

ACI 544.4R-18

Guide to Design with Fiber-Reinforced Concrete

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Guide to Design with Fiber-Reinforced Concrete

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Guide to Design with Fiber-Reinforced Concrete

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New developments in materials technology and the addition of field experience to the engineering knowledge base have expanded the applications of fiber-reinforced concrete (FRC). Fibers are made with different materials and can provide different levels of tensile/flexural capacity for a concrete section, depending on the type, dosage, and geometry. This guide provides practicing engineers with simple, yet appropriate, design guidelines for FRC in structural and nonstructural applications. Standard tests are used for characterizing the performance of FRC and the results are used for design purposes, including flexure, shear, and crack-width control. Specific applications of fiber reinforcement have been discussed in this document, including slabs-on-ground, composite slabs-on-metal decks, pile-supported ground slabs, precast units, shotcrete, and hybrid reinforcement (reinforcing bar plus fibers).

Keywords: crack control; fiber-reinforced concrete; flexural toughness; macrofiber; moment capacity; precast; residual strength; shear capacity; shotcrete; slabs-on-ground; steel fibers; synthetic fibers; tensile strength; toughness.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The aim of this guide is to provide practicing engineers with design guidelines and recommendations for fiber reinforcement. Several approaches for designing fiber-reinforced concrete (FRC) have been developed over the years that are based on conventional design methods modified by special procedures to account for contributions of the fibers. These methods generally modify the internal forces in the member to account for the additional tensile capacity

provided by the fibers. When compared with full-scale test data, these methods have provided satisfactory designs for FRC members (Parra-Montesinos 2006; Moccichino et al. 2006; Altoubat et al. 2009).

Concrete is a brittle material that is strong in compression but weak in tension. Steel bars are traditionally used to carry the tensile forces after concrete has cracked in structural applications. In reinforced concrete, the tensile strain of the concrete at cracking is much lower than the yield strain of the steel bars, which results in cracking of concrete before any significant load is transferred to the steel. Steel reinforcement is also used to limit the crack widths under specified levels for serviceability requirements. Unlike reinforcing bars, fibers are uniformly distributed in the volume of concrete; hence, the distance between fibers is much smaller than the spacing between bars. Fibers can provide post-crack tensile and flexural capacity and crack-width control in concrete elements.

Natural sources of reinforcement were used for brittle construction materials more than 3000 years ago, such as straw reinforcement in mud bricks. The first scientific studies on the use of steel fibers in concrete date back to the 1960s (Romualdi and Batson 1963; Naaman and Shah 1976). Since then, thousands of projects have been successfully completed using fiber reinforcement, including slabs-on-ground, composite steel decks, slabs-on-pile, precast, and shotcrete.

The major differences in the proposed methods are in the determination of the increase in tensile capacity of concrete provided by the fibers and the manner in which the total force is calculated. A conservative but justifiable approach in structural members such as beams, columns, walls, or elevated suspended slabs is that reinforcing bars should be used to support the total tensile loads. ACI 544.6R, however, describes the design for elevated suspended slabs where steel fibers are used as the primary reinforcement along with a minimum of continuous bars from columns to columns. Fibers can be used, in general, to supplement and reduce the reinforcing bars in various structural members. In applications where the presence of continuous reinforcement is not essential to the safety and integrity of the structure such as slabs-on-ground, pavements, overlays, shotcrete linings, slabs-on-piles (ACI 544.6R), and some precast units, fibers may be used as the sole means of reinforcement.

Fibers reliably control cracking and improve material resistance to deterioration as a result of fatigue, impact, and shrinkage, or thermal stresses. Fibers can contribute to the improved performance of concrete members in two ways: 1) by resisting the tensile stresses and, therefore, playing a structural role; or 2) by controlling crack development and, therefore, improving the durability of concrete. When fibers are intended to contribute to the structural performance of an element or structure, the FRC should be designed accordingly and the fiber contribution to the load-bearing capacity should be properly assessed and justified.

The commercial momentum for using steel fibers occurred during the 1970s for industrial floors as a major application. Other applications for steel fibers include composite metal

deck, pile-supported slabs, precast units, and shotcrete. Synthetic macrofibers became available in the 1990s with applications such as slabs-on-ground, composite decks, pavements, shotcrete, and some precast units. Steel fibers and synthetic macrofibers can be viable alternatives for full replacement of steel bars in concrete elements with continuous support such as slabs-on-ground or shotcrete. For free-standing elements such as suspended slabs and tunnel lining segments, steel fibers at medium to high dosages have been shown to successfully replace a large portion of steel bars in the section (ACI 544.6R; ACI 544.7R).

