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Report on Measuring Mechanical Properties of Hardened Fiber- Reinforced Concrete

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Report on Measuring Mechanical Properties of Hardened Fiber-Reinforced Concrete

Reported by Committee 544

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This report provides a synopsis of the existing testing methodologies for the determination of mechanical properties of hardened fiber-reinforced concrete (FRC). This report applies to the mechanical properties of conventionally mixed and placed FRC, including fiber-reinforced self-consolidating concrete (FRSCC), or fiber-reinforced shotcrete (FRS) using steel, glass, polymeric, and natural fibers.

The objective is to enable manufacturers to characterize the mechanical properties of hardened FRC and encourage researchers and testing laboratories to adopt common and unified test methods to build a meaningful database of mechanical properties of hard-

ened FRC materials and products. Test results from the test procedures used in this report are not intended for the design of FRC structures, but to gain a better understanding of factors influencing the determination of their mechanical properties and of FRCs and FRC products.

Keywords: compressive strength; fiber pullout; fiber-reinforced concrete; flexural fatigue resistance; flexural strength; impact resistance; multiaxial behavior; shear and torsion; tensile strength; toughness.

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

The use of fiber-reinforced concrete (FRC) has evolved from small-scale applications to routine factory and field applications that involve the global use of tens of millions of cubic yards (meters) annually. This growth of application, in conjunction with new fibers, admixtures, and mixture designs, has created an urgent need to review existing test methods and, where necessary, develop new methods for determining the fresh and hardened properties of FRC.

1.2—Scope

This report documents the determination of mechanical properties of hardened FRC. The objective is to characterize these mechanical properties and encourage common and unified test methods. This objective builds a meaningful database of mechanical properties of hardened FRC materials and products. Further, the results should not be taken out of the context presented for illustrating the tests and not for comparing fibers out of context. The results from the tests and procedures used in this document are not intended to be used for the design of FRC structures. The purpose of this document is to gain a better understanding of the many factors influencing tests for the determination of mechanical properties of FRCs and FRC products.

Although most of the test methods described in this report were developed initially for steel FRC (SFRC), they are applicable to concretes reinforced with glass, synthetic/polymeric, and natural fibers, except when noted. In Fig. 1.2, an example of different types of fibers commonly employed in FRC is provided.

This report applies to the mechanical properties of conventionally mixed and placed FRC or fiber-reinforced shotcrete (FRS) using steel, glass, synthetic/polymeric, and cellulose/natural fibers.

Some newer test methods and evaluation procedures under development are not included in this report. Examples of this are tensile creep and flexural creep of concrete where the section has cracked and the bridging fibers are carrying loads.

This report does not discuss test methods for thin glass FRC or mortar products produced by the spray-up process. The Prestressed Concrete Institute (PCI MNL 128) and the International Glassfibre Reinforced Cement Association (2016a,b) have prepared recommendations for test methods for these spray-up materials.

CHAPTER 2—NOTATION AND DEFINITIONS**2.1—Notation**

- a, b = dimensions, in. (mm)
- b = width, in. (mm)
- d = depth, in. (mm)
- d_f = fiber diameter, in. (mm)
- f_1 = first cracking nominal stress (as from results of flexural tests according to ASTM C1609/C1609M), psi (MPa)

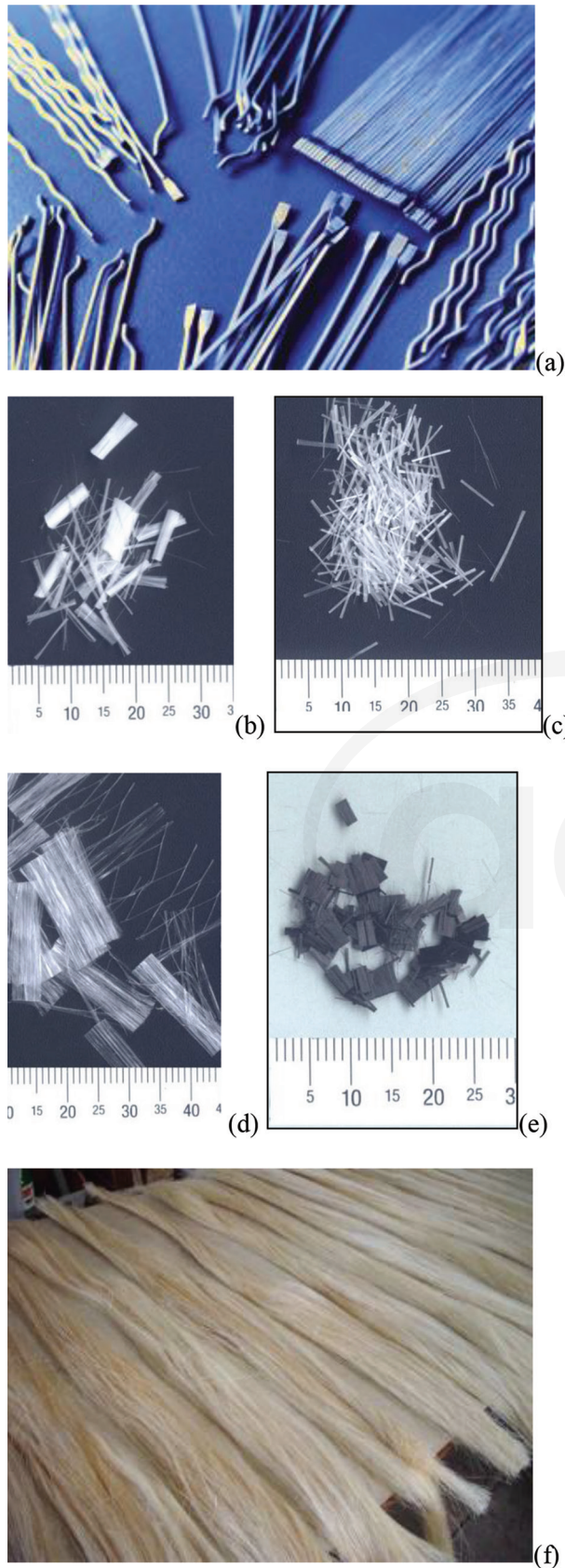


Fig. 1.2—Examples of different types of fibers used in FRC: (a) steel (with hooked ends, flattened ends, corrugated/undulated); (b) through (c) synthetic/polymeric microfibers; (d) glass; (e) carbon; and (f) natural; dimension scale where provided is in mm. (Note: 1 in. = 25.4 mm.)

- f_{150} = residual nominal bending strength corresponding to P_{150} , psi (MPa)
 f_{600} = residual nominal bending strength corresponding to P_{600} , psi (MPa)
 f_{eq} = equivalent nominal flexural strength, calculated with reference to predefined crack opening range, from nominal flexural stress versus crack opening curves obtained from flexural tests, psi (MPa)
 f_p = peak nominal stress (as from results of flexural tests according to ASTM C1609/C1609M); may coincide with or be higher than f_i , psi (MPa)
 f_R, f_{Rj} = residual nominal flexural strength, at a specified value of the crack mouth opening displacement, as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
 f_{R1} = residual nominal flexural strength, at CMOD = 0.02 in. (0.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
 f_{R1k} = characteristic value of f_{R1}
 f_{R2} = residual nominal flexural strength, at CMOD = 0.06 in. (1.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
 f_{R3} = residual nominal flexural strength, at CMOD = 0.10 in. (2.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
 f_{R3k} = characteristic value of f_{R3}
 f_{R4} = residual nominal flexural strength, at CMOD = 0.14 in. (3.5 mm), as from results of flexural tests on notched specimens as per EN 14651, psi (MPa)
 h = specimen height, in. (mm)
 L = length, span, in.-ft. (mm); also gauge length, in. (mm)
 l_f = fiber length, in. (mm)
 P = load, lbf (N)
 P_1 = first cracking load (as from results of flexural tests according to ASTM C1609/C1609M), lbf (N)
 P_{150} = residual load measured in flexural tests as per ASTM C1609/C1609M in correspondence of a midspan net deflection equal to 1/150 of the specimen length, lbf (N)
 P_{600} = residual load measured in flexural tests as per ASTM C1609/C1609M in correspondence of a midspan net deflection equal to 1/600 of the specimen length, lbf (N)
 P_p = peak load (as from results of flexural tests according to ASTM C1609/C1609M); may coincide with or be higher than P_1 , kip (kN)
 T_{150} = area under the load deflection curve obtained from flexural tests as per ASTM C1609/C1609M up to a value of the net deflection equal to 1/150 of the specimen length, in.-lb (J)
 V_f = fiber volume fraction (generally expressed in percent)
 δ = deflection, in. (mm)
 θ = angle, deg

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology.”

www.concrete.org/store/productdetails.aspx?ItemID=CT16. Definitions provided herein complement that resource.

aspect ratio—ratio of the length to the diameter of one single fiber or fiber filament. The diameter may be the actual or **equivalent diameter**, defined below.

crack—complete or incomplete separation of concrete in to two or more parts produced by breaking or fracturing.

equivalent diameter—for fibers with noncircular cross section, diameter of the equivalent circular cross section having the same area as the fiber cross section.

equivalent flexural residual strength—average flexural stress measured for an FRC beam based on the toughness, up to a specified deflection (or crack width).

fiber—slender and elongated solid material, generally with a length of at least 100 times its diameter; four primary types are defined generally by **ASTM C1116/C1116M** as follows: steel: **ASTM A820/A820M**; chopped polyolefin strand (synthetic or polymeric): **ASTM D7508/D7508M**; glass: **ASTM C1666/C1666M**; and cellulose/natural: **ASTM D7357**.

fiber volume fraction—total fiber volume in a unit volume of concrete (generally expressed as a percentage).

ligament—fracture cross section in a specimen, generally highlighted by the presence of one notch or two opposed notches, in prismatic specimens, or a circumferential notch, in cylinder specimens.

