

The ordinate in Figure 2 has been taken as the numerical dimensionless factor, R, divided by the theoretical correction factor, R_0[9]

$$R_0 = 1 + 2S^2 \tag{3}$$

for the purpose of comparison. As expected, it can be seen that the dependence of the factor, R, on the Poisson ratio, ν, is negligible for the two thick specimens of small shape factor, but becomes significant for the third specimen of a large shape factor. Therefore, by plotting stiffness factor, R, versus Poisson ratio, ν, from FEM computations for a specimen of large shape factor and measuring the stiffness factor, R, in Equation (1) from a dynamic test at a frequency of interest for a specimen with the same shape factor as in the plot, the Poisson ratio can be estimated as shown in Figure 3.

5.3 Specimen geometry and frequency range

As shown in Figure 2, the sensitivity of the dimensionless stiffness, R, to the Poisson ratio becomes higher as the shape factor value increases. Therefore, the shape factor shall be 2,0 at minimum. Although the values of $R(\nu)$ in Figures 2 and 3 are obtained from static FEM computations, in practice the value of $R(\nu)$ can be considered to be frequency dependent because the Young modulus input into the FEM codes can be given as a frequency-dependent parameter. Therefore, the useful frequency range in this part of ISO 18437 is determined by that of the Young modulus provided. Another factor relevant to the useful frequency range is the natural frequency of the specimen used for measurement of the dimensionless stiffness, R. Since the specimen is assumed to be a massless spring, the highest frequency, f_{max}, for such an assumption shall be less than about one-fifth of the first natural frequency, f_1, of a rod in longitudinal vibration with clamped boundary conditions at both ends, which is given by

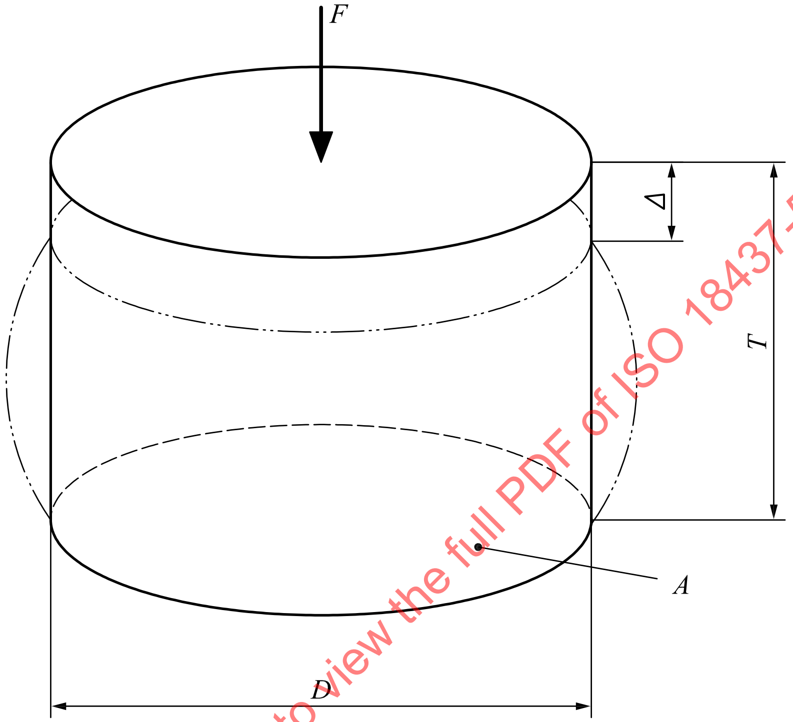
$$f_{\text{max}} = 0{,}2 f_1 = 0{,}2 \times \frac{1}{2T}\sqrt{\frac{E}{\rho}} \tag{4}$$

where

E is the Young modulus;

T is the thickness of the specimen;

ρ is the density of the material.



