INTERNATIONAL

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Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)[1]

This standard is issued under the fixed designation C1609/C1609M; 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.

1. Scope*

1.1 This test method evaluates the flexural performance of fiber-reinforced concrete using parameters derived from the load-deflection curve obtained by testing a simply supported beam under third-point loading using a closed-loop, servo-controlled testing system.

1.2 This test method provides for the determination of first-peak and peak loads and the corresponding stresses calculated by inserting them in the formula for modulus of rupture given in Eq 1. It also requires determination of residual loads at specified deflections, the corresponding residual strengths calculated by inserting them in the formula for modulus of rupture given in Eq 1 (see Note 1). It provides for determination of specimen toughness based on the area under the load-deflection curve up to a prescribed deflection (see Note 2) and the corresponding equivalent flexural strength ratio.

NOTE 1—Residual strength is not a true stress but an engineering stress computed using simple engineering bending theory for linear elastic materials and gross (uncracked) section properties.

NOTE 2—Specimen toughness expressed in terms of the area under the load-deflection curve is an indication of the energy absorption capability of the particular test specimen, and its magnitude depends directly on the geometry of the test specimen and the loading configuration.

1.3 This test method utilizes two preferred specimen sizes of 100 mm by 100 mm by 350 mm [4 in. by 4 in. by 14 in.] tested on a 300 mm [12 in.] span, or 150 mm by 150 mm by 500 mm [6 in. by 6 in. by 20 in.] tested on a 450 mm [18 in.] span. A specimen size different from the two preferred specimen sizes is permissible.

1.4 *Units*—The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.5 *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.*

1.6 *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:*[2]

C31/C31M Practice for Making and Curing Concrete Test Specimens in the Field
C42/C42M Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C78/C78M Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C125 Terminology Relating to Concrete and Concrete Aggregates
C172/C172M Practice for Sampling Freshly Mixed Concrete
C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory
C823/C823M Practice for Examination and Sampling of Hardened Concrete in Constructions
C1140/C1140M Practice for Preparing and Testing Specimens from Shotcrete Test Panels
C1812/C1812M Practice for Design of Journal Bearing Supports to be Used in Fiber Reinforced Concrete Beam Tests
E4 Practices for Force Calibration and Verification of Testing Machines

3. Terminology

3.1 *Definitions*—The terms used in this test method are defined in Terminology C125.

[1] This test method is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.42 on Fiber-Reinforced Concrete.

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[2] 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.

***A Summary of Changes section appears at the end of this standard**

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *end-point deflection, n*—the deflection value on the load-deflection curve equal to 1⁄150 of the span length, or a larger value as specified at the option of the specifier of tests.

3.2.2 *first-peak load, P_1, n*—the load value at the first point on the load-deflection curve where the slope is zero.

3.2.3 *first-peak deflection, δ_1, n*—the net deflection value on the load-deflection curve at first-peak load.

3.2.4 *first-peak strength f_1, n*—the stress value obtained when the first-peak load is inserted in the formula for modulus of rupture given in Eq 1.

3.2.5 *load-deflection curve, n*—the plot of load versus net deflection of a flexural beam specimen loaded to the end-point deflection.

3.2.6 *net deflection, n*—the deflection measured at mid-span of a flexural beam specimen exclusive of any extraneous effects due to seating or twisting of the specimen on its supports or deformation of the support and loading system.

3.2.7 *peak load, P_P, n*—the maximum load on the load-deflection curve.

3.2.8 *peak-load deflection, δ_P, n*—the net deflection value on the load-deflection curve at peak load.

3.2.9 *peak strength, f_P, n*—the stress value obtained when the peak load is inserted in the formula for modulus of rupture given by Eq 1.

3.2.10 *D*—nominal depth of the beam specimen in mm.

NOTE 3—To simplify nomenclature, the nominal beam depth is shown in units of mm for both the SI and inch-pound version of this test method.

3.2.11 *L*—span length or distance between the supports.

3.2.12 *residual load, P^D_{600}, n*—the load value corresponding to a net deflection of L/600 for a beam of nominal depth D.

3.2.13 *residual load, P^D_{150}, n*—the load value corresponding to a net deflection of L/150 for a beam of nominal depth D.