Mode I fracture—fracture mode where crack propagation occurs because of a uniaxial tensile stress state orthogonal to the crack plane.

residual flexural strength—flexural strength retained in a cracked fiber-reinforced concrete beam, typically measured at a certain deflection or crack width.

toughness—ability of fiber-reinforced concrete to sustain loads after cracking of the concrete, as described by its energy absorption capacity; in connection with fiber-reinforced concrete, the term “toughness” typically refers to flexural toughness or toughness in a bending test.

CHAPTER 3—SAMPLING AND SPECIMEN PREPARATION

3.1—General

In general, procedures outlined in **ASTM C31/C31M**, **C42/C42M**, **C192/C192M**, and **C1609/C1609M** as well as **EN 12350-1**, **EN 12390-1**, **EN 12390-2**, and **EN 14651** should be followed for specimen preparation. Additional guidance for preparing fiber-reinforced shotcrete specimens is available in **ACI 506.2**. Test specimens should be prepared using external vibration whenever possible. Internal vibration is not desirable and rodding is not acceptable, as these methods of consolidation may produce preferential fiber alignment and nonuniform fiber distribution that may cause variance in the results. Although external vibration may produce some alignment of fibers, its influence is generally negligible because of the short duration of vibration required for consolidation of test specimens. The method, frequency, amplitude, and time of vibration should be recorded.

Consistent test specimen preparation and testing can reduce variance as consistently biased. Consistency helps to

identify any influence by knowing what was done differently to produce bias in the results. Some test methods provide procedures for specimen preparation.

3.2—Test specimens

Test specimens should be cast in a single layer to avoid the reorientation of the fibers or fiber-free planes. Whenever a single dump method is not used to fill formwork, care should be used to avoid placing concrete in a manner that produces a lack of fiber continuity between successive placements. The preferred placement method is use of a wide shovel or scoop to place each concrete layer uniformly along the mold length. Any preferential fiber alignment by the mold surfaces can influence test results, particularly for small cross sections with long fibers. Generally, the smallest specimen dimension should be at least three times larger than the fiber length. Recommendations for selecting specimen size and preparing test specimens for flexural toughness tests are given in **ASTM C1399/C1399M**, **ASTM C1609/C1609M**, **EN 14651**, and **EN 14889-2**.

3.3—Sample size

Because statistical variation in the measured mechanical properties can be particularly high among samples with different fiber dispersion, fiber orientation, or both, more samples may be needed than for plain concrete for the same mechanical property and test to obtain a statistically representative set of results or lower variation on properties.

CHAPTER 4—COMPRESSIVE STRENGTH, MODULUS OF ELASTICITY, AND POISSON'S RATIO

4.1—General

Standard compressive strength testing procedures (**ASTM C39/C39M**; **EN 12390-3**) used for conventional concrete can be used for FRC as well. **ASTM C469/C469M** and **EN 12390-13** tests for modulus of elasticity and Poisson's ratio are also applicable to FRC. The cylinders should be 6 x 12 in. (150 x 300 mm) or 4 x 8 in. (100 x 200 mm) (diameter x height) in size and made using external vibration. Smaller specimens are not recommended, specifically with macrofibers that are longer, stiffer, or both, because of likely induced preferred orientation.

The presence of fibers can alter the mode of failure of cylinders, and be helpful in avoiding spurious shear type failure in plain concrete, thus obtaining a failure mode characterized by finer cracks parallel to the applied stress (Fig. 4.1a). The higher the fiber factor $V_f l_f / d_f$, the more pronounced the change in a failure mode (**Ou et al. 2012**) that actually causes the concrete response to be less brittle. Significant post-peak strength can be retained with increasing deformation beyond the maximum load, as a function of fiber type, dosage, and aspect ratio (Fig. 4.1b). Because smaller cylinders give higher strengths for conventional concrete and promote preferential fiber alignment in FRC, small cylinders with long fibers could result in unrealistically high compressive strengths.

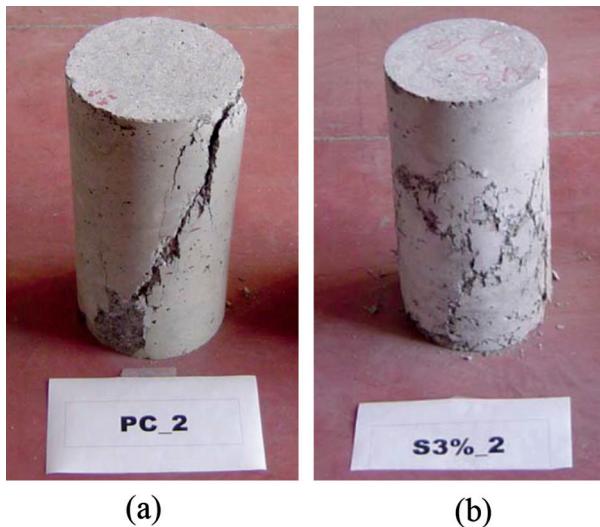


Fig. 4.1a—Failure mode for: (a) plain; and (b) steel FRC cylinders in compression (Bencardino et al. 2008) ($V_f = 3\%$; $l_f = 0.875$ in. [22 mm]; aspect ratio = 40).

The use of cube specimens for compressive strength tests is not recommended for FRCs. The perpendicular alignment between the casting/compaction and the loading directions could affect the role of the fibers, as aligned, in resisting the loads. Frictional stresses that develop at the specimen-to-machine platen interface could also interact with the crack-bridging mechanism provided by the fibers, leading to an overestimation of the strength.

Little reference data are available, however, for cube compressive strength tests, and the relationship between cube and cylinder strength has not been determined for FRC.

4.2—Compressive stress-strain curve

Test procedures to obtain the complete stress-strain curve of an FRC sample were developed using a two-stage process. During the first stage, the axial strain is used as the control parameter and prior to reaching the peak load, the mode of control is changed to the circumferential strain. This test method development is discussed in detail by Ariño and Mobasher (1999). A similar configuration was used by Colombo et al. (2010) to measure compressive behavior of steel FRC (SFRC) after exposure to high temperatures up to 1110°F (600°C). Desai et al. (2003) used this approach to study the effect of alkali-resistant (AR) glass fibers on the compressive stress-strain response of FRC.

In this test procedure, a 100 kip (450 kN) closed-loop controlled testing machine is used. Two linear variable differential transformers (LVDTs) measure the axial strain using a special ring-type fixture. In addition, a chain-type fixture with an extensometer is used to measure the transverse strain (Fig. 4.2a). The axial mode controls the initial prepeak microcracking phase. The circumferential displacement controls post-peak response. The axial strain within a middle gauge length of 2.5 in. (64 mm) on a 3 x 6 in. (76 x 152 mm) compression cylinder was used to avoid error from confinement in the end zones.

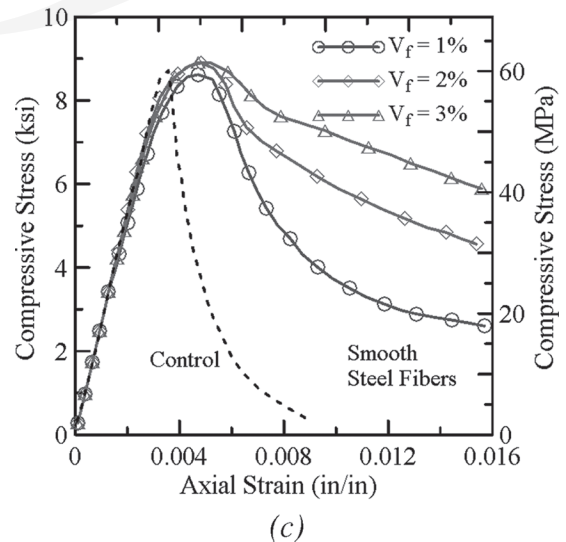
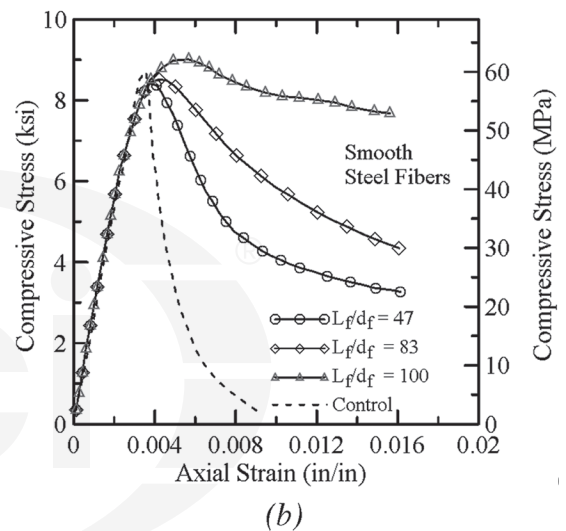
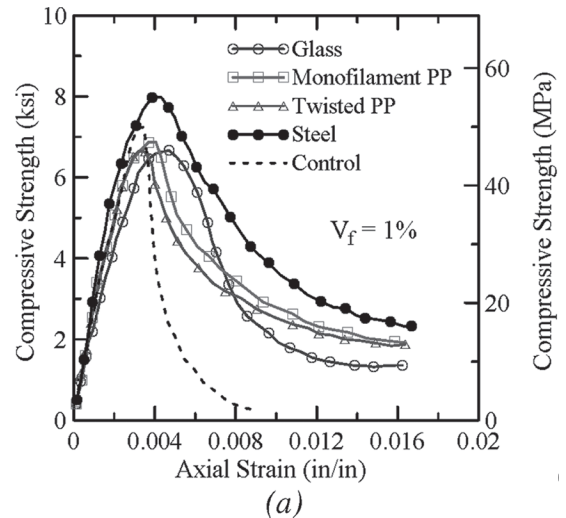