The term “fibers” in this document only concerns macrofibers made of steel and polymeric (polyolefin) synthetic materials; hence, the design guides are not applicable to microfibers. Fiber diameter of 0.012 in. (0.3 mm) is the defining limit between microfibers and macrofibers. Synthetic microfibers have been used in concrete since the 1970s and are solely intended to control plastic shrinkage cracks (and sometimes drying shrinkage cracks) without any significant improvement in the mechanical properties of hardened concrete (ACI 360R). They may also affect the bleeding rate of fresh concrete, improving the near-surface properties of the hardened concrete. These fibers have been used to reduce the spalling of concrete exposed to fire and explosion.

When macrofibers are used in concrete to replace steel reinforcement, they can provide enhanced ductility, toughness, and durability. Fiber dosage can be engineered to provide a desired level of crack control, post-crack tensile and flexural capacity, or both. Similar to steel bars for which the size and spacing are calculated to provide the required reinforcement ratio, the dosage of fibers is also calculated to satisfy engineering requirements. Parameters affecting the performance of FRC include fiber type (material, size, and geometry), as well as bond characteristics and concrete mixture design. Fiber dosage may be limited by the practicality of their use in concrete; however, chemical admixtures are widely used for incorporating higher dosages of fibers. In certain applications, especially with congested steel bars, hybrid reinforcement (steel bars plus fibers) can be a viable alternative to conventional reinforcement. Using FRC may allow for applying alternative construction techniques—for example, tailgating concrete instead of pumping it for slabs-on-ground when steel reinforcement is eliminated. This can help in scheduling the project, resulting in a more cost-effective construction. Improved job-site safety is also among the benefits of using fibers from the reduced handling or tripping over the reinforcement at the job site. Using fibers can additionally eliminate the problems caused by misplacing conventional steel at its design position. The durability aspects of FRC and the associated benefits from fibers are extensively presented in ACI 544.5R.

1.2—Scope

Although FRC has been used since the 1960s, there are no agreed design approaches in North America for some of its applications. Unlike reinforced concrete with steel bars or welded wire mesh, the design of fiber reinforcement is not

properly covered by national design codes. In Model Code 2010 (fib 2013), sections were added for new developments in the design of FRC as a part of the building code. ACI 318 has limited discussion on the use of fibers, such as provisions for using steel fibers as shear reinforcement in flexural members. ACI 360R presents the basics of fiber-reinforced slabs-on-ground, and ACI 506.1R discusses the design and application of fiber-reinforced shotcrete. It is the intent of this document to provide practicing engineers with simple yet appropriate design guidelines and state-of-the-art applications for FRC. This guide is intended for designers who are familiar with structural concrete containing conventional steel reinforcement, but who may need more guidance on the design and specification for FRC. In this document, fibers are treated as reinforcement in concrete and not as an admixture.

This guide discusses the types and typical dosages for fibers, general material properties, and available test methods for characterization of FRC. Explaining the design concepts and existing guidelines for fiber reinforcement is the focus of this document, including constitutive laws, design for flexure, design for shear, and design for crack-width control. This is further extended to specific applications for slabs-on-ground, composite slabs-on-metal decks, pile-supported ground slabs, precast units, shotcrete, and special applications. The final portion of this guide provides brief recommendations for specifying and building with FRC that includes general guidelines for mixing, placing, and finishing.

Although there are several types of fibers commercially available, this document is only applicable to steel fibers and polyolefin synthetic macrofibers that comply with ASTM C1116/C1116M. The formulas and applications discussed in this document should be verified for any other types of fibers. This document provides design guidelines based on the mechanical and structural properties of FRC as a composite material and not individual fiber products. Different fiber products may exhibit different performances in concrete; hence, it is crucial to design and specify FRC properties in addition to fiber types and materials that are suitable to achieve such properties.

1.3—Historical aspects

1.3.1 Introduction—Prior to presenting test methods, design philosophies, and applications of FRC, it is beneficial to review some of the historical aspects of this technology. This section summarizes the historical background of FRC since its development, including the mechanical characterization, analytical modeling, and test methods. Some of the earlier design and analysis guides addressing FRC during the 1970s and 1980s are discussed in Hoff (1982), ACI SP-44, SP-81, SP-105, and Shah and Skarendahl (1986). It should be noted that most of the earlier studies and applications of FRC incorporated steel fibers only.

1.3.2 Mechanical characteristics and modeling—Understanding the mechanical properties of FRC and their variation with fiber type and dosage is an important aspect of successful design. Fibers influence the mechanical properties of concrete in all failure modes, including compression.

tension, bending, shear, impact, and fatigue (Gopalaratnam and Shah 1987a). Excluding plain matrix properties, the most important variables governing the properties of FRC are the fiber bond efficiency and dosage. Fiber bond efficiency is controlled by the resistance of the fibers to pullout, which in turn depends on the bond strength at the fiber-matrix interface. Certain types of fibers may go through elongation and eventual rupture during the energy-absorbing process.