3.2.14 *residual strength, f^D_{600}, n*—the stress value obtained when the residual load P^D_{600} is inserted in the formula for modulus of rupture given in Eq 1.

3.2.15 *residual strength, f^D_{150}, n*—the stress value obtained when the residual load P^D_{150} is inserted in the formula for modulus of rupture given in Eq 1.

3.2.16 *specimen toughness, T^D_{150}, n*—toughness of beam specimen of nominal depth D at a net deflection of L/150.

3.2.17 *equivalent flexural strength, $f^D_{e,\,150}$, n*—the average stress value obtained from the flexural toughness of the beam specimen (absorbed energy calculated from the load-deflection curve), using Eq 3.

3.2.17.1 *Discussion*—ACI 544.4R-18[3] refers to $f^D_{e,\,150}$ as $f_{e,\,3}$.

3.2.18 *equivalent flexural strength ratio, $R^D_{T,\,150}$, n*—the equivalent flexural strength divided by the first-peak strength, expressed as a percentage.

NOTE 4—The equivalent flexural strength ratio is calculated as the ratio of the weighted equivalent load up to a net deflection of L/150 over the first-peak load multiplied by 100. The $R^{150}_{T,\,150}$ value is equivalent to the $R_{e,3}$ value defined in the Technical Report No. 34 of the Concrete Society.[4]

4. Summary of Test Method

4.1 Molded or sawn beam specimens having a square cross-section of fiber-reinforced concrete are tested in flexure using a third-point loading arrangement with a closed-loop, servo-controlled testing system and roller supports under the ends of the beam that are free to rotate on their axes as described in Practice C1812/C1812M. The testing machine shall conform to the requirements of the sections on Basis of Verification, Corrections, and Time Interval Between Verifications of Practices E4. Load and net deflection are monitored and recorded to an end-point deflection of at least 1⁄150 of the span. Data are recorded and plotted by means of an X-Y plotter, or they are recorded digitally and subsequently used to plot a load-deflection curve. Points termed first-peak, peak, and residual loads at specified deflections are identified on the curve, and are used to calculate flexural performance parameters.

5. Significance and Use

5.1 The first-peak strength characterizes the flexural behavior of the fiber-reinforced concrete up to the onset of cracking, while residual strengths at specified deflections characterize the residual capacity after cracking. Specimen toughness is a measure of the energy absorption capacity of the test specimen. The appropriateness of each parameter depends on the nature of the proposed application and the level of acceptable cracking and deflection serviceability. Fiber-reinforced concrete is influenced in different ways by the amount and type of fibers in the concrete. In some cases, fibers may increase the residual load and toughness capacity at specified deflections while producing a first-peak strength equal to or only slightly greater than the flexural strength of the concrete without fibers. In other cases, fibers may significantly increase the first-peak and peak strengths while affecting a relatively small increase in residual load capacity and specimen toughness at specified deflections.

5.2 The first-peak strength, peak strength, and residual strengths determined by this test method reflect the behavior of fiber-reinforced concrete under static flexural loading. The absolute values of energy absorption obtained in this test are of little direct relevance to the performance of fiber-reinforced concrete structures since they depend directly on the size and shape of the specimen and the loading arrangement.

5.3 The results of this test method may be used for comparing the performance of various fiber-reinforced concrete mixtures or in research and development work. They may also be used to monitor concrete quality, to verify compliance with construction specifications, obtain flexural strength data on fiber-reinforced concrete members subject to pure bending, or to evaluate the quality of concrete in service.

[3] ACI 544.4R-18: Guide to Design with Fiber-Reinforced Concrete, American Concrete Institute, Farmington Hills, MI, http://www.concrete.org.

[4] "Concrete Industrial Ground Floors—A Guide to Design and Construction," Technical Report 34, 3rd edition, Concrete Society, Slough, United Kingdom, 2003.

