INTERNATIONAL

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Standard Test Methods for Nondestructive Evaluation of the Stiffness of Wood and Wood-Based Materials Using Transverse Vibration or Stress Wave Propagation[1]

This standard is issued under the fixed designation D6874; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Nondestructive testing methods are used to determine the physical and mechanical properties of wood and wood-based materials. These test methods help ensure structural performance of products manufactured from a variety of wood species and quality levels of raw materials. These test methods also assist in evaluating the influence of environmental conditions on product performance.

Dynamic test methods based on the transverse vibration of a simply or freely supported beam, or the propagation of a longitudinal stress wave are methods used to nondestructively evaluate wood-based materials. These methods yield results comparable to traditional static test methods, permitting standardization of results, interchange and correlation of data, and establishment of a cumulative body of information on wood species and products of the world.

1. Scope

1.1 These test methods cover the non-destructive determination of the following dynamic properties of wood and wood-based materials from measuring the fundamental frequency of vibration:

1.1.1 Flexural (see Refs **(1-3)**)[2] stiffness and apparent modulus of elasticity (E_{tv}) properties using simply or freely supported beam transverse vibration in the vertical direction, and

1.1.2 Axial stiffness and apparent longitudinal modulus of elasticity (E_{sw}) using stress wave propagation time in the longitudinal direction.

1.2 The test methods can be used for a broad range of wood-based materials and products ranging from logs, timbers, lumber, and engineered wood products.

1.2.1 The two flexural methods can be applied to flexural products such as glulam beams and I-joists.

1.2.2 The longitudinal stress wave methods are limited to solid wood and homogeneous grade glulam (for example, columns but not products with distinct subcomponents such as wood I-joists).

1.3 The standard recognizes three implementation classes for each of these test methods.

1.3.1 *Class I*—Defines the fundamental method to achieve the highest degree of repeatability and reproducibility that can be achieved under laboratory conditions.

NOTE 1—Testing should follow Class I methods to develop training and validation data sets for method conversion models (see Annex A2).

1.3.2 *Class II*—Method with permitted modifications to the Class I method that can be used to address practical issues found in the field, and where practical deviations from the Class I protocol are known and their effects can be accounted.

NOTE 2—Practical deviations include, for example, environmental and test boundary conditions. Class II methods allow for corrections to test results to account for quantifiable effect such as machine frame deflections.

1.3.3 *Class III*—Method permitting the broadest range of application, with permitted modifications to suit a wider range of practical needs with an emphasis on repeatability.

NOTE 3—Online testing machines implemented to grade/sort lumber may be treated as Class III.

1.4 The standard provides guidance for developing a model for estimating a non-destructive test method result (for example, static modulus of elasticity obtained in accordance with Test Methods D198) from another non-destructive test method result (for example, dynamic longitudinal modulus of elasticity from measurement of longitudinal stress wave propagation time).

[1] These test methods are under the jurisdiction of ASTM Committee D07 on Wood and is the direct responsibility of Subcommittee D07.01 on Fundamental Test Methods and Properties.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

1.4.1 The standard covers only models developed from test data obtained directly from non-destructively testing a representative sample using one test method, and retesting the same sample following a second test method.

1.4.2 Results used for model development shall not be estimated from a model.

1.5 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D9 Terminology Relating to Wood and Wood-Based Products

D198 Test Methods of Static Tests of Lumber in Structural Sizes

D1990 Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens

D2395 Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials

D2915 Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products

D3043 Test Methods for Structural Panels in Flexure

D4442 Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials

D4444 Test Method for Laboratory Standardization and Calibration of Hand-Held Moisture Meters

D4761 Test Methods for Mechanical Properties of Lumber and Wood-Based Structural Materials

D7438 Practice for Field Calibration and Application of Hand-Held Moisture Meters

E4 Practices for Force Calibration and Verification of Testing Machines

E2655 Guide for Reporting Uncertainty of Test Results and Use of the Term Measurement Uncertainty in ASTM Test Methods

2.2 *ISO Standards:*[4]

ISO 7626/1 Mechanical vibration and shock—Experimental determination of mechanical mobility—Part 1: Basic terms and definitions, and transducer specifications

ISO 7625/5 Vibration and shock—Experimental determination of mechanical mobility—Part 5: Measurements using impact excitation with an exciter which is not attached to the structure

3. Terminology

3.1 *Definitions*—See Terminology D9 and Test Methods D198.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration, v*—the determination of the relationship between the response of a standardized instrumentation to properties determined by a standard method of a reference material in order to obtain comparable results between different instruments.

3.2.2 *fundamental mode of vibration, n*—the simplest mode of vibration for the given support condition.

3.2.2.1 *Discussion*—For a simply supported beam, the fundamental mode has the mode shape with a half-sine wave form (see Fig. 1).

3.2.2.2 *Discussion*—For a freely supported beam, the fundamental mode has the mode shape shown in Fig. 2.

3.2.3 *longitudinal stress wave, n*—the wave induced in a specimen by the transmission and attenuation of speed-of-audible sound generated by an excitation in the specimen's longitudinal direction.

3.2.3.1 *Discussion*—Resonant frequency (Fig. 3) is the frequency of the stress wave that reflects off the ends of the specimen following an end impact. The frequency may be determined from time-signal data collected by a single accelerometer, or by a microphone detecting sound waves emitted by the specimen following the impact. Higher frequencies will be present in the signal. Therefore, the signal will need to be analyzed to extract the fundamental frequency.