Key

A cross-sectional area

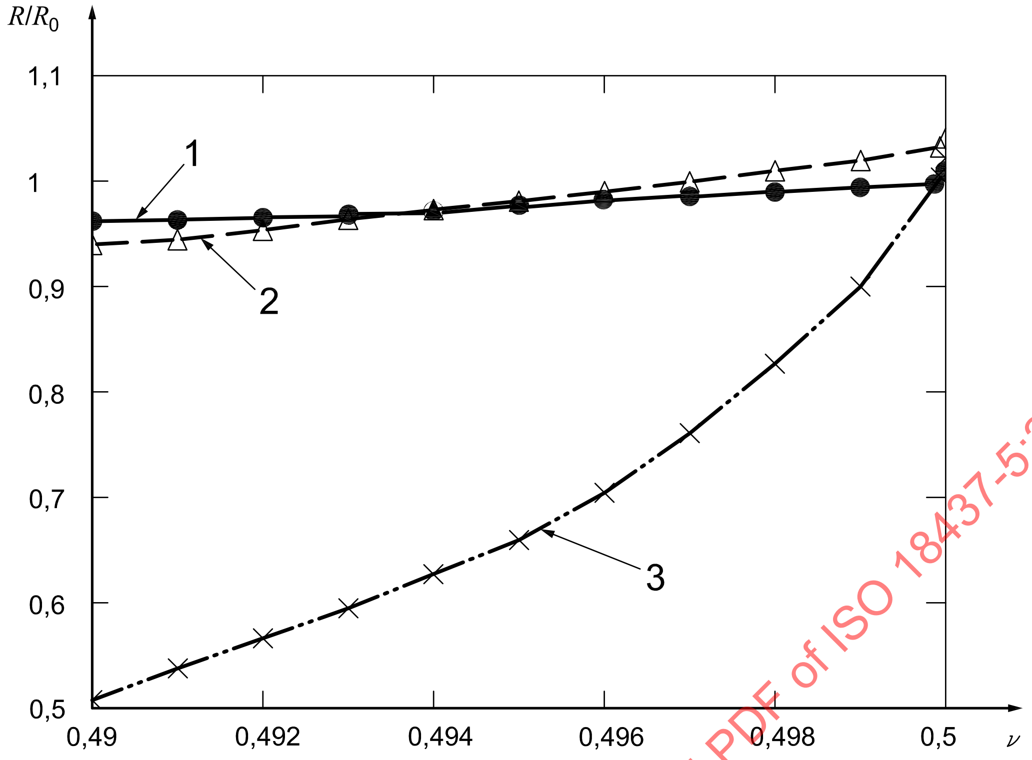
D diameter

Δ deflection

F axial force

T thickness

Figure 1 — A solid circular cylindrical specimen



Key

R numerical dimensionless stiffness

R_0 theoretical dimensionless stiffness

S shape factor

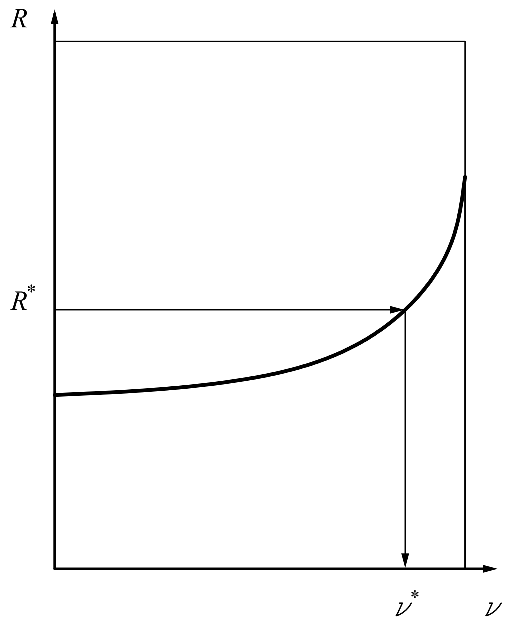
ν Poisson ratio

1 $S = 0{,}304$

2 $S = 0{,}770$

3 $S = 2{,}591$

Figure 2 — Example of the relationship between the ratio of numerical dimensionless stiffness to theoretical dimensionless stiffness, R/R_0, and Poisson ratio, ν, by FEM analyses on three specimens of different shape factors[2]



Key

R numerical dimensionless stiffness

ν Poisson ratio

Figure 3 — Plot of dimensionless stiffness versus Poisson ratio, $R(\nu)$, by FEM computations to obtain Poisson ratio, ν^*, from measurement of factor, R^*

5.4 Stiffness measurement

The dimensionless stiffness defined in Equation (1), as a function of angular frequency, $R(\omega)$, can be obtained either by directly measuring the dynamic stiffness, ratio of force to deformation $F(\omega)/\Delta(\omega)$, from a set-up as shown in Figure 4 a) or indirectly from the vibration transmissibility using a set-up consisting of the specimen and a lumped mass as shown in Figure 4 b)[8] and simply dividing by the nominal stiffness AE/T.