5.4 The results of this standard test method are dependent on the size of the specimen.

NOTE 5—The results obtained using one size molded specimen may not correspond to the performance of larger or smaller molded specimens, concrete in large structural units, or specimens sawn from such units. This difference may occur because the degree of preferential fiber alignment becomes more pronounced in molded specimens containing fibers that are relatively long compared with the cross-sectional dimensions of the mold. Moreover, structural members of significantly different thickness experience different maximum crack widths for a given mid-span deflection with the result that fibers undergo different degrees of pull-out and extension.

6. Apparatus

6.1 *Testing Machine*—The testing machine shall be capable of servo-controlled operation where the net deflection of the center of the beam is measured and used to control the rate of increase of deflection. Testing machines that use stroke displacement control or load control are not suitable for establishing the portion of the load-deflection curve immediately after first-peak. The loading and specimen support system shall be capable of applying third-point loading to the specimen without eccentricity or torque. The supporting rollers shall be able to rotate on their axes throughout the duration of a test and shall conform with Practice C1812/C1812M. The loading blocks shall conform to the requirements of Test Method C78/C78M.

6.2 *Deflection-Measuring Equipment*—Devices such as electronic transducers or electronic deflection gages shall be located in a manner that ensures accurate determination of the net deflection at the mid-span exclusive of the effects of seating or twisting of the specimen on its supports. One acceptable arrangement employs a rectangular jig, which surrounds the specimen and is clamped to it at mid-depth directly over the supports (Figs. 1 and 2). Two electronic displacement transducers or similar digital or analog devices mounted on the jig at mid-span, one on each side, measure deflection through contact with appropriate brackets attached to the specimen. The average of the measurements represents the net deflection.

6.3 *Data Recording System*—An X-Y plotter coupled directly to electronic outputs of load and deflection is an acceptable means of obtaining the relationship between load and net deflection—that is, the load-deflection curve. A data acquisition system capable of digitally recording and storing load and deflection data at a sampling frequency of at least 2.5 Hz is an acceptable alternative. After a net deflection of L/900 has been exceeded, it is permissible to decrease the data acquisition sampling and recording frequency to at least 2 Hz. This applies regardless of the rate of deflection used to load the specimen.

NOTE 6—For X-Y plotters, accurate determination of the area under the load-deflection curve and the loads corresponding to specified deflections is only possible when the scales chosen for load and deflection are reasonably large. A load scale chosen such that 25 mm [1 in.] corresponds to a flexural stress of the order of 1 MPa [150 psi], or no more than 20 % of the estimated first-peak strength, is recommended. A recommended deflection scale is to use 25 mm [1 in.] to represent about 10 % of the end-point deflection of 1⁄150 of the span, which is 2 mm [0.08 in.] for a 350 mm by 100 mm by 100 mm [14 in. by 4 in. by 4 in.] specimen size, and 3 mm [0.12 in.] for a 500 mm by 150 mm by 150 mm [20 in. by 6 in. by 6 in.] specimen size. When data are digitally stored, the test parameters may be determined directly from the stored data or from a plot of the data. In the latter case, use a plot scale similar to that recommended for an X-Y plotter.

7. Sampling, Test Specimens, and Test Units

7.1 *General Requirements*—The nominal maximum size of aggregate and cross-sectional dimensions of test specimens shall be in accordance with Practice C31/C31M or Practice C192/C192M when using molded specimens, or in accordance with Test Method C42/C42M when using sawn specimens, provided that the following requirements are satisfied:

7.1.1 The length of test specimens shall be at least 50 mm [2 in.] greater than three times the depth, and in any case not less

FIG. 1 Arrangement to Obtain Net Deflection by Using Two Transducers Mounted on Rectangular Jig Clamped to Specimen Directly Above Supports