3.2.3.2 *Discussion*—Time of flight (Fig. 4) is the time required for stress wave to travel a known distance through the specimen. This method is excluded from this standard. Because

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

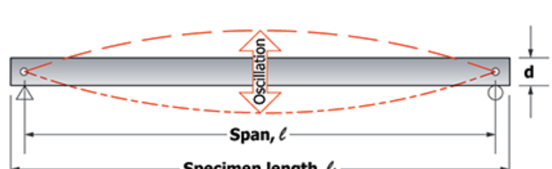

FIG. 1 Mode Shape of Simply Supported Beam Under Transverse Vibration in the Fundamental Mode

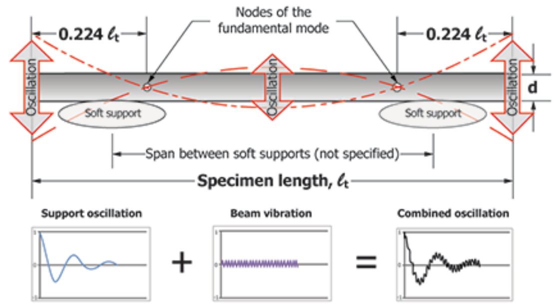

FIG. 2 Mode Shape of Freely Supported Beam Under Transverse Vibration in the Fundamental Mode

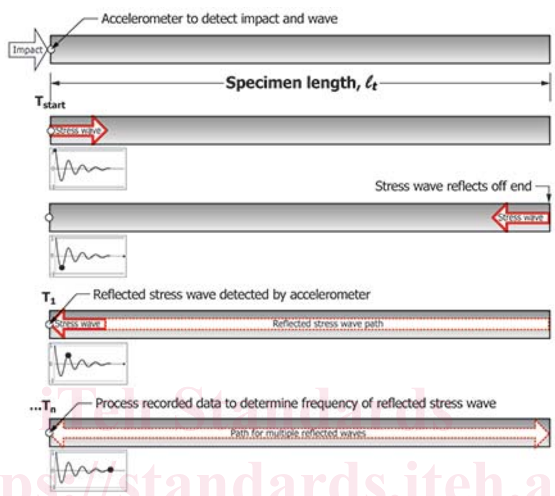

FIG. 3 Stress Wave Transmission in a Specimen (Resonant Frequency)

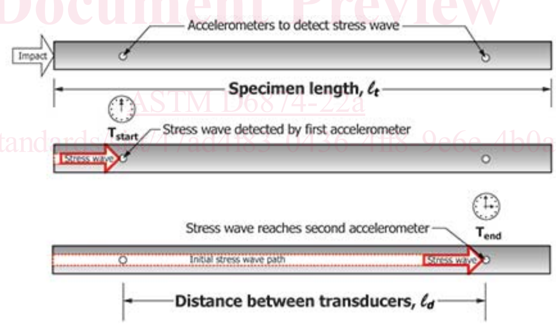

FIG. 4 Stress Wave Transmission in a Specimen (Time of Flight)

there are many frequencies excited in this manner, the signal needs to be analyzed to find the same wave that passes the first and second transducers. This is further complicated by the fact that higher frequencies attenuate faster than lower frequencies, and that these may vary depending on the specimen size and test configuration.

3.2.4 *modal analysis, v*—the process of determining the natural frequencies, modal damping ratios, and mode shapes of an object such as a beam for the vibration modes in the frequency range of interest from the Frequency Response Function (see Appendix X3).

3.2.5 *modal testing, v*—measurement of the Frequency Response Function (see Appendix X3).

3.2.6 *mode shape, n*—pattern of movement (that is, dynamic displacement, velocity, or acceleration) of an object for a vibration mode.

3.2.7 *oscillation, n*—the periodic movement of the specimen about a central position that includes both the rigid movement and the vibration of the specimen.

3.2.8 *standardization, v*—the determination of the response of the instrumentation to a reference material to demonstrate consistency of results from instruments of the same type.

3.2.9 *training test sample, n*—a test sample that provides results for establishing the statistical model to convert from one non-destructive test method to another non-destructive test method.

3.2.10 *transverse vibration, n*—the oscillation of a specimen in flexure that results from causing an initial displacement of the specimen at its mid-span or another other means of exciting the fundamental mode of vibration.

3.2.11 *validation test sample, n*—a test sample separate from the training test sample that provides results for checking the model's ability to accurately represent the relationship between the two non-destructive test methods established by the training test sample.

3.2.12 *vibration, n*—the component of the specimen's oscillation that results in an elastic strain in the specimen.

3.2.12.1 *Discussion*—The oscillation that remains after the periodic rigid body motion is removed.

3.2.13 *vibration mode, n*—the vibration behavior of a specimen that is characterized by its natural frequency, modal damping, and mode shape.

3.2.13.1 *Discussion*—The free vibration of a continuous object such as a beam or a log contains a summation of an infinite number of vibration modes. The free vibration from which the modulus of elasticity is computed shall not include any periodic rigid body motion, or oscillating motion that does not result in any elastic strain in the specimen.

4. Summary of Test Methods

4.1 Two dynamic modulus of elasticity methods are covered:

4.1.1 *Transverse Vibration Methods*—The specimen is deflected at its mid-span and allowed to oscillate in a transverse bending mode. Observations of the frequency of oscillation are used to calculate a flexural stiffness or apparent modulus of elasticity.

4.1.2 *Longitudinal Stress Wave Method*—A longitudinal stress wave is induced by impacting the end of a specimen. Indirect observation of the transmission time from measuring resonant frequency is used to calculate an axial stiffness or apparent longitudinal modulus of elasticity.

NOTE 4—The dynamic modulus of elasticity is determined when the specimen's stress state is changing. The static modulus of elasticity is the traditional method where the modulus of elasticity is determined at two different stress states where the stresses are not changing or changing at a slow rate as defined in the static test method. Examples of static test methods for wood and wood-based products are standard Test Methods D198, D4761, and D3043.

5. Significance and Use

5.1 The dynamic modulus of elasticity provided by these test methods is a fundamental property for the configuration tested.

5.1.1 The rapidity and ease of application of these test methods facilitate their use as a substitute for static measurements.

5.1.2 Dynamic modulus of elasticity is often used for surveys, for segregation of lumber for test purposes, for quality assessment of engineered wood products, and to provide indication of environmental or processing effect.

5.2 The modulus of elasticity, whether measured statically or dynamically, is often a useful predictor variable to suggest or explain property relationships.

5.3 Results from these test methods can be related to other measurements of modulus of elasticity, such as static methods (see Annex A1 and Appendix X4).

5.4 These methods use calculations that assume specimens are prismatic in cross-section and are uniform in modulus of elasticity and density.

5.4.1 As a result of the above assumptions, the obtained values of modulus of elasticity are dependent on how the specimen is stressed (see Commentary).