Fig. 4.1b—Stress-strain curves for fiber-reinforced mortars: (a) 1% V_f of different fiber types; (b) different V_f of smooth steel fibers (length 0.5 in. [12.5 mm], aspect ratio = 83); and (c) 2% V_f of steel fibers with different aspect ratios l_f/d_f (fiber length to fiber diameter ratio) (adapted from Fanella and Naaman [1985] and Ezeldin and Balaguru [1992]).

Refer to Fig. 4.2b for a comparison of the stress versus axial and circumferential strain curves for specimens containing 16.8 lb/yd³ (10 kg/m³) of 0.5 in. (12 mm) long AR glass fibers tested at 3, 7, and 28 days, where the effect of age is also clearly highlighted by a significant increase in strength and toughness.

Several distinct regions are observed in the response. The first region is the initial linear-elastic ascending stress-strain response. The second region is due to initiation of micro-cracks that results in a reduction in the stiffness and, thus, the nonlinear behavior of the specimen. This zone terminates at the ultimate strength. In the strain-softening region, there is significant ductility in the circumferential strain that

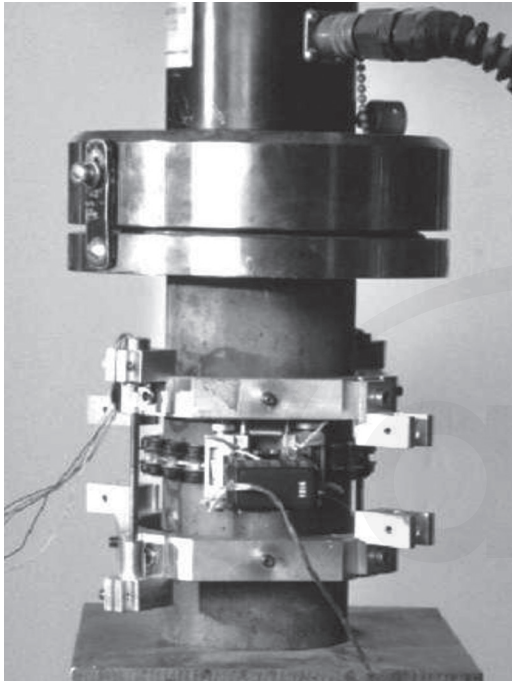


Fig. 4.2a—Testing apparatus for compressive stress-strain curves of concrete materials (Desai et al. 2003).

indicates the effect of dilatation. During the initial loading stages, the best choice of closed-loop control is the axial deformation parameter. Circumferential strain is a recommended method of obtaining the post-peak response, as it best captures the dilatation that takes place during failure.

CHAPTER 5—TENSILE BEHAVIOR

5.1—General

The capacity to retain a non-negligible and reliable tensile strength resistance in the post-cracking regime is a distinct feature of FRC. Therefore, the experimental identification of post-cracking tensile behavior and defining parameters to suitably characterize FRC from a design perspective is of the utmost importance. Many experimental tensile tests, direct or indirect, have been used; however, no tensile test standard has been established to date. Several technical organizations, such as ASTM International, the Japan Concrete Institute (JCI), and RILEM, have developed flexural tests meant to simulate the characteristics of FRC composites in tension. Such tests are insufficient to characterize the true tensile response, however, particularly when strain-hardening behavior and multiple cracking in tension are present. Similarly, the indirect split cylinder tensile strength test (ASTM C496/C496M) for FRC specimens is difficult to interpret after the first matrix cracking because of unknown stress distribution (Schrader 1978). Precise identification of the first crack in the split cylinder test can be difficult without strain gauges or other sophisticated means of crack detection, such as acoustic emission or laser holography (Maji and Shah 1988; Miller et al. 1988). The relationships among splitting tensile strength, direct tensile strength, and modulus of rupture have not been determined.

5.2—Direct tension tests

While no standard test exists to determine the direct tensile properties of FRC composites, it is essential to ensure

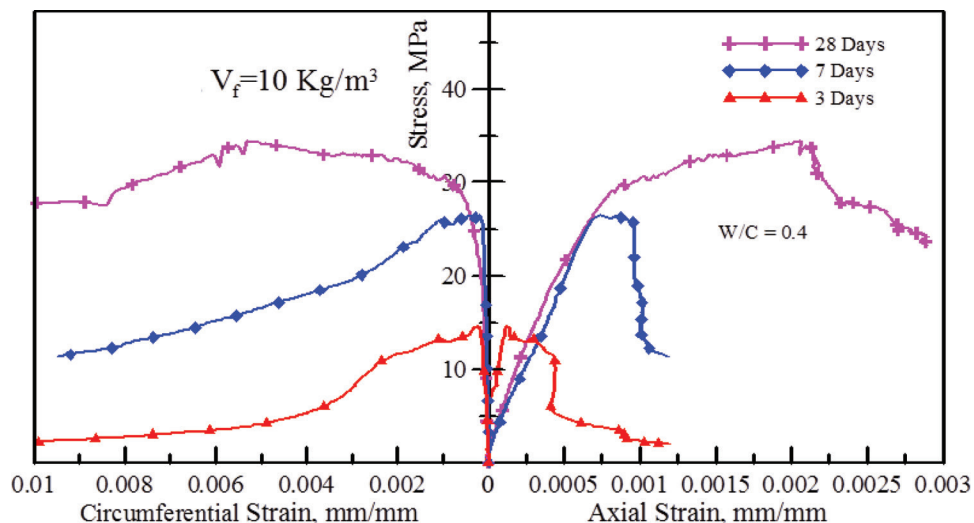


Fig. 4.2b—Stress versus strain for axial and circumferential response of concrete containing 16.8 lb/yd³ (10 kg/m³) of glass fibers (Desai et al. 2003). (Note: 1 in. = 25.4 mm; 1 ksi = 6.9 MPa; 1 kg/m³ = 1.686 lb/yd³.)

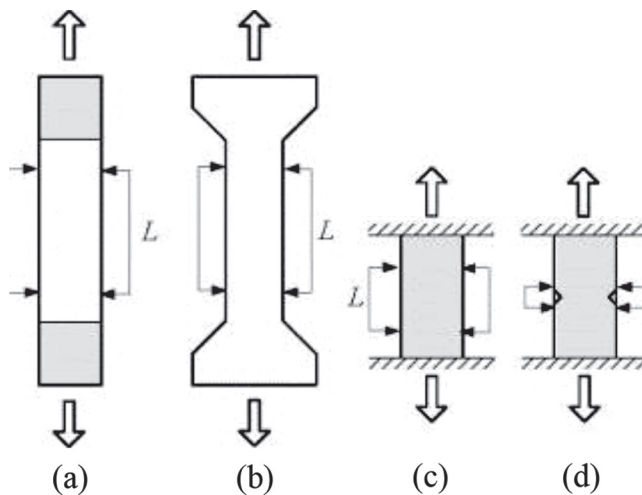


Fig. 5.2a—Examples of tensile tests of FRC composites: (a) thin sheets; (b) dog-bone shaped; (c) bonded ends fixed against rotation; and (d) bonded ends notched and fixed against rotation.

that a standard test allows measurement of the key properties being investigated. Moreover, it is recommended to record crack distribution, spacing, and width at maximum post-cracking or ultimate stress.