Pullout-type mechanisms are gradual and ductile compared with the more rapid and possibly tensile failure of fibers in tension. An alternative mechanism is provided by fibers whose anchoring system prevents pullout and provides ductility through the elongation of the fiber itself. The strengthening mechanism of the fibers involves transfer of stress from the matrix to the fiber by interfacial shear or by interlock between the fiber and matrix if the fiber surface is deformed. Stress is thus shared by the fiber and matrix in tension until the matrix cracks and then the total stress is progressively transferred to the fibers (Naaman and Shah 1976). The crack control through pullout-resisting mechanisms that is achieved from fibers bridging the crack surfaces will result in an increase in the load-carrying capacity, the energy dissipation (ductility), and at ultimate limit design states for FRC (Cunha 2010). Several models in a design practice format, such as closed-form solutions, have been proposed (Stang and Olesen 1998; Olesen 2001). More recently, Soranakom and Mobasher (2007) developed a closed-form solution capable of determining the moment-curvature relationship of a cross section of a beam reinforced longitudinally with steel bars and made with FRC. With the advent of new generations of fibers and chemical admixtures, as well as enhanced knowledge of particle distribution process, behavior of aggregate-paste and fiber-paste interface zones, specialty FRC mixtures have been developed. The special characteristics for these materials include post-crack tensile strength that is higher than the material strength at crack initiation (Fantilli et al. 2009).

1.3.3 Compression—At typical dosages, the effect of fibers on the compressive strength of concrete has been shown to be marginal to negligible (Shah et al. 1978; Fanella and Naaman 1985). Documented increases in compressive strength range from negligible in most cases to 23 percent for concrete containing 2 percent by volume of steel fiber (equal to 266 lb/yd³ [160 kg/m³]) with an aspect ratio of 100, tested with 6 x 12 in. (150 x 300 mm) cylinders (Williamson 1974). More recently, higher values of post-crack compressive strength have been reported using new generation of steel fibers (El-Dieb 2009).

Typical stress-strain curves for steel FRC in compression, at higher dosages, show a substantial increase in the strain at the peak stress and the slope of the descending portion is less steep than that of control specimens without fibers (Fanella and Naaman 1985). This is indicative of substantially higher toughness as a measure of the ability to absorb energy during deformation. The improved toughness in compression imparted by fibers is useful in preventing sudden and explosive failure under static loading, and in absorbing energy under dynamic loading. It should be noted that the modulus

of elasticity of concrete (in the linear ascending precrack region) is not affected by the fibers because they are only effective after concrete has cracked. During the failure stage in compression (after cracking), fibers guarantee a passive confinement similar to that of transverse reinforcement (Fantilli et al. 2011a,b). As a result, in reinforced concrete columns made with high-strength mixtures, the presence of fibers prevents the premature spalling of the brittle concrete cover and improves the ductility of the axially loaded members (Paultre et al. 2010).

1.3.4 Direct tension—Experimental procedures for measuring the tensile stress-strain curves for steel FRC date back to the work of Shah et al. (1978) and Gopalaratnam and Shah (1987b). Standardized direct tension tests for concrete are not available because of the variations in testing, which is attributed to the size of the specimen, concrete crushing at grips, stiffness of the testing machine, gauge length, mode of test control (closed loop versus open loop), and whether single or multiple cracks are present. While the initial ascending part of the curve up to first-cracking is similar to that of unreinforced concrete, strain-softening or strain-hardening behaviors can be observed in different specimens. The descending part depends on the stress-crack width relationship and fiber parameters such as geometry, material, dosage, and aspect ratio (Visalvanich and Naaman 1983). If only a single crack forms in the tension specimen, deformation is concentrated at the crack and the calculated strain depends on the gauge length. Thus, post-crack strain information should be interpreted with care in the post-crack region. The strength of FRC in direct tension (before cracking) is generally of the same order as that of unreinforced concrete—that is, 300 to 900 psi (2 to 6 MPa). Its toughness can be two to three orders of magnitude higher, primarily because of the energy absorption during fiber pullout and the deformation of multiple cracks (Shah et al. 1978; Visalvanich and Naaman 1983; Gopalaratnam and Shah 1987b). Many direct and indirect procedures have been developed for stress-crack width relationship measurement in FRC using direct tension test or a flexural test (Vandewalle 2000a,b, 2002). Details on such calculations can be found in ACI 544.8R.