5.4.2 Transverse vibration and longitudinal stress wave modulus of elasticity are correlated but not necessarily equal.

5.4.3 These methods provide a means to establish a model to predict one dynamic modulus of elasticity from another dynamic method or a static method (that is, D198, D4761, etc.).

5.4.4 The methods can also be used to estimate the Class I or Class II modulus of elasticity from the Class III method, or the Class I from the Class II method.

5.5 Testing specified to be undertaken in accordance with this Method shall include any requirements regarding the following for each Class:

5.5.1 Grades and species permitted to be combined to form the training and validation test sample.

5.5.2 Selection and positioning of manufacturing or growth characteristics to be included or permitted in the test sample.

5.5.3 Moisture content conditioning undertaken prior to testing.

5.5.4 Acceptable moisture content adjustment models.

5.5.5 Any other sampling and data adjustment requirements to obtain a representative sample of the population under consideration.

NOTE 5—Guidance or requirements from applicable product standards or specifications for representative sampling should be considered. See Annex A2.

NOTE 6—See Commentary Appendix X4 for additional information (for example, blocking parameter and blocking limits) that may need to be provided for generating a test sample suitable for developing the test method conversion model.

6. Precision and Bias

6.1 The precision and bias of these test methods have not yet been established.

TRANSVERSE VIBRATION METHODS

7. Apparatus

7.1 The testing equipment shall consist of four essential elements:

7.1.1 Support apparatus,

7.1.2 Excitation system,

7.1.3 Response and weight measurement devices, and

7.1.4 Time signal processing algorithm.

8. Test Procedure

8.1 *Standardization and Calibration*—The testing system shall be standardized and calibrated using standard reference materials. The procedures of Annex A1 shall be followed. The results of this test method are conditional upon proper standardization and appropriate choice of calibration method.

NOTE 7—It has been a practice to use aluminum bars or lumber specimens as standardization materials and also for calibration against a standard static test results.

8.2 *Excitation*—The procedures of excitation listed under each Class shall be followed. Repetitions and inter-laboratory testing are recommended to assess test procedures and to reduce the chance of bias caused by improper excitation.

8.3 *Calculation of Dynamic Modulus of Elasticity and Stiffness:*

8.3.1 *Basic Equations*—The following formulas, Eq 1 and Eq 2, shall be used to calculate apparent dynamic modulus of elasticity and bending stiffness from the measured oscillation in the fundamental mode for either the simply supported (Fig. 1) or freely supported (Fig. 2) beams:

$$E_{tv} = \frac{f^2 w \ell^3}{KIg\left(\frac{\ell_t}{\ell}\right)} \quad (1)$$

$$(EI)_{tv} = \frac{f^2 w \ell^3}{Kg\left(\frac{\ell_t}{\ell}\right)} \quad (2)$$

where:

E_{tv} = modulus of elasticity determined using transverse vibration, psi (MPa),
$(EI)_{tv}$ = bending stiffness determined using transverse vibration method, lb-in^2 (N-mm^2),
ℓ_t = specimen length, in. (mm),
ℓ = span, in. (mm) for simply-supported beams,
= ℓ_t, for freely supported beams,
w = total specimen weight, lbf (N),
f = fundamental vibration mode frequency, Hz (s^{-1}),
I = specimen moment of inertia, in^4 (mm^4); for example, $bh^3/12$, for a rectangular cross-section,
b = horizontal breadth (width), in. (mm),
d = vertical depth, in. (mm),
g = acceleration due to gravity, 386 in./s^2 (9807 mm/s^2), and
K = constant for free vibration of a beam (see Ref **(4)**)
= 2.47, if simply supported,
= 12.48, if freely supported.

9. Class I—Laboratory Use

9.1 *Apparatus*

9.1.1 *Support Apparatus:*

9.1.1.1 *Simply Supported Beams*—Vertical support is provided at the ends of the beam while rotation is unrestrained.

NOTE 8—The supporting material should be sufficiently stiff so that the vertical stiffness of the support is much greater than the flexural stiffness of the specimen. If the stiffness of the support is not sufficiently high compared to the stiffness of the specimen, the measured fundamental frequency will be affected. See Refs. **(5)** and **(6)**. Even support on carpet with a pad can affect the fundamental frequency.

(1) Reactions—The specimen shall be supported in a manner to prevent damage to the specimen at the point of contact between it and the reaction support.

NOTE 9—Dimension lumber specimens are typically light enough to enable them to be supported on knife edges or the load button of a load cell. Where flat bearing plates are required, ensure the plate does not impede free rotation of the specimen.

(2) The reactions shall be such that rotation of the specimen about the reaction due to deflection will be unrestricted.

(3) Transverse vibration that results in a large mid-span deflection (for example, when the vibration amplitude exceeds approximately half the specimen depth, *d*) shall have at least one support configured to provide unrestricted longitudinal movement of the specimen relative to the support (for example, a roller).

(4) Reaction Alignment—Provision shall be made at the reactions to allow for initial twist in the length of the specimen. If the bearing surfaces of the specimen at its reaction are not parallel to the bearing surface of the reactions, the specimen shall be shimmed or the bearing surfaces shall be permitted to rotate about an axis parallel to the span to provide adequate contact across the width of the specimen.

(5) Lateral Support—No lateral support shall be applied. Specimens unstable in this mode shall not be tested using this method.

(6) Lengthwise Positioning and Overhang of the Specimen—The specimen shall be positioned with an equal portion of the length overhanging each support. If basic equation (Eq 1) is used, then the span (ℓ) to length (ℓ_t) ratio shall equal or exceed 0.98 (for example, an overhang of 1 in. (25 mm) at each end of an 8-ft (2400-mm) long member).

NOTE 10—Excessive or unequal overhang may alter results obtained. Overhang that differs by one specimen depth (*d*, as defined in 8.3.1) or less may be neglected.

NOTE 11—When developing data for method conversion (see Annex A2), it is recommended that the span not be varied to meet the maximum overhang criteria. Doing so may introduce additional measurement errors associated with setting the test span. If possible, samples should be cut to a common length so that the test can be carried out at the same span.