Figure 5.2a illustrates examples of specimens that have been used for direct tension testing. The specimen shown in Fig. 5.2a(a) is appropriate for thin sheets and plates. In such a specimen, the ends are provided with thin aluminum plates bonded to their surface to minimize damage by the jaws of the tensile grips. The dog-bone shaped specimen in Fig. 5.2a(b) is characterized by a cross section with bell-shaped ends to ensure that failure occurs within the body of the specimen, thereby allowing strains $\Delta L/L$ to be measured within the gauge length L . The specimen in Fig. 5.2a(c) can be a prism or a cylinder with its ends bonded to stiff steel loading platens. Figure 5.2a(d) shows a notched tensile prism, or cylinder, used to evaluate the stress versus crack opening, σ - w , under tensile loading. In this case of strain-softening FRC, the crack opening can be obtained from the measured displacement ΔL and cleansed out of the elastic strain, as in the right-hand side of Fig. 5.2b.

The test specimens presented in Fig. 5.2a(a), (b), and (c) are suitable for strain-hardening FRCs, where multiple cracking is expected before the localization of a single unstable crack. Stress is calculated from the load and strain from the displacement as shown on the left-hand side of Fig. 5.2b.

The notched prism test of Fig. 5.2a(d) is particularly suitable for a strain-softening FRC composite where localized failure is expected, or to supplement information from tests in Fig. 5.2a(a), (b), and (c). Yang and Fischer (2005) have shown that information from a sufficient number of such tests (Fig. 5.2a(d)) and their variability can be used to predict the entire tensile stress-strain response of a strain-hardening FRC.

Because no standard test has been developed for FRC, available research investigations on the subject show a wide variety of sizes. Because size effects are significant, correlation between different investigations cannot be properly

Strain Hardening Composite	Strain Softening Composite
Area: A Strain: $\varepsilon = \frac{\Delta L}{L}$	Crack Width: $w = \Delta L - L \frac{P}{A} \approx \Delta L$

Fig. 5.2b—Computation of strain or approximate crack opening.

carried out. Until a standard test is developed, the following four recommendations can be used as a guide for specimen size (Naaman and Reinhardt 2003):

- 1) Use prisms of square or circular cross section, with a side or diameter equal at least to 2 in. (50 mm), three times the fiber length, six times the size of maximum aggregate, both of these, or whichever is larger.
- 2) Gauge length for measuring strain should be at least two to three times the minimum size (side or diameter) of the tensile prism.
- 3) For tests involving thin sheets, the specimen section can be rectangular, with the longer side satisfying at least the aforementioned criteria and the smaller side equal to sheet thickness.
- 4) Tensile prisms with tapered or specially confined ends are often used for direct tensile tests and, when carried out properly, should lead to realistic results (Graybeal and Baby 2013).

Using the proper test equipment is essential when stable softening behavior is required. The tests should be carried out in closed-loop control of a very stiff testing apparatus. Note that the shape of the softening branch of the tensile response depends on the boundary conditions. In case of a pin-ended boundary condition, the specimen is free to rotate when the onset of the macrocracking takes place and no additional restraint is introduced. In the case of a fixed end platen, the eccentricity originated by the crack opening has to be balanced by the introduction of a bending moment that contributes to the generation of multiple cracking. This behavior influences, to a certain extent, the softening behavior where a horizontal plateau could occur when a second macrocrack develops. The higher cracking density found in cases of fixed boundary conditions generally leads to larger values of fracture toughness relative to the ones achieved in uniaxial tension tests conducted using pin-ended platens (van Mier et al. 1996; van Vliet 2000).

To ensure stable tensile tests, the control signal for the servo testing equipment should be the average signal of the LVDTs placed in the corners of prismal specimens or the notched controlled fracture surface (Fig. 5.2c). It is

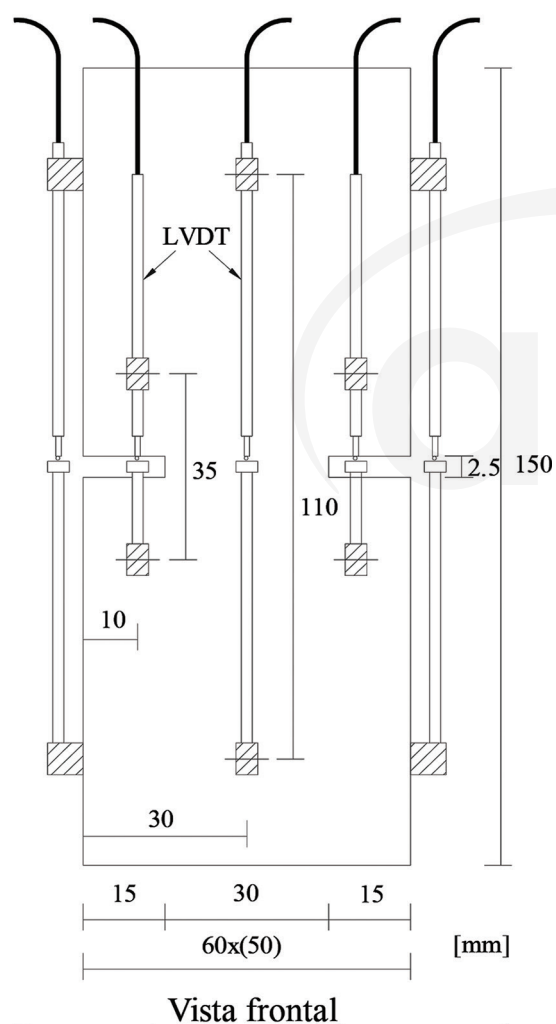
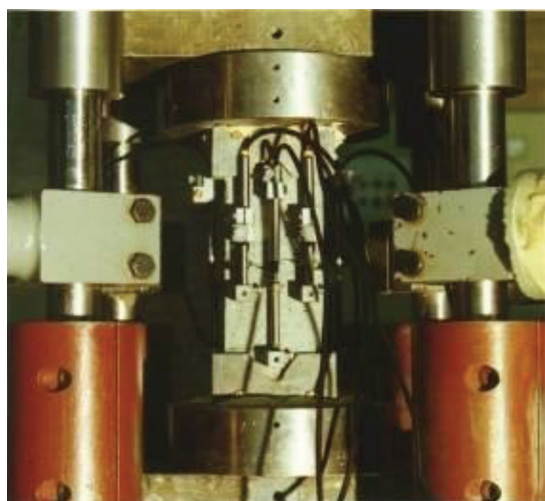
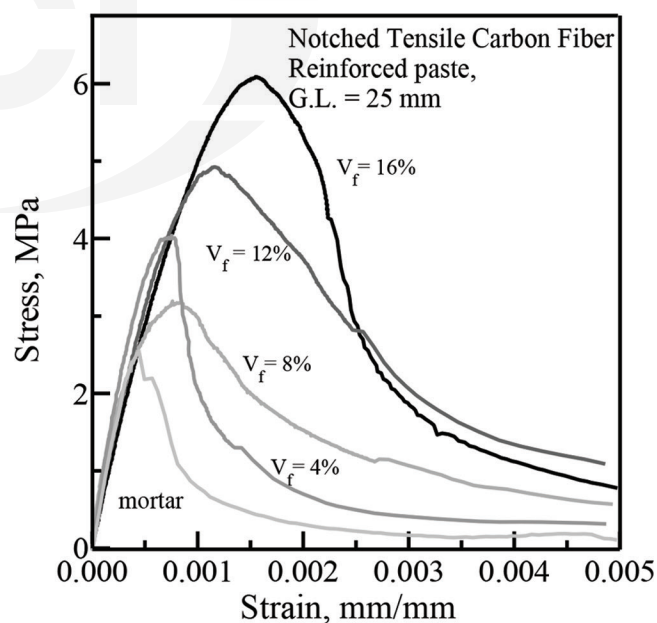


Fig. 5.2c—Arrangement of the measuring devices to ensure stable tensile tests (Hordijk 1991). (Note: 1 in. = 25.4 mm.)

assumed that a three-dimensional (3-D) nonuniform crack opening process can occur in the critical crack. In cylindrical specimens, place three LVDTs around the specimen, forming 120-degree angles between consecutive LVDTs.



(a)



(b)

Fig. 5.2d—(a) Test configuration by Mobasher and Li (1996); and (b) tensile stress-versus-strain curves of carbon fiber-reinforced pastes. (Note: 1 in. = 25.4 mm; 1 ksi = 6.9 MPa.)