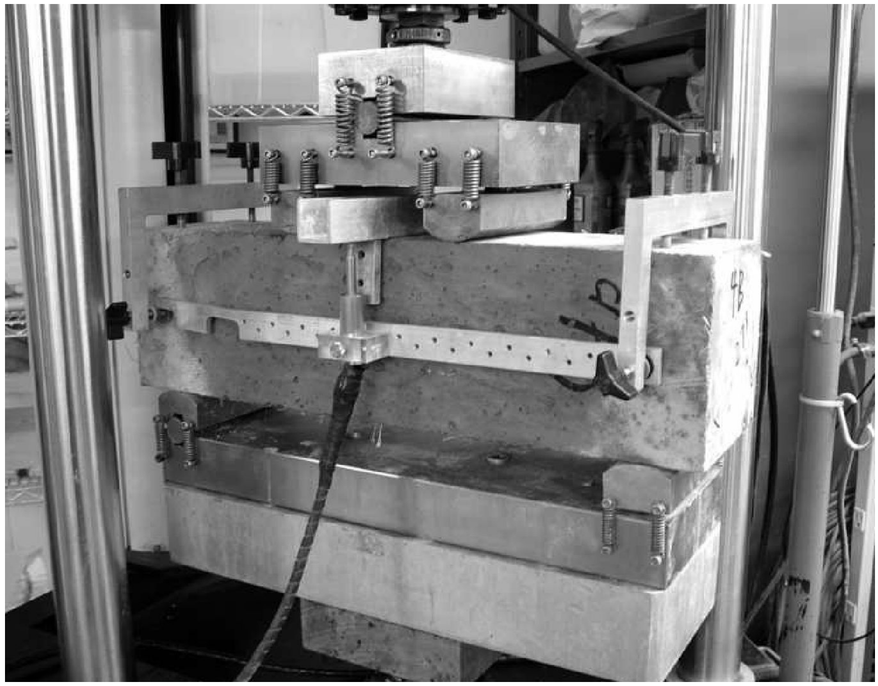


FIG. 2 Arrangement to Obtain Net Deflection by Using Two Transducers Mounted on Jig Secured to Specimen Directly Above Supports

than 350 mm [14 in.]. The length of the test specimen shall not be more than two times the depth greater than the span.

7.1.2 The tolerances on the cross-section of the test specimens shall be within ± 2 %. The test specimens shall have a square cross-section within these tolerances.

7.1.3 The width and depth of test specimens shall be at least three times the maximum fiber length.

7.1.4 When the specimen size is not large enough to meet all the requirements of 7.1 – 7.1.3, specimens of square cross-section large enough to meet the requirements shall be used. The three times maximum fiber length requirement for width and depth may be waived at the option of the specifier of tests to permit specimens with a width and depth of 150 mm [6 in.] when using fibers of length 50 mm to 75 mm [2 in. to 3 in.].

NOTE 7—The results of tests on beams with relatively stiff fibers, such as steel fibers, longer than one-third the width and depth of the beam may not be comparable with test results of similar-sized beams with fibers shorter than one-third the width and depth because of preferential fiber alignment, and different size beams may not be comparable because of size effects. The degree of preferential fiber alignment may be less for fibers that are flexible enough to be bent by contact with aggregate particles or mold surfaces than for rigid fibers that remain straight during mixing and specimen preparation.

7.2 *Freshly Mixed Concrete*—Obtain samples of freshly mixed fiber-reinforced concrete for the preparation of test specimens in accordance with Practice C172/C172M.

7.2.1 Fill each mold in one layer by dispensing the concrete directly into the mold from discharge point of the sample container, positioned perpendicular to the length of the mold (see Fig. 3a). Overfill the molds by approximately 20 mm [¾ in.] so that mold remains filled after consolidation (see Fig. 3b).

NOTE 8—The mold is filled in a single layer without using an auxiliary tool to distribute the concrete within the mold so that the orientation and distribution of the fibers are disturbed as little as possible during specimen fabrication. The amount of required overfilling will depend on the consistency of the concrete mixture. Trial and error may be required to achieve complete filling after consolidation.

7.2.2 Consolidate the concrete by external vibration only using apparatus as defined in Practice C192/C192M. Consolidation is considered adequate when the top surface becomes approximately level and entrapped air voids no longer break through the surface. Consolidation by rodding or internal vibration is prohibited.

NOTE 9—Generally, consolidation is achieved with about 10 s of vibration. but longer times may be required for lower slump concrete. Vibration time should rarely have to exceed 20 s.

7.2.3 Using a magnesium float, strike-off the excess concrete from the mold starting in the middle and working to either end using a sawing motion, so that the concrete surface is even with the top of the mold (see Fig. 3c). Finish the surface with a minimum amount of manipulation so that it is free of depressions or projections greater than 3 mm [⅛ in.] (see Fig. 3d).