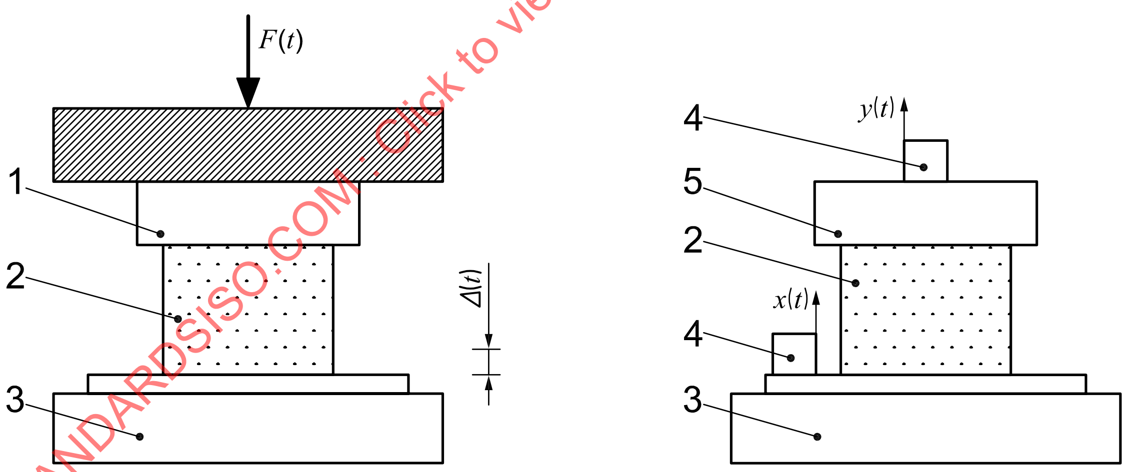
Because the dynamic stiffness is often amplitude dependent[6] and control of the deformation amplitude in the transmissibility measurement set-up is rather difficult, direct measurement of the dynamic stiffness is recommended. The experimental set-up and procedure used here are almost the same as those in ISO 18437-4 for measuring the Young modulus by the dynamic stiffness approach. Most of the contents of ISO 18437-4 are applicable for the stiffness measurement in this part of ISO 18437.

5.5 Data acquisition

Typically the driver is excited with a random signal; the two-channel spectrum analyser acquires the data and performs a fast Fourier transform (FFT) analysis and averaging. The averaging process shall be repeated at least 32 times to improve the coherence. Coherence shall be greater than 0,95. The data contain information concerning the stiffness of the assembly and wave effects in the test specimen. The mass of the mounting block and sample length shall be chosen so that the first resonance of the mass spring system is clearly well above the measurement range. The direct method shown in Figure 4 a) is the preferred method as mentioned above. In that case the factor, R, is given by

$$R(\omega) = \frac{F(\omega)T}{\Delta(\omega)AE} \tag{5}$$

where T, A, and E are thickness, cross-sectional area and Young modulus of the specimen, respectively.



a) Set-up for dynamic stiffness measurement

b) Set-up for transmissibility measurement

Key

1 force transducer
2 specimen
3 vibration exciter
4 vibration transducer
5 lumped mass

Figure 4 — Examples of test arrangements for direct and indirect measurement of dynamic stiffness

6 Two-sample measurement method[5]

6.1 Introduction

In this method a compression test is used to measure the stiffness of two disc-shaped samples of different large shape factors. The measured stiffness of the two samples together with the known polynomial FEM relationship between the compression stiffness, Poisson ratio and the shape factor lead to a system of two equations and two unknowns. The solution of the system yields the required Poisson ratio for the material and also the Young modulus.

6.2 Basic theory

For a long slender rod, whose shape factor is $S < 0{,}025$, the static compression stiffness is virtually unaffected by either the Poisson ratio or the boundary conditions and the shape factor. Thus the Young modulus, E, is related to the one dimensional static compression stiffness, K_0, as follows:

$$E = \frac{K_0 T}{A} \tag{6}$$

where A is the cross-sectional area and T the length or thickness of the specimen.