Mobasher and Li (1996) developed a uniaxial tensile testing methodology by using double-edge notched and unnotched prismatic specimens (Fig. 5.2d(a)). Figure 5.2d(b) shows the typical results for a cement paste reinforced with

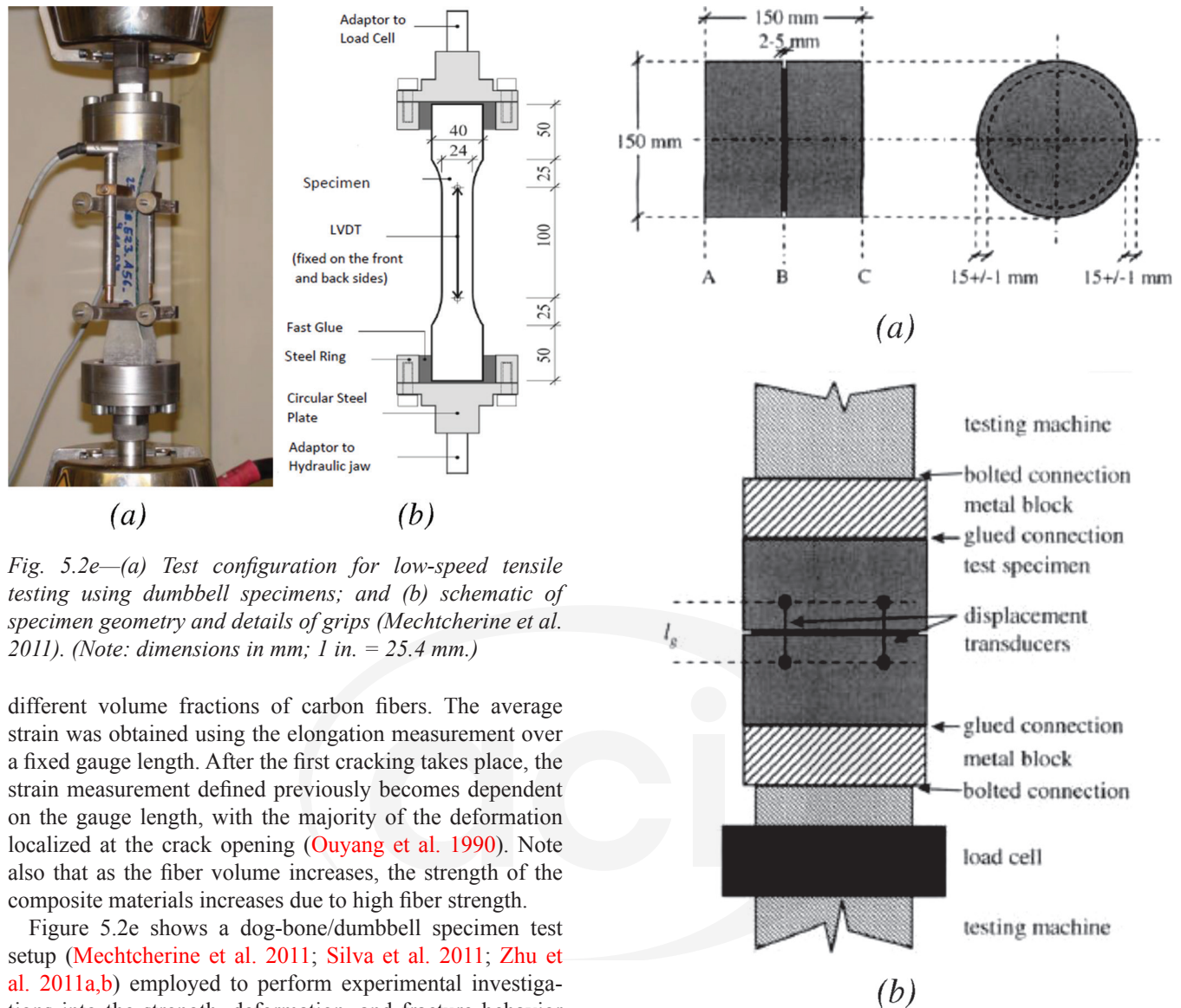


Fig. 5.2e—(a) Test configuration for low-speed tensile testing using dumbbell specimens; and (b) schematic of specimen geometry and details of grips (Mechtcherine et al. 2011). (Note: dimensions in mm; 1 in. = 25.4 mm.)

different volume fractions of carbon fibers. The average strain was obtained using the elongation measurement over a fixed gauge length. After the first cracking takes place, the strain measurement defined previously becomes dependent on the gauge length, with the majority of the deformation localized at the crack opening (Ouyang et al. 1990). Note also that as the fiber volume increases, the strength of the composite materials increases due to high fiber strength.

Figure 5.2e shows a dog-bone/dumbbell specimen test setup (Mechtcherine et al. 2011; Silva et al. 2011; Zhu et al. 2011a,b) employed to perform experimental investigations into the strength, deformation, and fracture behavior of strain-hardening FRC composites subjected to low- and high-rate tensile loading ranging from 0.0001 to 50 s⁻¹.

RILEM (2000, 2001) recommends a cylinder with a diameter of 6 in. (150 mm) and a height of 6 in. (150 mm), in which a 0.6 in. (15 mm) deep circumferential notch is cut at midheight. The specimen is glued to the press platens by means of an epoxy resin (Fig. 5.2f) and instrumented with six LVDTs: three with a gauge length of 2 in. (50 mm) and placed to measure the crack opening displacement (COD); and the other three measure the relative displacement between the two end platens of the press. The recommended displacement rates are 0.2×10^{-3} in./min (5 μ m/min) up to a displacement of 0.004 in. (0.1 mm) and 0.004 in./min (100 μ m/min) until the completion of the test (approximately 0.8 in. [20 mm] COD).

Similar test configurations were used by Barros et al. (1994) (Fig. 5.2g) and by Colombo et al. (2010) (Fig. 5.2h). Notched cylinder specimens were placed in a fixed plates test setup. Three half-bridge LVDTs were placed at 120 degrees along the specimen perimeter and astride the notch over a gauge length of 2 in. (50 mm) to measure the COD. Moreover, three full-bridge LVDTs, still placed at 120-degree intervals, were

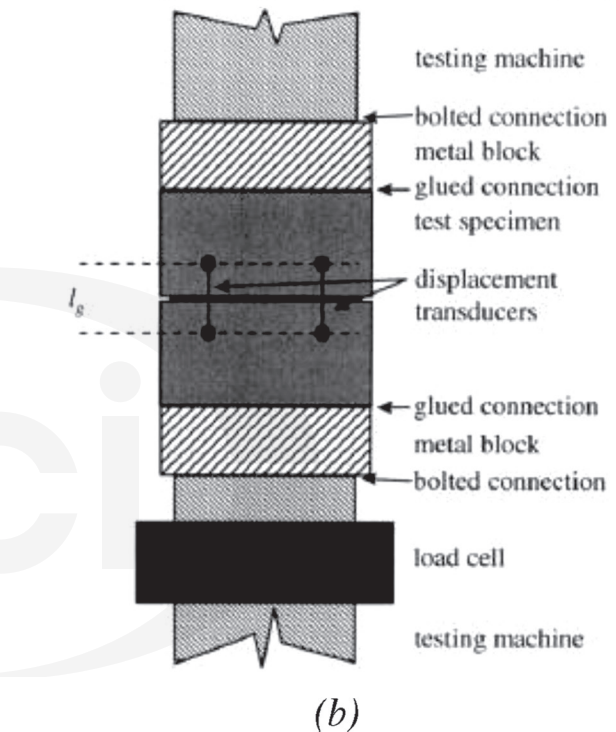


Fig. 5.2f—(a) Specimen geometry; and (b) schematic of the test configuration as per by RILEM (2000, 2001). (Note: 1 in. = 25.4 mm.)

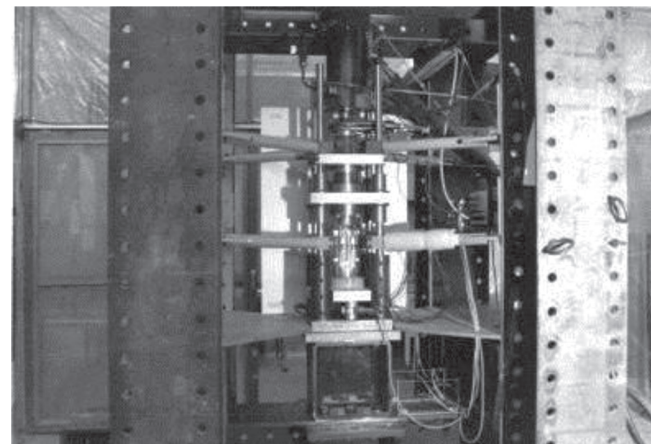


Fig. 5.2g—Photo of a testing rig used in tensile tests (Barros et al. 1994).