1.3.5 Flexural strength—The influence of fibers on flexural response of concrete is much greater than on compressive response. Two flexural strength values are commonly reported. One, termed the first-peak strength (first-crack flexural strength), corresponds to the load at which the load-deformation curve departs from linearity. This is when concrete matrix cracks. The other corresponds to the maximum load achieved, commonly called the ultimate flexural strength, peak strength, or modulus of rupture. Strengths are calculated from the corresponding load using the formulas for modulus of rupture given in ASTM C78/C78M, although the linear stress and strain distributions on which the formula is based no longer apply after the matrix has cracked. Procedures for determining first-crack and ultimate flexural strengths, as discussed in ACI 544.2R and ASTM C1609/C1609M, are based on testing 6 x 6 x 20 in. (150 x 150 x 500 mm) beams using four-point loading configuration as well as BS EN 14651:2005 using 6 x 6 x 22 in. (150

x 150 x 550 mm) beams with a notch at midspan and three-point loading. Other sizes and shapes may provide higher or lower strengths, depending on span length, width, and depth of cross section, and the ratio of fiber length to the minimum cross-sectional dimension of the test specimen.

The original approach of predicting the flexural strength of small beams reinforced with steel fibers was done by [Swamy et al. \(1974\)](#), who used empirical data from laboratory experiments, using the fiber bond and introduced a random distribution factor, bond stress, and fiber stress. Based on the [ACI 318](#) ultimate strength design method, the tensile strength of the fibrous concrete is added to the contribution by the reinforcing bars to obtain the ultimate moment ([Henager and Doherty 1976](#)).

1.3.6 Toughness and residual strength—Toughness is one of the most important characteristics of FRC. Flexural toughness may be defined as the area under the load-versus-deflection (or load versus crack opening) curve in a beam test, which is the total energy absorbed prior to complete failure of the specimen. Flexural toughness indexes were used in the past as the ratio of the area under the load-deflection curve for FRC to a specified point, to the area up to first crack ([Bonakdar et al. 2005](#)). In more recent years, the parameter residual strength has replaced the toughness index for characterizing FRC. The strength of FRC after concrete has cracked is referred to as residual strength, typically expressed in psi or MPa. The residual strength can be measured in flexure or tension, depending on the test; however, the term “residual strength” is typically for flexure, obtained from a beam test such as [ASTM C1609/C1609M](#) and [BS EN 14651:2005](#). Round panels have also been used according to [ASTM C1550](#), specifically for measuring the flexural toughness or energy absorption of fiber-reinforced shotcrete; this parameter is typically expressed in joules. These panels are 32 in. (800 mm) in diameter and approximately 3 in. (75 mm) in thickness and are tested using three supports and one central loading point.

FRC is superior to plain concrete in fracture energy. Whereas the traditional fracture mechanics are used to quantify the energy to initial cracking in the material, the total fracture energy parameter originally suggested by [Hillerborg \(1985\)](#) quantifies the energy to propagate the crack to complete failure. Although there is no standard test for quantifying fracture of concrete and FRC, several recommended test procedures have been implemented. Test results for total fracture energy of FRC can vary due to the heterogeneous nature of the material. More details on the test methods and quantification of FRC for total fracture energy have been published by [Kim and Bordelon \(2015\)](#) and [Mobasher et al. \(2015a\)](#).

1.3.7 Shear—Use of fibers as shear reinforcement in reinforced concrete beams has been the focus of several investigations in the past four decades ([Mansur et al. 1986](#); [Kwak et al. 2002](#); [Minelli and Vecchio 2006](#); [Parra-Montesinos 2006](#); [Altoubat et al. 2009](#); [Shoaib et al. 2014](#)). Research by [Talboys and Lubell \(2014\)](#) has demonstrated that the shear stress at failure in steel FRC beams and slabs decreases as the strain in the longitudinal reinforcing bars increases. This can

be explained by the fact that fiber reinforcement enhances shear resistance of concrete by bridging tensile stresses across diagonal cracks. This can result in a reduction of diagonal crack spacing and width, which improves aggregate interlock effects. The reduction in crack spacing due to the presence of fibers indicates that the use of fibers could lead to a reduction of the size effect in shear for beams and slabs without stirrups where the shear at failure is known to decrease as the overall beam depth increases. [ACI 318-14](#) Section R26.12.5 briefly presents the performance criteria for using steel fibers as shear reinforcement in structural elements.

Numerous tests indicate that stirrups and fibers can be used effectively in combination ([Altoubat et al. 2009](#)). The increase in shear capacity due to fiber reinforcement has been quantified in several investigations and steel fibers have been used in practical applications to replace the stirrups. More recently, both steel and synthetic macrofibers have been employed in concrete for full-scale tests in flexural members ([Altoubat et al. 2009](#); [Minelli et al. 2014](#); [Shoaib et al. 2014](#); [Conforti et al. 2015](#)).