9.1.1.2 *Freely Supported Beams*—The free support condition (soft supports, such as by air bags) shall provide vertical support when the specimen is at rest, and permit rotation and vertical movement when the specimen is excited and vibrating in the fundamental mode. The stiffness of the supports shall be identical and sufficiently flexible at both support points to permit the specimen to oscillate at a frequency that is less than approximately one-tenth of the fundamental vibration frequency of the specimen.

NOTE 12—The frequency of oscillation of the specimen contains the movement of the specimen relative to the fixed ground and will depend on the stiffness of the supports and the specimen. The fundamental vibration frequency of the specimen contains only movement of the specimen relative to the nodes of the fundamental mode (see Fig. 2) and is dependent on the stiffness of the specimen.

NOTE 13—In order to accurately isolate and not affect the measured vibration frequency of the specimen, the supporting material should be sufficiently flexible so that the vertical stiffness of the support is much smaller than the stiffness of the specimen. If the stiffness of the support is not sufficiently low compared to the stiffness of the specimen, the measured fundamental vibration frequency of the specimen will be affected. The support may be a spring, elastic string, elastic mat, or air bag selected or adjusted to have the desired compliance. See commentary.

(1) Reactions and Lateral Support—The specimen shall be supported in a manner as specified in 9.1.1.1*(1)* to 9.1.1.1*(5)*.

(2) Lengthwise Positioning and Overhang of the Specimen—The specimen shall be positioned such that the length of overhang at each support is approximately equal. The supports shall be positioned to minimize rigid body rotation of the specimen.

NOTE 14—The freely supported beam method is not as susceptible as the simply supported beam method to measurement errors arising from unequal overhangs. A large unequal overhang is likely to result in rigid body rotation of the specimen.

NOTE 15—Ideally, the supports should be placed at the nodes of the fundamental mode. Supports located far from the node, particularly when they are not sufficiently flexible, or at mid-length may alter the beam vibration frequency. As the supports are moved closer together, the specimen becomes susceptible to rigid body rotation (that is, downward movement at one support and upward movement at the other support) which should be avoided or minimized. Such rotation effects can be assessed by applying a downward impact at only one end and observing if significant oscillation due to rigid body rotation occurs.

9.1.2 *Excitation System*—The specimen shall be excited so as to produce a vertical oscillation in a repeatable and reproducible manner in the fundamental mode. The method of analysis is based on oscillation in this mode (Fig. 2).

NOTE 16—It is recommended to measure the time signals of the excitation.

9.1.2.1 *Manual Method*—A manual deflection and release of the specimen will provide sufficient impetus for oscillation for many products. The initial deflection shall be vertical with an effort to exclude lateral components; neither excessive impact nor prolonged contact with the specimen are recommended.

NOTE 17—For example, a manual tap on a 16-foot 2-by-12, supported flat-wise having a modulus of elasticity of 2.0×10^6 psi will result in a vertical fundamental vibration frequency of between 3 and 4 Hz in either of the two transverse vibration methods.

NOTE 18—A manual tap with a hammer instrumented with an integrated load cell is preferred.

9.1.2.2 *Mechanical Methods*—Use of a mechanical exciter to cause a deflection as noted in 9.1.2.1 is permitted. Caution shall be exercised to limit the excitation forces to avoid exciting a non-linear response.

9.1.3 *Response and Weight Measurement Devices*—Measurement of the frequency of oscillation shall be obtained by either a force transducer installed at one or both supports; or a displacement, velocity, or acceleration transducer installed at mid-span. The time signals from the transducers shall be recorded in analog or digital form that preserves the accuracy as specified in the applicable standards in 2.2.

NOTE 19—Displacement sensors are normally not used to measure the vibration signals. In practice, accelerometers, which are both cost effective and rugged, are the most common.

NOTE 20—The minimum speed and resolution of the data acquisition system, and the minimum sampling rates used must anticipate the frequency to be measured.

9.1.3.1 *Force Transducer*—Changes in the force in response to the vibration at one or both of the supports is one method used to obtain the vibration time signal. Force transducers shall be selected and calibrated to ensure accuracy in accordance with Practices E4 and shall be sufficiently stiff to not affect the fundamental frequency of the system. Test procedures shall include steps to eliminate transient force readings.

NOTE 21—If the stiffness of load transducers is not sufficiently high, it will alter the natural transverse vibration frequency of the specimen and produce erroneous results. This is issue is normally not related to the transducer calibration.

9.1.3.2 *Deflection, Velocity, or Acceleration Transducer*—Measurement of the mid-span displacement, velocity, or acceleration in response to the initial displacement are alternative methods to obtain the vibration time signal. Displacement, velocity or acceleration transducers shall meet the requirements of ISO 7626/1.

9.1.4 *Time Signal Processing Algorithm*—A procedure implemented manually, or in hardware and software for processing the time signals to obtain the fundamental natural frequency shall be established.

9.1.4.1 The standardization procedure shall include the time signal processing algorithm and all calibrated transducers.

9.1.4.2 Changes to the time signal processing algorithm or any of the transducers shall be subject to the standardization procedures.

9.1.5 *Determining the Fundamental Mode*—Document the procedures used to identify the frequency associated with the fundamental vertical oscillation mode, and to ensure that the data acquired is only related to the fundamental vertical mode (Fig. 1).

NOTE 22—Appendix X3 and Ref **(7)** provide the procedure to determine the mode shape.

NOTE 23—When validated for a specific flexural stiffness and span-to-depth ratio, a short delay before acquiring the data may also be used to ensure the data acquired is only related to the fundamental vertical mode.

9.2 *Test Specimen*

9.2.1 Specimens shall be solid and prismatic (uniform in cross-section area along the length). Deviations in shape and uniformity in dimension from end-to-end and side-to-side incidental to sampling, such as wane included in a lumber grade description, shall be noted as part of the sample or specimen description.

9.2.2 *Span to Depth Ratio*—Specimens shall be tested at the permitted span-to-depth ratio.

9.2.2.1 Except as permitted in 9.2.2.2, the span-to-depth ratio shall be greater than or equal to 20.

9.2.2.2 Where the span-to-depth is less than 20, modal analysis shall be conducted on tests on a representative sample to show that the procedures used will determine the vibration frequency corresponding to the fundamental frequency.