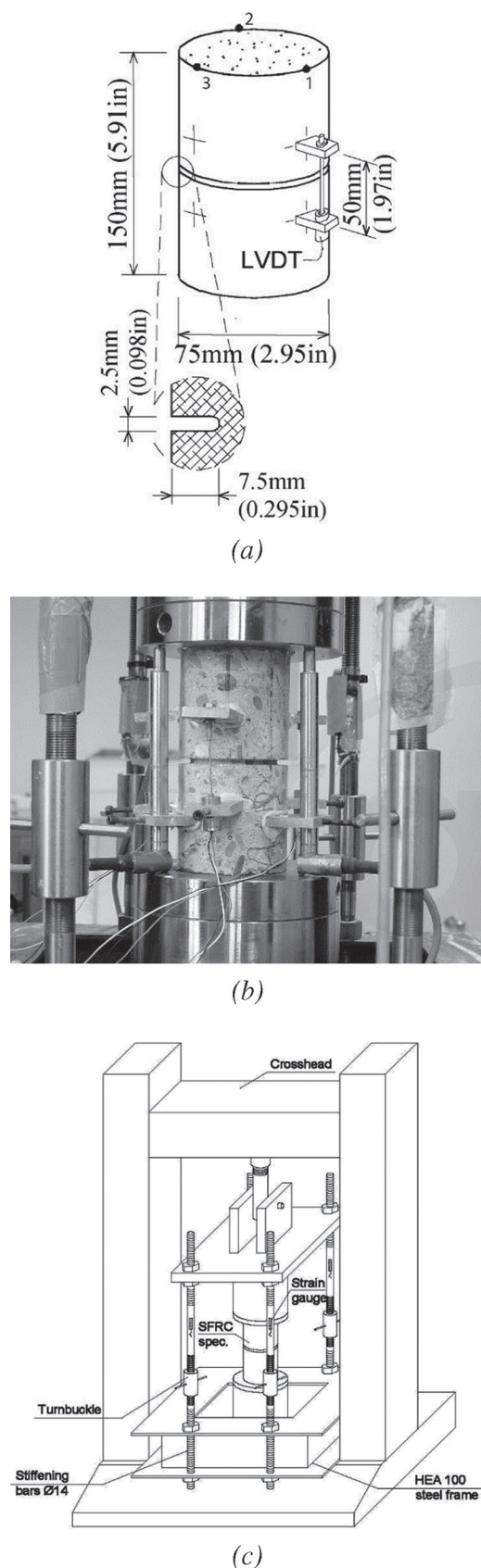


Fig. 5.2h—(a) Geometry of the notched cylinder for uniaxial tensile test of FRC; (b) direct tensile test: detail of instrumentation; and (c) schematic of the configuration (Colombo et al. 2010).

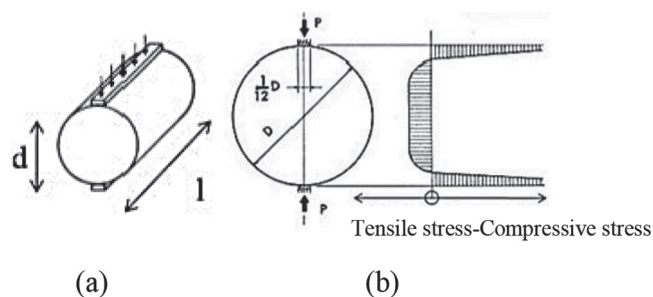


Fig. 5.3—(a) Schematics of splitting tensile test; and (b) stress distribution along diameter fracture plane.

used to measure the relative displacement between the end platens of the press. One of these displacements was used as a feedback signal for the test. As an example of testing protocol, the displacement rate applied during the test was equal to 0.0016×10^{-3} in./s (0.04 $\mu\text{m/s}$) in the precracking and softening regime up to 0.024 in. (0.6 mm) crack opening, and then shifted up to 0.016×10^{-3} in./s (0.4 $\mu\text{m/s}$) from there onward.

5.3—Indirect tension tests

Although direct tensile testing is the most appropriate method to determine the tensile strength and stress-versus-strain/crack opening constitutive relationships of FRCs, it is not recommended for standard testing of new FRC mixtures. Direct tensile tests are difficult to carry out and interpret. Because specimens are normally small, the number of fibers in the governing fracture plane is small and might not be representative of the fiber orientation effect, due to the method of manufacturing (fib 2013). Fiber orientation, however, can be effectively governed through the casting flow by suitably exploiting the performance of the concrete mixture in the fresh state (for example, in the case of high flowability or self-consolidating ability) (Ferrara et al. 2011). From a design-oriented perspective, the problems related to dispersion and orientation of fibers should be considered when characterizing mechanical behaviors of the material. Due to the high sensitivity of FRC mechanical properties to the alignment of fibers, with respect to applied tensile stress, results could be an even stronger anisotropy.

To overcome the inherent difficulties of a direct tension test, alternative test methods have been introduced that fall under the indirect tensile tests category. They are similar to the Brazilian splitting test (ASTM C496/C496M; EN 12390-6), where a compressive load is applied to a cylinder specimen, along two diametrically opposed generating lines of the cylinder. A uniform transverse tensile stress state is thus generated almost along the diameter plane parallel to the applied loads, which leads to specimen failure once the tensile strength of the material is reached (Fig. 5.3). This avoids the need to glue specimen end faces to press platens or to detail specimen ends to prevent end fracture.

5.3.1 Wedge splitting test—The wedge splitting test (WST) (Fig. 5.3.1(a)), originally proposed by Linsbauer and Tschegg (1986) and later developed by Brühwiler and Wittmann (1990), which determines the fracture behavior of plain concrete, has been used for FRCs as well (Elser et al.

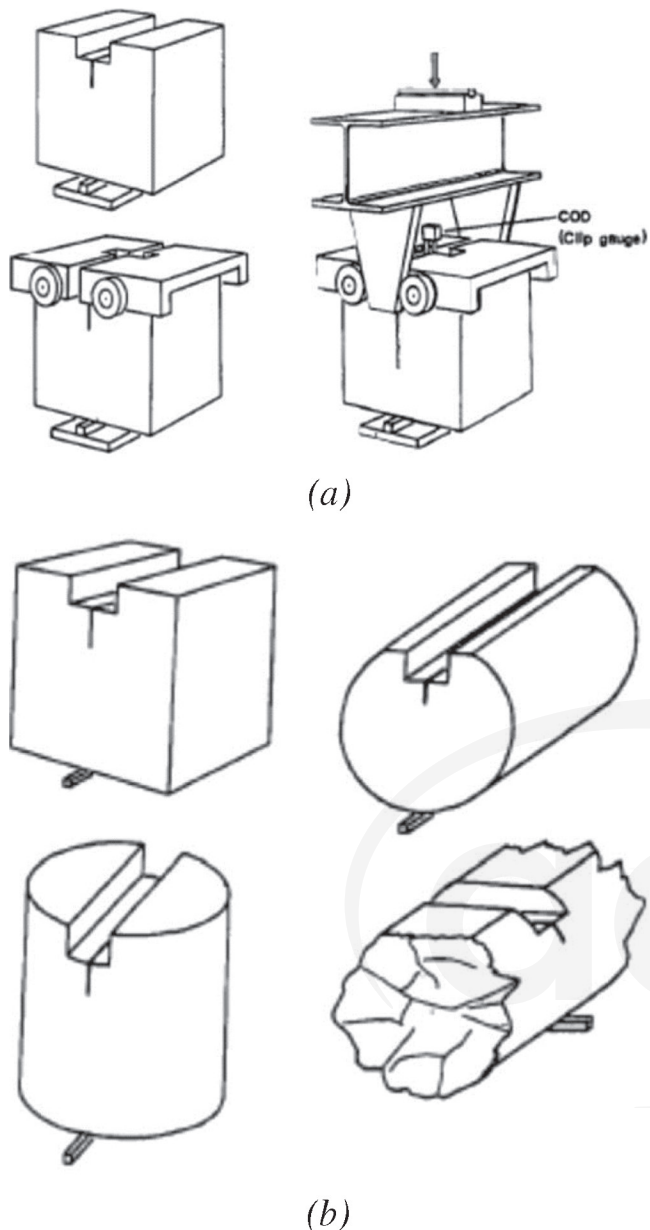


Fig. 5.3.1—(a) WST principle; and (b) specimen shapes (Brühwiler and Wittmann 1990).

1996a,b; Löffgren et al. 2004). Benefits of this test method include the need for a lower amount of material required to cast test specimens than, for example, bending tests, and the use of simple testing equipment. Different specimen sizes have been proposed, including those fabricated in standard molds with freshly poured concrete or ones obtained from cores drilled from existing structures (Fig. 5.3.1(b)). It is understood that cast cubic specimens have been used for FRC testing. The specimen size consists of 8 in. (200 mm) cubes with side notches and a starter groove from 2 to 3 in. (50 to 75 mm) deep that have been used for fibers from 2 to 2.4 in. (50 to 60 mm) in length. Smaller 6 in. (150 mm) cubes, with scaled depth of the starter groove, have been used for 1.4 in. (35 mm) long fibers.

Crack openings can be measured either by a clip gauge at the notch mouth or by LVDTs on the side of the specimen

(Kim and Bordelon 2015). Inverse analysis is required to obtain a stress-crack opening relationship (Löffgren et al. 2004). Variation in the number of fibers across the notch preordained fracture plane is the major contributing factor to the experimental scattering. Because of the larger fracture area to specimen volume ratio, results of replicate specimens are likely to be affected by lower variability than in the case of other tests (Kim and Bordelon 2015).

5.3.2 Double edge wedge splitting (DEWS) test—di Prisco et al. (2013) conceived a double-edge wedge splitting (DEWS) geometry, as shown in Fig. 5.3.2. The trajectory of principal compressive stresses is deviated from the fracture plane because of the suitably conceived test geometry and a uniaxial tensile stress state (pure Mode I fracture) is likely to be induced along the same fracture plane. As a result, once the transverse tensile stress induced along the ligament by the applied compressive load is calculated by means of simple equilibrium equations and the crack opening displacement (COD) across the fracture plane is measured, the stress-COD relationship is directly identified from the results of DEWS tests without any need for inverse analysis. The spatial uncoupling between tensile and compressive stresses represents a distinct feature of the DEWS test. This also avoids the development of plastic deformations in the small area beneath the loading device, which may be quite significant in the case of even highly tough and ductile FRC-based materials. The same result cannot be achieved with the Brazilian splitting tensile test, which identifies the first cracking strength of the material when fibers do not contribute to stable crack propagation (Denneman et al. 2011).