Earlier studies conducted include the work of [Batson et al. \(1972\)](#) with steel fibers, in which tests on 96 beams were performed varying the fiber size, type, and volume fractions, along with the shear span-depth ratio (a/d), where a is the shear span (distance between concentrated load and face of support), and d is the depth to centroid of reinforcing bars. In third-point loading experiments, a decrease in a/d and an increase in the steel fiber volume increased the shear stresses developed at failure. A fiber volume fraction in the range of 0.88 to 1.76 percent (equal to 117 to 232 lb/yd³ [70 to 140 kg/m³]) for $a/d = 3.6$ to 2.8 would change the shear strength from 450 to 510 psi (3.1 to 3.8 MPa) and mode of failure from shear to flexure.

The earliest work addressing underground applications was by [Paul and Sinnamon \(1975\)](#), who used Batson’s approach to determine a procedure for predicting the shear capacity of segmented concrete tunnel liners made with steel FRC (SFRC). The influence of steel fiber reinforcement on the shear strength of reinforced concrete flat plates was investigated by [Swamy et al. \(1979\)](#) with fiber contents of 0.6, 0.9, and 1.2 percent by volume (equal to 80, 120, and 160 lb/yd³ [48, 72, and 96 kg/m³]). The increase in shear strength was 22, 35, and 42 percent, respectively, compared to the control specimens.

The use of synthetic macrofibers as a means of shear reinforcement has been studied by [Altoubat et al. \(2009\)](#) and [Yazdanbakhsh et al. \(2015\)](#). Full-scale FRC beams with shear span-depth ratios of 3.5 and 2.3 were tested, and synthetic macrofibers were added at various dosages of 0.5, 0.75, and 1.0 percent volume fraction (equal to 7.5, 11.2, and 15 lb/yd³ [4.5, 6.7, and 9 kg/m³]). The results showed that the shear strength of the beams was increased by up to 30 percent relative to the control beam. It was shown that these fibers could provide the required shear capacity based on [ACI 318](#), although the practical applications of synthetic fibers and code implementations have yet to be established.