9.2.3 *Specimen Dimensions*—Specimen dimensions (for example, diameter, width, depth, length, etc.) shall be measured to at least three significant figures. Sufficient measurements of the cross-section shall be made to establish the number of measurements needed to determine the average dimensions along the length.

NOTE 24—The cross-section size of Surfaced Dry (S-Dry) dimension lumber can typically be established by measuring the cross-section at one location along the length.

9.2.4 *Moisture Content*—Moisture content (MC) of specimens shall be measured in accordance with Test Methods D4442 or Practice D7438, or both. Specific reference to the current moisture status of the specimens shall be made; for example, equilibrated, recently kiln dried containing gradients, air dried, packaged specimens of unknown drying history, and so forth. Identification of MC gradients caused by drying or surface wetting is recommended.

NOTE 25—MC gradients within a piece may affect the dynamic modulus of elasticity (see X1.1.23).

9.2.5 *Specimen Weight*—The specimen weight used in Eq 1 or Eq 2 shall be determined to at least 3 significant figures.

10. Class II—Field Use

10.1 *Apparatus*

10.1.1 *Support Apparatus:*

10.1.1.1 *Simply Supported Beams*—The support apparatus shall meet the requirements of 9.1.1.1.

10.1.1.2 *Lengthwise Positioning and Overhang of the Specimen*—The specimen shall be positioned such that an equal portion of the length overhangs each support. If basic equation (Eq 1) is used, then the span (ℓ) to length (ℓ_t) ratio shall equal or exceed 0.85. If other ℓ/ℓ_t ratios are used, more exacting analysis and equations shall be used; see Ref (**8**).

NOTE 26—Excessive or unequal overhang may alter results obtained. Overhang that differs by one specimen depth (*d*, as defined in 8.3.1) or less may be neglected.

10.1.1.3 *Freely Supported Beams*—The support apparatus shall meet the requirements of 9.1.1.2.

10.1.2 *Excitation System*—The excitation system shall meet the requirements of 9.1.2.

10.1.3 *Response and Weight Measurement Devices*—The response and weight measurement devices shall meet the requirements of 9.1.3.

10.1.4 *Time Signal Processing Algorithm*—The time signal processing algorithm shall meet the requirements of 9.1.4.

10.2 *Test Specimen*

10.2.1 Specimens shall be solid and prismatic (uniform in cross-section area along the length). Deviations in shape and uniformity in dimension from end-to-end and side-to-side incidental to sampling, such as wane included in a lumber grade description, shall be noted as part of the sample or specimen description.

10.2.2 *Span-to-Depth Ratio*—The span-to-depth ratio used shall meet the requirements of 9.2.2.

10.2.3 *Specimen Dimensions*—The specimen dimensions used to compute the modulus of elasticity shall be recorded.

10.2.3.1 Unless the effect of cross-section modification is a test evaluation objective, test the specimens without modifying the dimensions of the commercial cross-section.

10.2.3.2 Where the average dimensions of the sample are used, a representative sub-sample of specimens shall be selected and measured for specimen dimension in accordance with 9.2.3. The sub-sample size shall be sufficient to estimate the 95% confidence limits of each average dimension.

NOTE 27—Where the sample consists of specimens produced at different facilities or at different times, the average dimension of the sample may not be representative of the combined population. Measuring the dimensions of each specimen is recommended.

10.2.3.3 Where the average dimensions of the sample are not used, specimen dimensions shall be measured in accordance with 9.2.3.

10.2.4 *Moisture Content*—A sample representative of the moisture content of the test population shall be measured for moisture content in accordance with Test Methods D4442, Practice D7438, or both.

10.2.4.1 Where the 95% confidence interval for the average moisture content is 2% or greater, the moisture content shall be determined as specified in 9.2.4.

10.2.4.2 Where the 95% confidence interval for the average moisture content is less than 2%, it is permitted to report only the average and 95% confidence interval for the average moisture content.

10.2.5 *Specimen Weight*—The specimen weight used in Eq 1 or Eq 2 shall be determined to at least two significant figures.

NOTE 28—For the simply supported method, the specimen weight may be estimated from a force reading at one support (that is, the "half-weight"). It is recommended to verify that the test population tested in this manner provides a weight reading within the tolerance specified in 10.2.5.

11. Class III—Other Applications

11.1 *Apparatus*

11.1.1 *Support Apparatus:*

11.1.1.1 *Simply Supported Beams*—The support apparatus shall meet the requirements of 9.1.1.1.

11.1.1.2 *Lengthwise Positioning and Overhang of the Specimen*—The lengthwise positioning and overhang of the specimen shall be meet the requirements of 10.1.1.2.

11.1.1.3 *Freely Supported Beams*—The support apparatus shall meet the requirements of 9.1.1.2.

11.1.2 *Excitation System*—The excitation system shall meet the requirements of 9.1.2.

11.1.3 *Response and Weight Measurement Devices*—The response and weight measurement devices shall meet the requirements of 9.1.3.

11.1.4 *Time Signal Processing Algorithm*—The time signal processing algorithm shall meet the requirements of 9.1.4.

11.2 *Test Specimen*

11.2.1 Specimens shall meet the requirements of 10.2.1.

11.2.2 *Span-to-Depth Ratio*—The span-to-depth ratio used shall meet the requirements of 10.2.2.

11.2.3 *Specimen Dimensions*—The specimen dimensions used to compute the modulus of elasticity shall be recorded.

11.2.3.1 Where a dimension monitoring program is not in effect or is not able to provide specimen dimension information on the sample, a sample representative of the dimensions of the test population shall be measured in accordance with 9.2.3.

NOTE 29—Monitoring programs include measurements for quality assurance.

11.2.4 *Moisture Content*—The specimen moisture content shall be within the range of moisture content permitted for the protocol established in accordance with Annex A1.

11.2.4.1 Where a moisture monitoring program is not in effect or is not able to provide specimen moisture content information on the sample, a sample representative of the dimensions of the test population shall be measured in accordance with 10.2.4.

11.2.5 *Specimen Weight*—The specimen weight shall be determined as required by the protocol evaluated in accordance with Annex A1.