As discussed, the DEWS test distinctively features the possibility of inducing a pure Mode I fracture on the critical cross section of the specimen (ligament). This is accomplished through a tensile stress state indirectly induced by applying a compressive load similar to the Brazilian test (5.3), except the transverse tensile and the longitudinal compressive stresses should be kept uncoupled. Begin with a thin square specimen with a side equal to approximately 6 in. (150 mm), a thickness related to the length of the fibers used in the mixture design, and two triangular grooves with a 45-degree inclination that have been created along two opposite edges.

The load application device, which is a steel roller directly pushed by the machine platens, is accommodated into these grooves. The specimen geometry should feature two notches starting from the groove vertexes. This is instrumental in clearly identifying the ligament and moving the crack tip ahead of the highly stressed load application zones. When the roller is wedged into the groove, the 45-degree inclined groove edges deviate the compressive stress paths away from the ligament, subjecting it to a pure tensile stress-state indirectly induced by the wedging action. Contact between the rollers and groove edges is carefully detailed to minimize friction that, through a tangential force, could affect the transverse tensile load induced on the ligament (Fig. 5.3.2). Brass platens were applied by di Prisco et al. (2013) to the groove edges and three different contact solutions were examined: direct contact between the steel roller and the brass plates; insertion of a Teflon® layer; and a graphite as a lubricant. As from simple equilibrium consid-

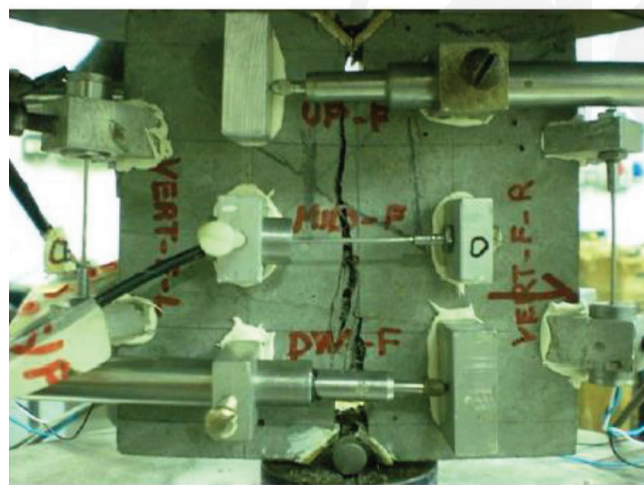
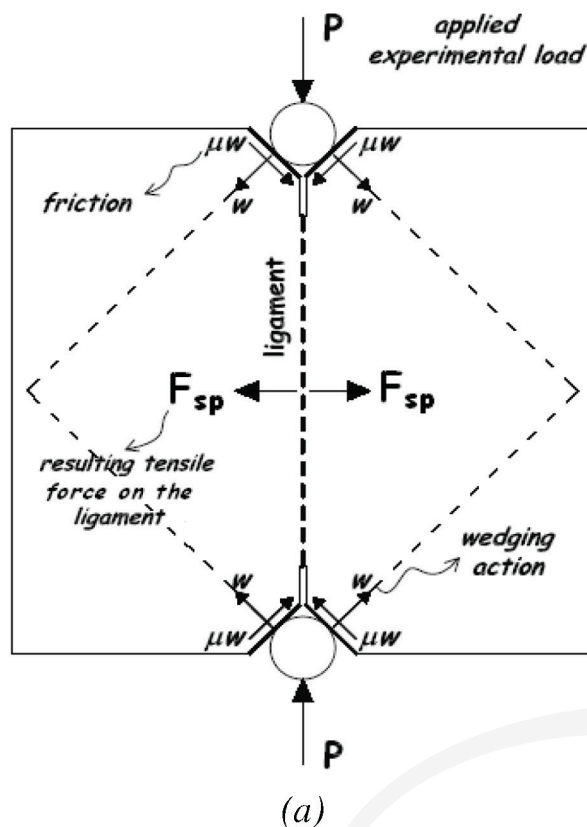


Fig. 5.3.2—(a) Geometry and force diagram in DEWS test specimen; and (b) an instrumented specimen (di Prisco et al. 2013).

erations (Eq. (5.3.2)), the transverse splitting tensile force F_{sp} , induced by the applied vertical load P , is calculated as

$$F_{sp} = P \frac{\cos \theta - \mu \sin \theta}{\sin \theta + \mu \cos \theta} \quad (5.3.2)$$

where θ is the inclination angle of the wedge grooves ($= 45$ degrees), and μ is the friction coefficient. This depends on

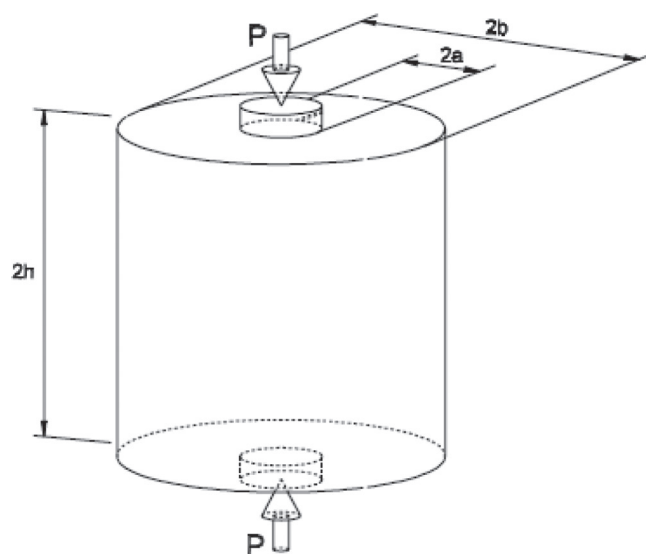


Fig. 5.3.3a—Barcelona test layout (Molins et al. 2009).

the contact detail and can be identified by means of a dedicated testing apparatus, conceived to simulate the behavior of the specimen under the applied compressive vertical load, and measure the transverse tensile force actually transmitted to the intended fracture surface. The most reliable results were obtained by gluing brass platens to the groove edges and lubricating the contact surface with graphite, which resulted in a friction coefficient $\mu = 0.06$ and, consequently, in a splitting tensile force $F_{sp} = 0.89P$.

Figure 5.3.2(b) shows a set of LVDTs used on both faces of the specimen to measure the COD and obtain complete information over the nominal stress ($F_{sp}/\text{ligament area}$) versus COD relationship of the tested fiber-reinforced cement composites (FRCCs). Details about the reliability of the procedure for the identification of a stress-versus-strain/crack opening relationship for FRCCs straightforwardly from the DEWS tests can be found in di Prisco et al. (2013).

5.3.3 Double punch-Barcelona test—The double punch-Barcelona test (Molins et al. 2009) consists of compressing a cylindrical FRC concrete specimen placed vertically within two steel circular punches centered at the top and bottom surfaces (Fig. 5.3.3a). Normally the height and diameter are identical with a ratio of the punch diameter to specimen diameter equal to 1:4. The most commonly used cylinder dimension is 6 in. (150 mm). The failure mechanism (Fig. 5.3.3b(a)) normally presents three radial cracks, although in some cases only two or four planes can be observed. It was also demonstrated that normal working errors of 0.2 in. (5 mm) eccentric placing of the punches presented no noticeable effect on the results. Inverting the up-down position of the molded face did not affect results either. Two main advantages of the test are:

- 1) The specimen shape and size, which can be easily handled and also easily cored from existing structures.

- 2) Simplicity of the test configuration and procedure, which employs a compression testing machine and measures the total circumferential crack opening, which is not notably different than compression tests. Also, test results feature a lower stan-

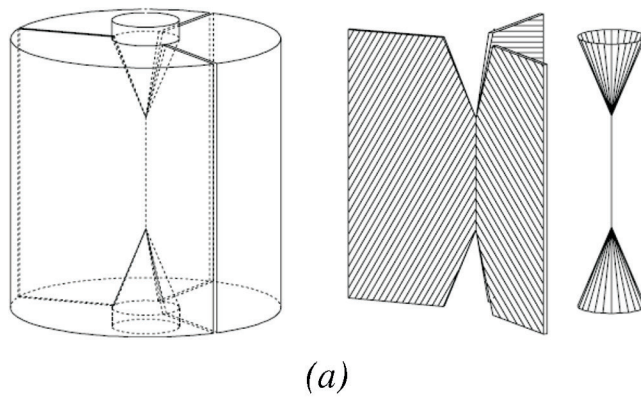


Fig. 5.3.3b—(a) Barcelona test failure mechanisms surfaces; and (b) specimen after testing (Molins et al. 2009).

dard deviation than those obtained by bending tests or direct tension test, because of the larger specific failure surface.

In the Barcelona test, both total circumferential opening displacement (TCOD) and vertical displacement between loading plates are measured. The TCOD is measured by a circumferential extensometer placed at midheight of the specimen, as shown in Fig. 5.3.3c. The test is controlled by vertical displacement between the press plates, which should be applied at a rate of 0.02 in./min (0.5 mm/min).