1.3.8 Shrinkage—When concrete is subjected to shrinkage, fibers are not expected to have an effect in the

absolute shrinkage value. For restrained shrinkage, however, fibers provide a means of crack control both in plastic and drying shrinkage. Tests using ring-type concrete specimens cast around a restraining steel ring, or with a stress riser, have shown that fibers can substantially reduce the amount of cracking and the mean crack width (Malmberg and Skarendahl 1978; Swamy and Stavrides 1979). Fibers can also provide an adequate internal restraining mechanism in conjunction with shrinkage-compensating cements, so that the concrete system will perform its crack control function even when restraint from conventional reinforcement is not provided. Fibers and shrinkage-compensating cements have been used in a complementary fashion by Paul et al. (1981) (refer also to ACI 223R).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_s	= cross sectional area of steel, in. ² (mm ²)	M_n	= nominal moment of a concrete or RC/FRC section, lb-in. (N-mm)
a	= depth of compressive zone, in. (mm)	M_u	= normalized ultimate moment of a section, lb-in. (N-mm)
a_e	= radius of circle with area equal to that of the contact area, in. (mm)	M_u'	= normalized allowable moment of a section, lb-in. (N-mm)
b	= section width, in. (mm)	P_0	= known load value, lbf (kN)
C	= equivalent compressive forces on a cross section, lbf (kN)	P_{150}^D	= FRC flexural residual load at a deflection of $L/150$, lbf (kN)
d	= depth of reinforcement, in. (mm)	P_{600}^D	= FRC flexural residual load at a deflection of $L/600$, lbf (kN)
d_e	= effective depth of cross section, in. (mm)	P_P	= peak load, lbf (kN)
E	= elastic modulus of concrete, psi (MPa)	$R_{T,150}^D$	= equivalent flexural strength ratio at a deflection of $L/150$, percent
F	= force component in stress diagram, lbf (N)	T	= concentrated tensile forces on a cross section, lbf (kN)
$F_{Fts-FRC}$	= FRC tensile strength under serviceability state, psi (MPa)	T_{150}^D	= FRC flexural toughness up to a deflection of $L/150$, lb-in. (Joule)
$F_{Ftu-FRC}$	= FRC tensile strength under ultimate state, psi (MPa)	w	= crack width in RC/FRC section, in. (mm)
F_{st}	= steel bar/mesh tensile force, lbf (N)	α	= normalized transitional strain
f_c	= compressive strength of plain concrete, psi (MPa)	β_{tu}	= normalized tensile strain at maximum stress
f_c'	= specified compressive strength of concrete, psi (MPa)	ϵ_1	= tensile strain at onset of first cracking
f_{150}^D	= FRC flexural residual strength at a deflection of $L/150$, psi (MPa)	ϵ_2	= tensile strain at the onset of the stable strain softening branch
f_{600}^D	= FRC flexural residual strength at a deflection of $L/600$, psi (MPa)	ϵ_3	= tensile strain at the end of the softening branch
$f_{e,3}$	= FRC equivalent flexural strength at a deflection of $L/150$, psi (MPa)	ϵ_c	= compressive strain
f_P	= peak strength, psi (MPa)	ϵ_{cr}	= first cracking tensile strain
$f_{R,1}$	= FRC flexural residual strength at CMOD ₁ , psi (MPa)	ϵ_{cu}	= ultimate (maximum) compressive strain
$f_{R,3}$	= FRC flexural residual strength at CMOD ₁ , psi (MPa)	ϵ_{cy}	= compressive strain at yielding
f_t	= tensile strength of plain concrete, psi (MPa)	ϵ_t	= tensile strain
f_{ut-FRC}	= FRC ultimate tensile residual strength, psi (MPa)	ϵ_{tu}	= ultimate (maximum) tensile strain
f_y	= specified yield strength of steel, psi (MPa)	γ_c	= partial safety factor for plain concrete
h	= section thickness or height, in. (mm)	λ	= normalized top compressive strain
K	= modulus of subgrade reaction, lb/in. ³ (N/mm ³)	λ_{cu}	= normalized ultimate (maximum) compressive strain
k	= neutral axis depth ratio	λ_{tu}	= normalized compressive strain when reaching ultimate tensile strain
k_s	= factor for size effect in shear calculations	μ	= normalized post-peak residual tensile strength
L	= radius of relative stiffness, in. (mm)	μ_{crit}	= critical normalized post-peak residual tensile strength
M_0	= moment capacity of the slab after cracking, lb-in. (N-mm)	ν	= concrete Poisson's ratio
M_{cr}	= cracking moment of a concrete section, lb-in. (N-mm)	ρ	= reinforcement ratio for longitudinal reinforcement, $\rho = A_s/(bd)$
		σ_1	= tensile stress at onset of first cracking, psi (MPa)
		σ_2	= tensile stress at the onset of the stable strain softening branch, psi (MPa)
		σ_3	= tensile stress at the end of the softening branch, psi (MPa)
		σ_c	= compressive stress, psi (MPa)
		σ_{cp}	= average normal stress acting on concrete cross section, psi (MPa)
		σ_{cy}	= compressive yield strength, psi (MPa)
		σ_p	= post-crack tensile strength, psi (MPa)
		σ_t	= tensile stress, psi (MPa)
		ϕ	= curvature, 1/in. (1/mm)
		ϕ_{cr}	= cracking tensile strength, psi (MPa)
		ϕ_u	= maximum curvature, 1/in. (1/mm)
		ω	= compressive to tensile strength ratio

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

aspect ratio—ratio of the length to the diameter or the equivalent diameter of one single fiber.

balling—formation of large clumps of entangled fibers that may occur before or during the mixing process.

chemical bond fibers—fibers whose composition or surface characteristics promote chemical interaction with the concrete matrix to increase bond strength.

collated fibers—fibers bundled together either by cross-linking or by chemical or mechanical means.

denier—a number equivalent to the mass in grams of 9000 meters of a continuous fiber filament.

ductility—the ability of a material to undergo permanent deformation without rupture.

embossed fibers—fibers with surface indentations or ripples that provide mechanical anchorage with the concrete matrix.

equivalent diameter of fiber—diameter of a circle with an area equal to the average cross-sectional area of the fiber.

equivalent flexural residual strength—average flexural stress measured for a fiber-reinforced concrete beam, up to a specified deflection or crack width.

equivalent flexural residual strength ratio—ratio of the equivalent flexural residual strength and the flexural strength of concrete, percent.

fiber dosage—total fiber mass or weight in a unit volume of concrete, generally expressed in lb/yd³ (kg/m³).