11.2.5.1 The accuracy of the method for estimating the specimen weight used in Eq 1 or Eq 2 shall be recorded.

11.2.5.2 The specimen weight, when measured for each specimen, shall be recorded to at least two significant figures.

STRESS WAVE METHOD

12. Apparatus

12.1 The testing equipment shall consist of three essential elements:

12.1.1 A support apparatus,

12.1.2 An excitation system, and

12.1.3 A measurement system to determine the stress wave transmission time, or a time signal processing algorithm.

13. Test Procedure

13.1 *Standardization and Calibration*—The testing system shall be standardized and calibrated using standard reference materials. The procedures of Annex A1 shall be followed. The results of this test method are conditional upon proper standardization and appropriate choice of calibration method.

NOTE 30—It has been a practice to use aluminum bars or standardization materials and, often, also for calibration against a standard static test results.

13.2 *Excitation*—The procedures of excitation listed under each Class shall be followed. Repetitions and inter-laboratory testing are recommended to assess test procedures and to reduce the chance of bias caused by improper excitation.

13.2.1 To quantify measurement uncertainty for precision and bias estimates, specific data sets shall be taken during the test sequence to allow calculation of this contribution to measurement tolerances.

13.3 *Calculation of Dynamic Modulus of Elasticity and Stiffness:*

13.3.1 The following equations, Eq 3 or Eq 4, shall be used to calculate the longitudinal modulus of elasticity and axial stiffness from the measured frequency of the reflected stress wave (Fig. 3):

$$E_{sw} = \frac{4\ell_t w f^2}{gA} \quad (3)$$

$$(EA)_{sw} = \frac{4\ell_t w f^2}{g} \quad (4)$$

where:

E_{sw} = modulus of elasticity determined using longitudinal stress wave, psi (MPa),
EA_{sw} = axial stiffness determined using longitudinal stress wave, lb (N),
ℓ_t = specimen length, in. (mm),
f = frequency of the first mode of the longitudinal vibration, s^{-1} (Hz) (see Fig. 3), and
A = cross-section area of the specimen, in.^{2} (mm^2).

14. Class I—Laboratory Use

14.1 *Apparatus*

14.1.1 *Support Apparatus:*

14.1.1.1 The support apparatus shall provide vertical support yet permit longitudinal movement.

NOTE 31—A thick elastic mat or air bag are examples of suitable supports.

(1) Lateral Support—No lateral support shall be applied. Specimens unstable in this mode shall not be tested using this method.

14.1.2 *Excitation System*—The specimen shall be excited as to produce a stress wave that propagates through the length of a specimen in a repeatable and reproducible manner (Fig. 4). The magnitude of the impact force, and the duration of contact with the specimen shall be kept to a minimum.

NOTE 32—A mechanical exciter, such as a hammer, is preferred.

14.1.3 *Measurement System*—A transducer shall be used to obtain the time-signal data of the longitudinal stress wave reflected off the ends of the specimen. Analysis of the time-signal data shall be used to determine the resonant frequency. The dynamic modulus of elasticity or dynamic axial stiffness shall be calculated in accordance with 13.3.1.

14.1.4 *Time Signal Processing Algorithm*—A procedure implemented manually, or in hardware and software for processing the time signals shall be established.

14.1.4.1 The standardization procedure shall include the time signal processing algorithm and all calibrated transducers.

14.1.4.2 Changes to the time signal processing algorithm or any of the transducers shall be subject to the standardization procedures.

14.1.5 *Determining the Resonant Frequency*—Document the procedures used to identify the frequency associated with the fundamental frequency, and to ensure that the data acquired is only related to the fundamental frequency of the longitudinal stress wave.

14.2 *Test Specimen*

14.2.1 Specimens shall be uniform along the length. Deviations in shape and uniformity in dimension from end-to-end and side-to-side incidental to sampling, such as wane included in a lumber grade description, shall be noted as part of the sample or specimen description.

14.2.2 *Specimen Dimensions*—Specimen dimensions (for example, diameter, width, depth, length, etc.) shall be measured as specified in 9.2.3.

NOTE 33—The cross-section size of Surfaced Dry (S-Dry) dimension lumber can typically be established by measuring the cross-section at one location along the length.

14.2.3 *Moisture Content*—The MC shall be determined as specified in 9.2.4.

14.2.4 *Specimen Weight*—The specimen weight used in Eq 3 or Eq 4 shall be recorded as specified in 9.2.5.

15. Class II—Field Use

15.1 *Apparatus*

15.1.1 *Support Apparatus:*

15.1.1.1 The support apparatus shall meet the requirements of 14.1.1.

15.1.2 *Excitation System*—The excitation system shall meet the requirements of 14.1.2.

15.1.3 *Measurement System*—The measurement system shall meet the requirements of 14.1.3.

15.1.4 *Determining the Resonant Frequency*—The signal processing system shall meet the requirements of 14.1.4.

15.2 *Test Specimen*

15.2.1 The characteristic specimen shape shall be as defined in the model and validated in accordance with Annex A1.

15.2.2 *Specimen Dimensions*—The specimen dimensions used to compute the modulus of elasticity shall be recorded.

15.2.2.1 Unless the effect of cross-section modification is a test evaluation objective, test the specimens without modifying the dimensions of the commercial cross-section.

15.2.2.2 Where dimensions used are the average dimensions of the sample, a representative sub-sample of specimens shall be selected and measured for specimen dimension in accordance with 14.2.2. The sub-sample size shall be sufficient to estimate the 95% confidence limits of each dimension.

NOTE 34—Where the sample consists of specimens produced at different facilities or at different times, the average dimension of the sample may not be representative and measuring the dimensions of each specimen is recommended.

15.2.2.3 Where the average dimensions of the sample are not used, specimen dimensions shall be measured in accordance with 14.2.2.

15.2.3 *Moisture Content*—The specimen MC shall be determined as specified in 9.2.4.

15.2.4 *Specimen Weight*—The specimen weight used in Eq 3 or Eq 4 shall be determined to at least two significant figures.

16. Class III—Other Applications

16.1 *Apparatus*

16.1.1 *Support Apparatus:*

16.1.1.1 The support apparatus shall meet the requirements of 14.1.1.

16.1.2 *Excitation System*—The excitation system shall meet the requirements of 14.1.2.

16.1.3 *Measurement System*—The measurement system and measured parameters shall be as defined in the protocol evaluated in accordance with Annex A1.