When the specimen is short, typically $S > 0{,}025$, the Poisson ratio, boundary conditions and shape factor greatly affect the compression stiffness resulting in a value for the static compression stiffness, $K_m(0)$, at $\omega = 0$. Based on the relationship between the Young modulus and stiffness in the ideal case for a long specimen given in Equation (6), an apparent Young modulus, E_a, for the short specimen with large shape factors can be defined as follows:

$$E_a = \frac{K_m(0) T}{A} \tag{7}$$

Combining Equations (6) and (7) yields that the ratio of apparent Young modulus to the true Young modulus is equal to the ratio of stiffness, i.e. normalized stiffness, as follows:

$$\frac{E_a}{E} = \frac{K_m(0)}{K_0} \tag{8}$$

Since, for large shape factors, the fixed boundary conditions cause the sample to bulge sideways significantly, the modulus or stiffness ratio in Equation (8) is highly sensitive to the Poisson ratio. Thus, an analysis of the variation of this modulus ratio as a function of Poisson ratio and shape factor using the FEM can provide a measure of the normalized stiffness. A typical FEM result on the stiffness ratio versus shape factor with the Poisson ratio as a parameter is shown in Figure 5.

The results in Figure 5 can be easily transformed into the stiffness ratio versus the Poisson ratio with the shape factor as a parameter and subsequently represented in the form of a polynomial of order, n, in terms of the Poisson ratio, ν, namely

$$P(S,\nu) \equiv \frac{K_m(0)}{K_0} = 1 + \sum_{i=1}^{n} c_i(S)\nu^i \tag{9}$$

where the quasi-static approximation, $K_m(0) = K_m(\omega)$, is valid for measurements well below the first resonance of the sample.

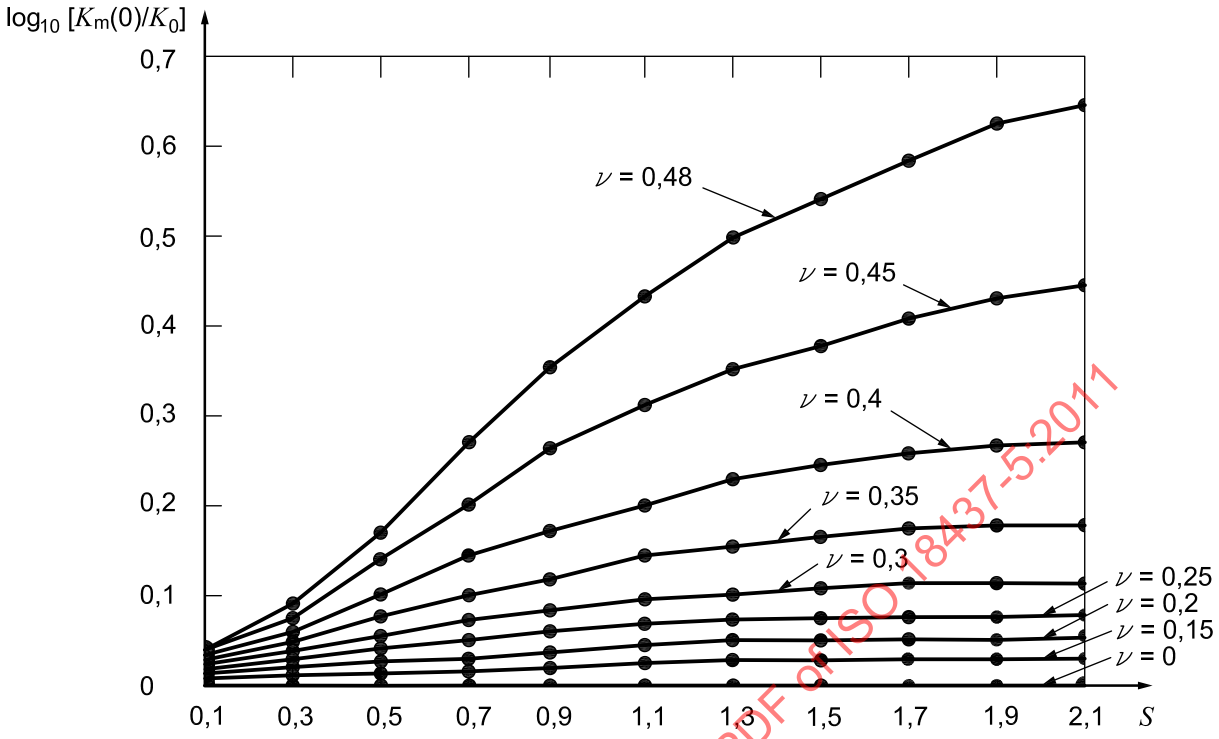


Figure 5 — Example of variations of the normalized static compression stiffness as a function of the shape factor and Poisson ratio