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

fibrillated fibers—fiber configuration that has sections of the fiber splitting to form fiber branches (before mixing into concrete).

fibrillating fibers—fiber configuration that has sections of the fiber splitting to form fiber branches (after mixing into concrete).

limit of proportionality—flexural stress measured at the onset of first cracking in a bending test.

monofilament fibers—single fiber, which may be circular or prismatic in cross section.

residual flexural strength—flexural strength retained in a cracked FRC beam, measured at a certain deflection or crack width.

steel fibers—discrete fibers made of steel, used as reinforcement in concrete.

synthetic fibers—chopped fibers made of polyolefin, such as polypropylene and polyethylene materials, used as reinforcement in concrete.

and natural. A subclassification is often used based on the size and functionality of the fibers; hence, fibers can be classified as microfibers or macrofibers with the fiber diameter of 0.012 in. (0.3 mm) as the separating limit. On a much smaller scale, nanofibers also exist whose contribution to concrete properties are quite different than microfibers and macrofibers, and are not discussed herein. Steel fibers and polymeric synthetic fibers are the most-used types of fibers in construction industry and are the focus of this document. Other types of synthetic fibers, such as PVA and glass, have been used in some limited applications for concrete reinforcement; however, they are outside the scope of this document. The design guidelines in this guide have been derived and verified for FRC with steel and synthetic macrofibers only. Therefore, they should not be applied to any other types of FRC without a detailed evaluation and proof of the applicability.

3.1.1 Steel fibers—**ASTM A820/A820M** is the standard specification for steel fibers for use in concrete. Steel fibers for concrete reinforcement are short, discrete lengths of steel sufficiently small to be randomly dispersed in concrete using common mixing procedures. ASTM A820/A820M provides classification for five general types of steel fibers, based primarily on the product or process used in their manufacture: Type I: cold-drawn wire; Type II: cut sheet; Type III: melt-extracted; Type IV: mill cut; and Type V: modified cold-drawn wire. Steel fibers come in many geometries, including rectangular, flat, cylindrical, and variations or combinations of these. In addition, fiber anchorage mechanisms in concrete include continuous deformations such as twists, dimples or crimps, end anchorage such as hooks, or simply bond for undeformed fibers. Bond to the concrete matrix is enhanced by mechanical anchorage, surface area, alloying, surface roughness, or a combination of these. Fiber geometry and anchorage significantly affects resistance to pullout forces and overall performance of FRC. Another characteristic is the aspect ratio or the ratio of the length to diameter. Typically, for the same mixture proportions, as the fiber aspect ratio increases, so does the reinforcing performance. According to ASTM A820/A820M, the average tensile strength of fiber material should not be less than 50,000 psi (345 MPa). Steel macrofibers have typical diameters in the range of 0.01 to 0.05 in. (0.3 to 1.3 mm) and a length in the range of 1.2 to 2.5 in. (30 to 65 mm). The actual dosage for steel fibers depends on the specific application and the required engineering performance, as described in later chapters. Specifications should include the performance requirements rather than the prescriptive dosage for fibers.

3.1.2 Synthetic fibers—Synthetic fibers are made with polyolefin materials, which typically include polypropylene and polyethylene. **ASTM D7508/7508M** is the standard specification for synthetic fibers, including synthetic macrofibers and microfibers. ASTM D7508/7508M requires the minimum tensile strength of synthetic macrofibers to be 50,000 psi (345 MPa), whereas there are no restrictions on the tensile strength of microfibers. Synthetic macrofibers have typical diameters in the range of 0.01 to 0.05 in. (0.3 to 1.3 mm) and a length in the range of 1.2 to 2.5 in. (30 to 65 mm). The actual dosage for synthetic fibers depends on the specific application and the required engineering performance, as described in later chapters. Specifications should include the performance requirements rather than the prescriptive dosage for fibers.

CHAPTER 3—CHARACTERISTICS OF FRC

3.1—Classification of fibers

Fibers come in different material types, geometries, and sizes and typically range from 1/8 to 2.5 in. (3 to 65 mm) in length. **ASTM C1116/C1116M** classifies FRC based on the fiber material. These fibers include steel, glass, synthetic,

to 65 mm). The specified dosage for synthetic macrofibers depends on the application and the required engineering performance, as described in later chapters. These fibers are available in various configurations such as rope or tape filaments and they may be twisted or embossed. Bond to the concrete is achieved primarily through friction; however, chemical bonding in concrete has been reported.

Synthetic microfibers are mainly used for controlling cracks from plastic shrinkage (and sometimes drying shrinkage). Their contribution to the mechanical properties of hardened concrete is insignificant. These fibers are relatively fine with a typical diameter in the range of 0.0004 to 0.012 in. (0.01 to 0.3 mm) and a length in the range of 1/8 to 2 in. (3 to 50 mm). Synthetic microfibers are used in relatively small dosages, typically between 0.5 and 1.5 lb/yd³ (0.3 and 0.9 kg/m³) or 0.03 to 0.1 percent by volume. Some manufacturers carry blended fibers that typically includes synthetic microfibers (for plastic shrinkage crack control) and macrofiber (steel or synthetic) for enhancing the mechanical properties of concrete.