16.1.4 *Determining the Resonant Frequency*—The signal processing system shall meet the requirements of 14.1.4.

16.2 *Test Specimen*

16.2.1 The characteristic specimen shape shall be as defined in the model as established in accordance with Annex A1.

16.2.2 *Specimen Dimensions*—The specimen dimensions used to compute the modulus of elasticity shall be recorded.

16.2.2.1 Specimen dimensions shall be as defined in the model as established in accordance with Annex A1.

16.2.2.2 Where a nominal size is used for all specimens, a specimen dimension monitoring program shall maintain the specimen dimensions within the ranges covered by the model as established in accordance with Annex A1.

16.2.2.3 Where a specimen dimension monitoring program is not able to provide specimen dimension information on the sample, a sample representative of the dimensions of the test population shall be measured in accordance with 9.2.3.

NOTE 35—Monitoring programs include measurements for quality assurance.

16.2.3 *Moisture Content*—The specimen moisture content shall be determined as required by the protocol evaluated in accordance with Annex A1.

16.2.4 *Specimen Weight*—The specimen weight shall be determined as required by the protocol evaluated in accordance with Annex A1.

16.2.4.1 The accuracy of the method for estimating the specimen weight used in Eq 3 or Eq 4 shall be recorded.

16.2.4.2 The specimen weight, when measured for each specimen, shall be recorded to at least two significant figures.

17. Report

17.1 *General:*

17.1.1 The report shall be sufficiently complete to permit reproduction of the test, including the calibration process and steps taken to reduce sources of error.

NOTE 36—Inadequate explanation of the basis of the modulus of elasticity and stiffness measurement results in data of unknown comparability. For example, specific steps taken to specify a load cell with adequate stiffness so as to not to influence the fundamental transverse vibration frequency of the specimens tested should be noted.

17.1.2 The report shall document the traceability of transducer calibrations to nationally acceptable references.

17.1.3 The report shall contain at least the following elements:

17.1.3.1 *Equipment*—Description of the apparatus, including the manufacturer of the device, the model, and the calibration system if incorporated in the manufactured device. If mechanical excitation is employed, the mechanism shall be described along with the method of assuring adequate excitation.

17.1.3.2 *Test Setup*—Description of the specimen supports including how the transducer stiffness is considered in the support design and standardization of the test procedures, if not reported as part of 17.1.3.1; the support surfaces; and the provisions employed for support of twisted or irregular surfaces.

17.1.3.3 *Environment*—Describe the temperatures during calibration and data collection and other factors in the operating environment that may affect measurement. Note changes in these factors over the data collection period.

17.2 *Class I – Laboratory Use:*

17.2.1 *Calibration*—A description and rationale for the use of the materials for standardization and for calibration shall be provided in sufficient detail to allow for an independent assessment of the calibration.

17.2.2 *Test Data*—Present the test data using units consistent with that used for 17.2.1 and for describing the elements in 17.1.3. The data presentation shall include an estimate of the precision and bias of the data and method of estimation.

17.3 *Class II – Field Use:*

17.3.1 *Calibration*—Identify whether the *E*, *EI*, or *EA* were calculated using the fundamental formula (Eq 1-4) or the adjusted formula (see Eq A1.1). If the latter was used, describe the source of the factors k_s and z. A description and rationale for the use of the materials for standardization and for calibration shall be provided in sufficient detail to allow for an independent assessment of the calibration.

17.3.2 *Test Data*—Present the test data using units consistent with that used for 17.3.1 and for describing the elements in 17.1.3. The data presentation shall include an estimate of the precision and bias of the data and method of estimation.

17.3.3 *Data Adjustments*—All adjustments made to test data shall be fully explained, including actions taken to meet the reporting requirements of Practice D2915.

17.4 *Class III – Other Applications:*

17.4.1 *Calibration*—Identify whether the *E*, *EI*, or *EA* were calculated using the fundamental formula (Eq 1-4) or the adjusted formula (see Eq A1.1). If the latter was used, describe the source of the factors k_s and z. A description and rationale for the use of the materials for standardization and for calibration shall be provided in sufficient detail to allow for an independent assessment of the calibration.

17.4.2 *Test Data*—Present the test data using units consistent with that used for 17.4.1 and for describing the elements in 17.1.3. The data presentation shall include an estimate of the precision and bias of the data and method of estimation.

17.4.3 *Data Adjustments*—All adjustments made to test data shall be fully explained, including actions taken to meet the reporting requirements of Practice D2915.

ANNEXES

(Mandatory Information)

A1. CALIBRATION AND STANDARDIZATION

A1.1 Calibration

A1.1.1 The test system shall be calibrated against reference materials whose properties are traceable and established following nationally acceptable standards.

NOTE A1.1—This clause covers calibration of reference materials such as metallic or non-metallic bars. Wood samples may also be used provided they are protected from environmental effects (see A1.2.1).

A1.1.2 Transducers incorporated within the test system shall have calibrations traceable to national measurement standards maintained by a National Metrology Institute (NMI).

NOTE A1.2—The NMIs in the United States and Canada are the National Institute of Standards and Technology (NIST) and the National Research Council (NRC), respectively.

A1.1.3 The calibration shall apply only to the components at the time of calibration. Recalibration shall be undertaken when components are repaired or replaced.

A1.1.4 When the dynamic *E*, or dynamic stiffness *EI* values are derived directly from the test system measurements in accordance with the Class I implementation of Eq 1 to Eq 2 of Section 8, or Eq 3 or Eq 4 of Section 13, calibration is dependent solely upon the transducer calibrations; no additional calibration adjustments shall be made.

A1.2 Method Conversion

A1.2.1 When a standardized system output calibrated in accordance with A1.1 is used to achieve a calibration against results of another test method (for example, Test Methods D4761 or D198 static tests, or between the two dynamic *E* methods presented in this standard), Eq 1 or Eq 3, whichever is applicable, shall be modified as follows:

$$\hat{E} = k_s E_0 + z \tag{A1.1}$$

where $\hat{E}$ is a predicted modulus of elasticity, E_0 is the measured dynamic modulus of elasticity from the applicable test (E_{tvs}, E_{tvf}, or E_{sw}), k_s is a calibration coefficient established by test with the calibrating material, and z is a calibration offset factor. Similarly, E_0 may be a measured static *E* from Test Methods D4761 or D198, which is then used to predict a dynamic *E*.