6.3 Determining Poisson ratio

For two samples of the same material, the Young modulus is the same. That is, combining Equations (8) and (9) states that the ratio defined in Equation (10) is independent of the shape factor, the Poisson ratio, and the Young modulus.

$$\frac{E_\mathrm{a}(S_1,\omega)}{P(S_1,v)} = \frac{E_\mathrm{a}(S_2,\omega)}{P(S_2,v)} \tag{10}$$

where the measured apparent Young modulus is complex and is a function of frequency. With two apparent Young modulus measurements for specimens with two shape factors provided, this equation has only one admissible root, which is the Poisson ratio of the sample. The admissible root shall be positive, real and a realistic value for Poisson ratio.

Once the Poisson ratio is determined, the true Young modulus can be obtained using either the shape factor S_1 or S_2 from the ratio of the apparent Young modulus to the polynomial form as follows:

$$E(\omega) = \frac{E_\mathrm{a}(S,\omega)}{P(S,v)} \tag{11}$$

6.4 Specimen geometry and frequency range

6.4.1 General

Although many shape factors can be chosen, in this part of ISO 18437, two shape factors shall be used, namely $S_1 = 0{,}651\,9$ and $S_2 = 0{,}194\,6$. For these two samples, the coefficients of Equation (9), c_i, $i = 1, 2 \ldots 8$ for S_1 and S_2, are given in Table 1. The frequency dependence of the measurements is valid for frequencies below 20 % of the first resonance of the sample as shown in Equation (4).

Table 1 — Polynomial coefficients for Equation (9)

c_i	i							
	1	2	3	4	5	6	7	8
for S_1	−0,036 853	3,187 4	−36,020	335,46	−1 647,6	4 544,6	−6 551,1	3 915,3
for S_2	−0,002 041 4	0,508 97	−1,876 0	17,548	−82,541	220,67	−306,88	176,33

6.4.2 Data acquisition

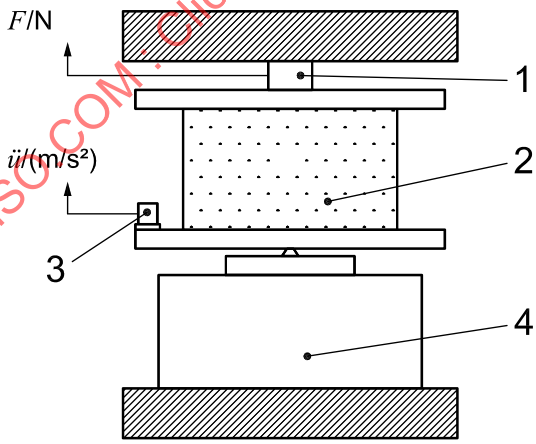
Data acquisition is similar to the one sample method except data are acquired for two samples. Typically the driver is excited with a random signal; the two-channel spectrum analyser acquires the data and performs an FFT analysis and averaging. The averaging process shall be repeated at least 32 times to improve the coherence. Coherence shall be greater than 0,95. The data contain information concerning the stiffness of the assembly and wave effects in the test specimen. The mass of the mounting block and sample length shall be chosen so that the first resonance of the mass spring system is clearly above the measurement range. Using the direct method shown in Figure 6, the apparent Young modulus, E_a, is given by

$$E_a(\omega) = \frac{F(\omega)T}{\Delta(\omega)A} \quad (12)$$

where the two measurements provide the apparent Young moduli, $E_a(S_1, \omega)$ and $E_a(S_2, \omega)$.

7 Test equipment

In the direct method rigid terminations are required. A typical test arrangement is shown in Figure 6.



Key

1 force transducer
2 specimen
3 accelerometer
4 vibration exciter

F force
$\ddot{u}$ acceleration

Figure 6 — Schematic of test set-up