During testing, the specimen undergoes three phases that depend on integrity and the resistant mechanism. In the first stage, which coincides with the initial load application, the radial internal stress generated by the applied compressive point load is resisted by the concrete matrix that does not show any major cracks. Once stress reaches the tensile strength of the material, the specimen enters the second stage. The upper and lower wedges (Fig. 5.3.3b) are abruptly formed. These wedges are conical in shape with a diameter equal to that of the punches used in the test. Between two

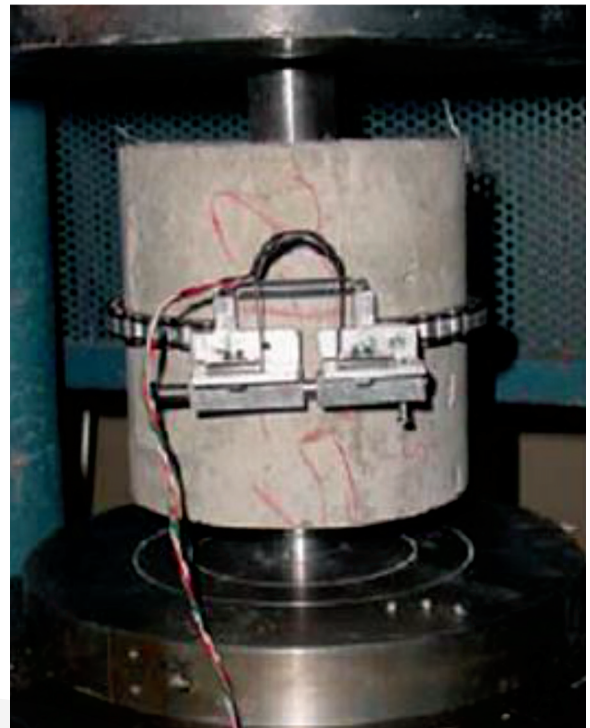


Fig. 5.3.3c—Instrumented Barcelona test specimen (Molins et al. 2009).

and four major cracks appear, dividing the specimen in parts that are kept together by the fibers bridging them. As the cracks stabilize, the third stage begins, following a kinematic mechanism that involves sliding between the conical wedge and the fragmented specimen. During this stage, the debonding and pullout of the fibers dissipates more energy, which leads to a significant increase in toughness. Alignment of the fibers according to the generated stresses in the plane perpendicular to the loading direction improves the post-cracking response. This is due to both an increased number of effective fibers crossing the crack and an improved pullout behavior of those fibers with low angles of inclination relative to the cracking plane.

The test proved highly suitable to measuring the total energy dissipated along the fracture process and classifying the toughness of the material. The test, however, provided little, if any, information on the stress-crack opening relationship, at least to the present state of published research, mainly because of the unpredictability of the number of fracture planes that will be created as a result of the cracking process.

Moreover, the use of a circumferential extensometer is required to measure the circumferential displacement in the post-cracking regime. To simplify and generalize this test standardized in Spain (AENOR UNE 83515), Carmona Malatesta et al. (2012, 2013) and Pujadas et al. (2013) performed extensive experimental investigations, with reference to concretes containing different types and dosages of fibers, in which the circumferential and axial displacements of the specimens were measured. Results showed that a linear correlation holds between these displacements in a wide range of post-cracking regimes, with low variability

among replicate tests. This allows the use of axial displacement measurements instead of circumferential ones.

Effects of specimen size and origins was investigated (Aire et al. 2015) and identification of constitutive relationship from the Barcelona test was also addressed (Blanco et al. 2014).

Due to the specimen shape and size, no information about the fiber orientation dependence of the material behavior could be obtained from the testing methodology as described previously.

To overcome this drawback, Pujadas et al. (2014) proposed a more comprehensive approach, the multidirectional double punch test, in which the use of 6 in. (150 mm) side cubic samples was recommended. Cubic specimens cast in cubic molds, cubic samples cut from prismatic beams at 6 in. (150 mm) of the edge of the beam (CUT1, Fig. 5.3.3d(a)) and cubic samples obtained also from prismatic beams by cutting at 3 in. (75 mm) and 9 in. (225 mm) from the edge of the beam (CUT2, Fig. 5.3.3d(b)) were studied. The different boundary conditions from concrete pouring, formwork geometry, and

the wall effect for each of the three specimen types tested induced different fiber orientation. This was mainly in the case of highly flowable and self-consolidating FRCs. In this sense, the use of a cubic specimen allows three different loading conditions (directions X-, Y-, and Z-axis), activating different groups of fibers in each case (Fig. 5.3.3e). Therefore, a different toughness and residual tensile strength can successfully be obtained in each loading direction (Pujadas et al. 2014).

CHAPTER 6—FLEXURAL BEHAVIOR: STRENGTH, TOUGHNESS, AND CLOSED-LOOP TESTS

6.1—General

To overcome the inherent difficulties in performing a direct tension test, several standards, as hereafter reviewed, recommend bending tests, either three-point bending or four-point bending. Specimen manufacturing procedures are also recommended in the related standards, to avoid any preferential alignment of the fibers that can affect measured response. In the case of self-consolidating FRC, specimen casting may be tailored to reproduce, as close as possible, the casting procedure of the intended application, mainly with reference to the flow-induced orientation of the fibers with respect to the applied tensile stress.

An inverse analysis procedure is needed to identify the uniaxial tensile stress versus crack opening constitutive relationship from the results of bending tests (ACI 544.8R). Simplifying assumptions that are based on uncracked section modulus and linear stress distribution over the cross section, leading to an equivalent elastic stress, can be largely unconservative and lead to significant overestimation of the true material strength.

Generally, a bend-loading fixture should eliminate extraneous support settlements. Using a sufficient number of rollers to release various degrees of freedom and adjust to various deformations of the sample under load is, therefore, essential in applying a continuous line load throughout the test. A good control parameter for a flexural test is the crack mouth opening displacement (CMOD) parameter, which measures the crack/notch opening across its mouth at the tensile face of the flexural sample. Figure 6.1 shows an example of a closed-loop flexural test setup and related results. A test span of 12 in. (300 mm) and a notch depth of 0.5 in. (13 mm) were used. The deflection of the beam was also measured using a spring-loaded linear variable differ-

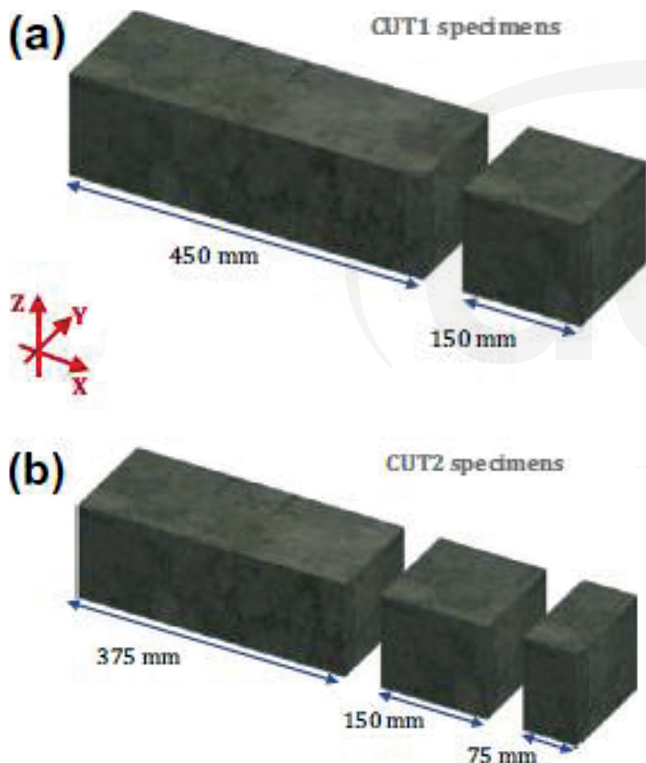


Fig. 5.3.3d—Scheme of cubic samples cut from prismatic beams (Pujadas et al. 2014). (Note: 1 in. = 25.4 mm.)

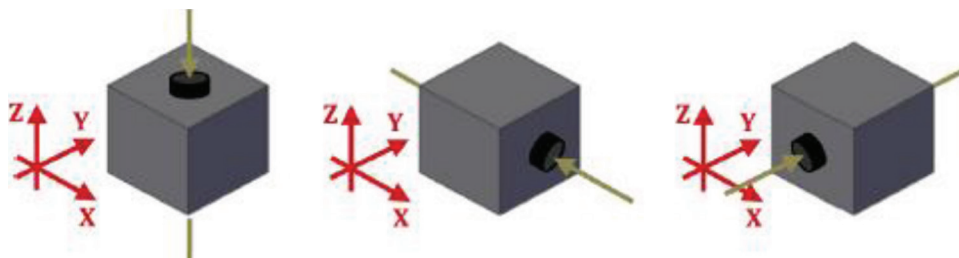


Fig. 5.3.3e—Scheme of multidirectional double punch test methodology (Pujadas et al. 2014).