A1.2.1.1 Three linear regression models are presented in this standard. The models compare the results from two test methods measuring the same material property with the idea of predicting the result of one test method from the result of the second test method.

(1) The first linear regression model presented in this standard is Simple Linear Regression, SLR, with a single explanatory variable. SLR determines a line that predicts the dependent variable as a function of the independent variable. The independent variable is assumed to have no measurement errors while the dependent variable is assumed to have measurement errors. *Simple* refers to a single predictor. An additional stipulation might be that Ordinary Least Squares, OLS, method be used, which is commonly not stated. OLS minimizes the sum of squared (dependent) deviations, that is, vertical distance between the data sample and line. Besides OLS, one might minimize the sum of absolute dependent deviations, or the method that chooses a line whose slope is the median of the slopes determined by pairs of sample points. In this standard SLR or "Simple Linear Regression" uses OLS.

(2) The second linear regression model presented in this standard is outlined in Appendix X6. This model is Errors-in-Variables, EiV. This model does not separate the variables into independent and dependent but assumes errors in both variables. In this model a data sample is randomly divided by the user into two subsamples, training and verification. The training subsample is further reduced using a measured correlated third variable, assumed to have no measurement errors. The correlated third variable is used to rank the data from the two test methods, taking the middle 60 % of the ranked data and discarding (randomly) 67 % of the ranked middle, that is, data blocking. The reduced training subsample is 60 % of the original training subsample. Removing data primarily from the middle artificially increases the correlation of the two test

methods in the reduced training subsample. Maximum Likelihood Estimation, MLE, an iterative method, is applied to the reduced training subsample to determine the regression line. The nonblocked verification subsample is used as a visual check. The original parent data sample is also used as a visual check. In this standard EiV or "Errors-in-Variables" will refer to this second linear regression model using MLE.

(3) The third linear regression model presented in this standard is detailed in Appendix X7. This model is Total Least Squares, TLS. TLS also assumes errors in both variables. In this model: a data sample is not divided into subsamples; a third variable is not needed; and there is no data blocking. This model minimizes the sum of squared (orthogonal) deviations, that is, perpendicular distance between the data sample and line. In this standard TLS or "Total Least Squares" will refer to this third linear regression model.

A1.2.1.2 Calibration of transverse vibration response to predict values related to standard static test values has traditionally often been done with a single reference specimen. With this method, only k_s is determined ($z = 0$) and the calibration cannot represent any intercept adjustment in the correlation between the vibration response and the static response of the specimens.

(1) Reference standards for calibration based on a single point should be those whose mechanical properties do not change significantly with time or environmental conditions. The properties of the reference material shall be determined by standard tests and the vibration characteristics shall be in the range of the test.

(2) Reference standards whose physical and mechanical properties may change significantly with the environment shall be used only in a carefully controlled environment and only under conditions where the properties have been maintained constant in that environment since the static determination. If the properties change significantly with time, the material use should be restricted to tests of short duration and the time period between the static and dynamic tests be limited. The properties of the reference material shall be determined by standard tests and the vibration characteristics shall be in the range of the test.

A1.2.1.3 Calibration of transverse vibration response that represents the relationship between the dynamic and static differences over the test range with both slope and intercept adjustment requires regressing the response of specimens in both test modes. The result is information that permits use of both slope and intercept adjustment in the formula, Eq A1.1. All cautions in selecting reference standard material noted in A1.2.1.2 apply. Further, the regression developed must fully represent, for example, the material characteristics (including density, visual grade quality level in the case of visually graded lumber), the material moisture conditions, specimen size, E:G ratio, and the range of properties anticipated in the test. Consideration should be given to the quality level because the the test methods assume homogeneity. The E:G ratio is important because each of the test methods (static or dynamic) are influence differently by the modulus of rigidity (G).

A1.2.2 This standard limits Class I testing to sections that are nominally prismatic. This includes samples with random deviations from a prismatic section, provided these deviations are also reported (for example, as part of the sample's grade description) so that the user of the data understands that the variability in the results also includes geometric variations from the ideal. This would be similar to assuming material homogeneity. A sample of tapered rectangular sections is an example of a geometric variation that is not random; however, a sample of a rectangular prismatic product of which some pieces may have a slight taper because of manufacturing variations can be tested if it is covered in the specimen or product description (for example, tolerances).

A1.2.3 The transverse vibration of logs and logs with taper are not within the scope of the standard. However, guidance may be found in Refs **(9)** and **(10)**.

A1.2.4 Under certain conditions, the simple linear regression model applied to the EiV blocked training subsample, substituting SLR for MLE, may be acceptable (see example in Appendix X6).

A1.3 System Standardization

A1.3.1 Standardization shall be performed on the dynamic test apparatus to verify the integrity of the system. Suitable reference materials for standardization have properties that are not subject to significant change under the test conditions. Reference materials are often recommended or provided, or both, by the manufacturer of the test system. The standardization test shall provide at least one reference point (output) within the operating range of interest. The standard reference material shall provide dynamic performance within the range of the test.

A1.3.2 Typically, a metal bar has been employed as the reference material for standardization. Care shall be taken to compensate for the effect of temperature variation on the metal properties when standardization tests are repeated over the duration of the test program.

NOTE A1.3—Traditionally, a single metal bar has often been used both for standardization and calibration, thus blurring the distinction between the two functions.

A1.3.3 While wood specimens and other materials subject to change in properties with change in the test environment may be used, this is discouraged unless the specimen test conditions are maintained sufficiently constant, such as in a conditioning room environment where the wood specimen is in equilibrium.

A1.3.4 Standardization of the test system shall be repeated at sufficient intervals during the test sequence to ensure continued adequate performance of the system.

A1.4 Standardization of Results

A1.4.1 Results shall be reported following standardized procedures established by the applicable product standards.

A1.5 Report

A1.5.1 Test results obtained using Eq A1.1 for analyses require consideration of the following elements in addition to those to be reported in Section 17.

NOTE A1.4—Requirements for each Class will be dependent on the