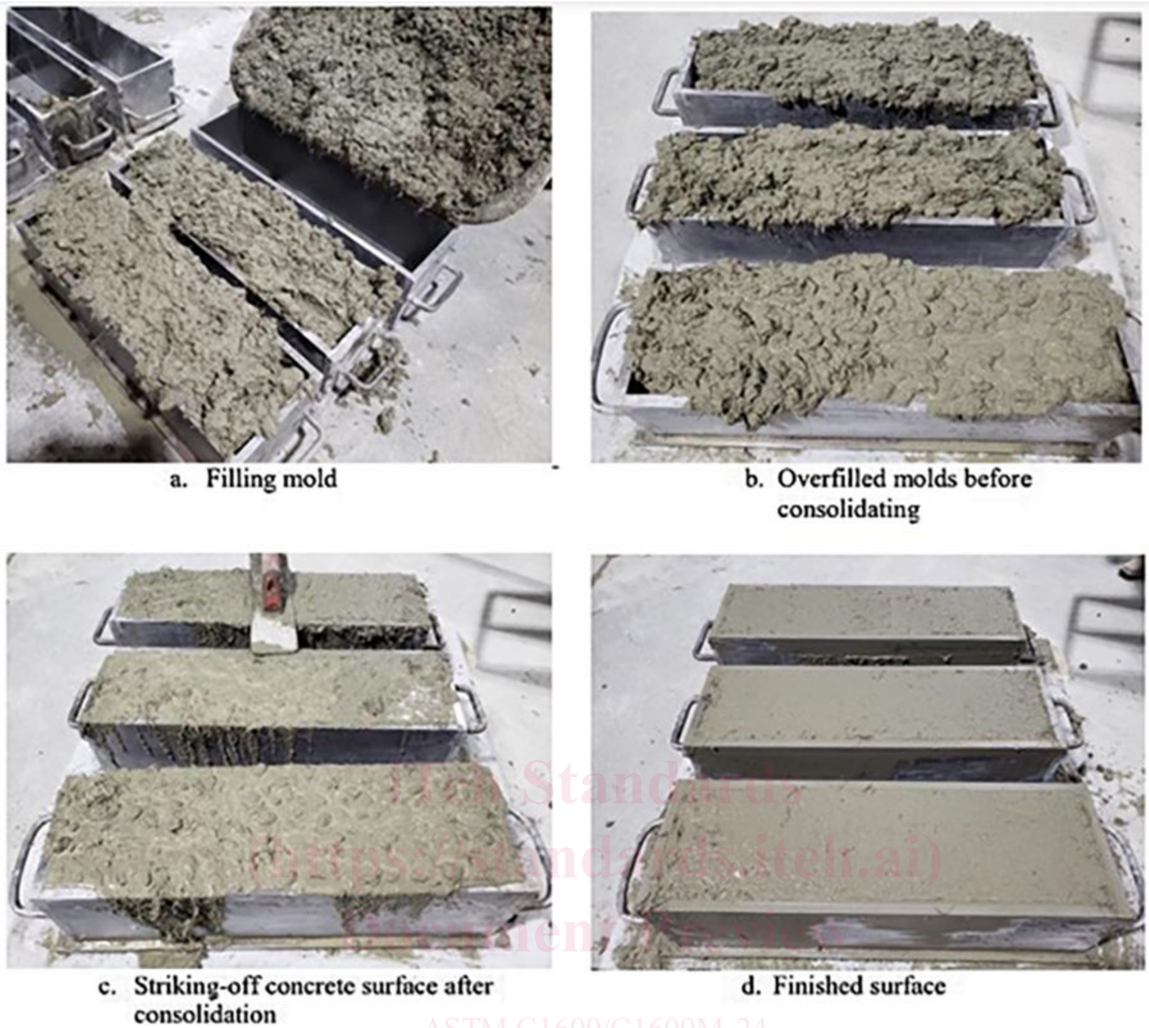
7.2.4 For field-made specimens, cure in accordance with the standard curing requirements of Practice C31/C31M. For laboratory-made specimens, cure in accordance with Practice C192/C192M.

7.3 *Hardened Concrete*—Select samples of hardened fiber-reinforced concrete from structures in accordance with Practice C823/C823M.

7.3.1 Prepare and condition sawn specimens in accordance with Test Method C42/C42M.

7.4 Prepare specimens from shotcrete panels in accordance with Practice C1140/C1140M.

7.5 *Test Unit*—Prepare and test at least three specimens from each sample of fresh or hardened concrete.



a. Filling mold

b. Overfilled molds before consolidating

c. Striking-off concrete surface after consolidation

d. Finished surface

FIG. 3 Making Fiber-Reinforced Concrete Test Specimens

8. Evaporation Control

8.1 When the time between removal of test specimens from a moist curing environment and the start of testing is likely to exceed 15 min, minimize drying by covering with wet burlap, applying a curing compound, or by other appropriate techniques.

9. Procedure

9.1 Molded or sawn specimens shall be turned on their side with respect to the position as cast before placing on the support system. Specimens representing shotcrete shall be loaded in the same direction as the specimen was shot.

9.2 Arrange the specimen and the loading system so that the specimen is loaded at the third points in accordance with Test Method C78/C78M. The span length shall be three times the specimen depth or 300 mm [12 in.], whichever is greater.

NOTE 10—If full contact cannot be reasonably assured between the specimen, the load-applying devices, and the supports before loading, grind the contact surfaces of the specimen so that full contact is achieved. Alternatively, use capping materials at the load or support points.

9.3 Operate the testing machine so that the net deflection of the specimen increases at a constant rate in accordance with Table 1. Up to a net deflection of L/900, the rate of increase of net deflection shall be in accordance with the second column of Table 1. For net deflection beyond L/900 and up to the end point deflection, a higher rate of increase of net deflection is permitted in accordance with the third column of Table 1.

TABLE 1 Rate of Increase in Net Deflection

Beam size[A]	Up to net deflection of L/900	Beyond net deflection of L/900
100 mm by 100 mm by 350 mm	0.025 mm ⁄min to 0.075 mm/min	0.05 mm ⁄min to 0.20 mm/min
[4 in by 4 in by 14 in.]	[0.001 in. ⁄min to 0.003 in./min]	[0.002 in. ⁄min to 0.008 in./min]
150 mm by 150 mm by 500 mm [6 in. by 6 in. by 20 in.]	0.035 mm ⁄min to 0.10 mm/min [0.0015 in. ⁄min to 0.004 in./min]	0.05 mm ⁄min to 0.30 mm/min [0.002 in. ⁄min to 0.012 in. min]

[A]The initial loading rate up to deflection of L/900 for other sizes and shapes of specimens shall be based on reaching the first-peak deflection 40 s to 100 s after the start of the test. Beyond a net deflection of L/900, the rate of increase of net deflection shall not exceed 8 times the initial rate.

When increasing the loading rate, the rate of increase of net deflection shall be increased in increments not exceeding 0.05 mm/min [0.002 in./min]. Subsequent increases of the rate of increase of net deflection shall be at least 30 s apart. Include the rate(s) of increase of net deflection in the test report.

NOTE 11—First-peak deflection for third-point loading is estimated assuming linear-elastic behavior up to first peak from the equation:

$$\delta_1 = \frac{23P_1L^3}{1296EI}\left[1+\frac{216d^2(1+\mu)}{115L^2}\right]$$

where:

δ_1 = the first peak deflection, mm [in.]
P_1 = the first-peak load, N [lbf]
L = the span length, mm [in.]
E = the estimated modulus of elasticity of the concrete, MPa [psi]
I = the cross-sectional moment of inertia, mm^4 [in.^{4}]
d = the average depth of specimen at the fracture, as oriented for testing, mm [in.] and
μ = Poisson's ratio

For a Poisson's ratio of 0.20 and a d to L ratio of 1/3, the value of the portion of the equation in brackets is 1.25.

NOTE 12—For a 350 mm by 100 mm by 100 mm [14 in. by 4 in. by 4 in.] specimen size, the net deflection at first-peak load is approximately 0.04 mm [0.0016 in.], and for a 500 mm by 150 mm by 150 mm [20 in. by 6 in. by 6 in.] specimen size, it is approximately 0.05 mm [0.002].

9.4 If the rate of increase of net deflection cannot be controlled (see Note 13) during the test, it is permitted to reduce the initial net deflection rate to 50 % of the limits in 9.3 until a net deflection of L/900 is reached. After a net deflection of L/900, the rate of increase of net deflection shall not exceed 8 times the initial rate until the specified end-point deflection is reached. When increasing the loading rate, the rate of increase of net deflection shall be increased in increments not exceeding 0.05 mm/min [0.002 in./min]. Subsequent increases of the rate of increase of net deflection shall be at least 30 s apart. Include the rate(s) of increase of net deflection in the test report.

NOTE 13—The rate of increase of net deflection is out of control if a sudden acceleration of the net deflection of a beam occurs leading to a rate at least 20 times higher than the rate specified in 9.3 and 9.4. The lower loading rate is permitted for brittle (higher strength) concretes to provide better control of the increase of net deflection immediately after the peak load.

9.5 When using deflection-measuring equipment for the first time, or after alterations or maintenance, confirm the reliability of the measured net deflection by comparing the measured deflection at first-peak load with the value estimated from the formula in Note 11.

9.6 Unless otherwise required by the specifier of tests, terminate the test at a net deflection of 1⁄150 of the span.

9.7 Further testing to a greater end-point deflection shall be specified at the option of the specifier of tests, and shall be specified as the span divided by some whole number less than 150.

9.8 To determine the dimensions of the specimen cross section for use in calculating the flexural performance of the specimen, take measurements across one of the fractured faces after testing. The width and depth are measured with the specimen as oriented for testing. For each dimension, take one measurement at each edge of the cross section. Use the two measurements for each direction to determine the average width and the average depth. Take all measurements to the nearest 1 mm [0.05 in.]. Note if the fracture or fractures occur outside of the middle third of the tested specimen.

9.9 Determine the position of the fracture by measuring the distance along the middle of the tension face from the fracture to the nearest point of support.

9.10 When the fracture occurs outside the middle third of the span, discard the results.

10. Calculation

10.1 Values of load and deflection used in subsequent calculations shall be obtained from the load-deflection curve, or from stored digital data.

10.2 Determine the first-peak load as that value of load corresponding to the first point on the load-deflection curve where the slope is zero, that is, the load is a local maximum value. Determine the corresponding deflection value. See Figs. 4 and 5.

NOTE 14—Small ripples or fluctuations in the load-deflection curve due to electronic noise or mechanical vibration should not be confused with a definite change in the slope of the load-deflection curve in the vicinity of first peak load, particularly when the portion of the curve in question is magnified.

10.3 Calculate the first-peak strength using the first-peak load determined in 10.2, the average specimen dimensions determined in 9.8, and the following formula for modulus of rupture:

$$f = \frac{PL}{bd^2} \quad (1)$$

where:

f = the strength, MPa [psi],
P = the load, N [lbf],
L = the span length, mm [in.],
b = the average width of the specimen at the fracture, as oriented for testing, mm [in.], and
d = the average depth of the specimen at the fracture, as oriented for testing, mm [in.].

10.3.1 Record the number rounded to the nearest 0.05 MPa [5 psi] as the first-peak strength, f_1.

10.4 Determine the peak load as that value of load corresponding to the point on the load-deflection curve that corresponds to the greatest value of load obtained prior to reaching the end-point deflection. Determine the corresponding deflection value.

10.5 Calculate the peak strength using the peak load determined in 10.4, the average specimen dimensions determined in 9.8, and Eq 1. Record the number rounded to the nearest 0.05 MPa [5 psi] as the peak strength, f_P.

10.6 Determine the residual load values, P_{600}^D and P_{150}^D as appropriate for the specimen depth, corresponding to net deflection values of 1⁄600 and 1⁄150 of the span length.

10.7 Calculate the residual strengths, f_{600}^D and f_{150}^D using the residual loads determined in 10.6, the average specimen dimensions determined in 9.8, and Eq 1. Record the numbers rounded to the nearest 0.05 MPa [5 psi] as the residual