3.2—Performance of FRC

Unlike reinforcing bars, fibers are uniformly distributed in concrete and the average distance between fibers is much smaller than the typical spacing for reinforcing bars. As a result, tensile stresses are borne by the fibers at very early stages of the cracking process and, therefore, crack development and patterns can change with respect to plain or conventionally reinforced concrete. The decision on the type, material, size, geometry, and dosage for fibers depends on the application as well as the environmental exposure. Ultimately, the performance of FRC should be evaluated using standard test methods for the application for which it is used.

Fiber reinforcement can change the post-crack response of concrete from brittle to ductile under various types of loads, including compression, tension, flexure, and impact (Bonakdar et al. 2013). The addition of fibers to concrete can specially improve the crack resistance and toughness under tensile and flexural loads. Therefore, they can be used for structural purposes and to reduce the amount of required conventional reinforcement. The reduction of steel reinforcing bars is more significant in structures with a multiple degree of redundancy (di Prisco et al. 2009). In flexure, no major change takes place up to the cracking point of concrete. Fibers cannot be expected to modify the behavior of uncracked elements because fiber reinforcement mechanisms are mainly activated through crack development. When uncracked, FRC can be assumed to be homogeneous and isotropic, but this assumption does not hold for FRC in its cracked state. After cracking, fibers bridge the cracks and start to carry tensile stresses, giving load-bearing capacity to FRC in its cracked state. This is usually referred to as residual strength or post-cracking strength. Steel and synthetic macrofibers have been shown to significantly improve the post-crack response of concrete, providing residual strength values that can be used for design purposes (Buratti et al. 2011). With the same mixture design, fiber type, and concrete strength, higher fiber contents provide higher

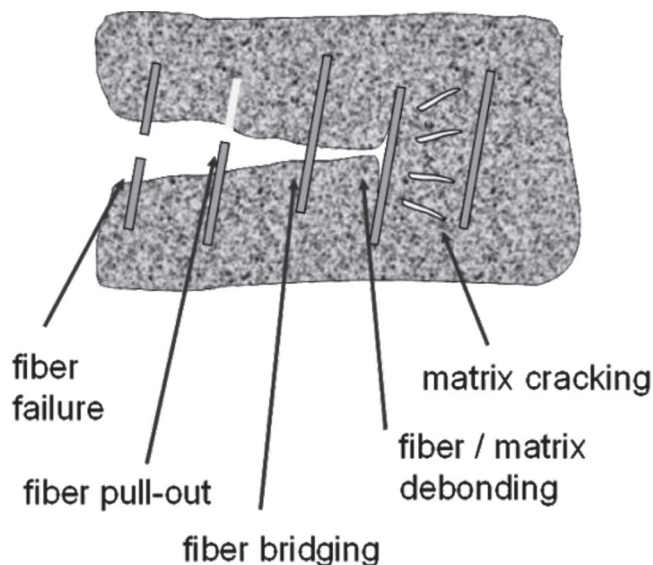


Fig. 3.2a—Schematics of the mechanism in which fiber reinforcement works.

values of residual strength in tension or flexure, as long as the mixture can properly accommodate the fibers. The type and geometry of fibers also affect the post-crack properties of FRC. Ultra-high-performance FRC (UHPFRC) incorporates high-strength concrete and high dosages of fibers that can result in strain-hardening, as explained in later chapters. For steel fibers, dosages of more than approximately 60 lb/yd³ (36 kg/m³) and for synthetic macrofibers, dosages of more than approximately 15 lb/yd³ (9 kg/m³) may provide strain-hardening properties. Self-consolidating concrete, using plasticizers, is typically used for accommodating high dosages of fibers, resulting in improved mechanical and durability properties (Naaman and Reinhardt 1996).

The stages involved in FRC failure are schematically shown in Fig. 3.2a and are summarized in the following: 1) crack forms in cement matrix; 2) debonding and sliding between fiber and matrix; 3) bonded fiber bridging the crack; 4) frictional sliding, deformation of anchorage, and eventual fiber pullout; and 5) potential fiber rupture under tension. The term “failure” can be associated with the final stage when fibers are no longer able to resist the stresses, or when their strength is ignored in design. For specific types or geometries of fibers, only some of the described stages may occur. The load or stress level carried by fibers in a cracked concrete section is referred to as residual load or residual stress. The area under the load-deflection curves is the energy absorbed by the FRC and is referred to as toughness, which is used for design purposes. Figure 3.2b shows different stages of crack control for an FRC beam under a flexural load test. The beam was purposely cracked to much larger crack widths, than required, to demonstrate the ability of fibers in bridging the crack under sustained loads.

Contrary to reinforcing bars or welded mesh, most fibers are designed to deform and slip without failing in tension. Fibers are activated as soon as cracks are formed in the concrete. The main advantage of adding fibers to concrete is

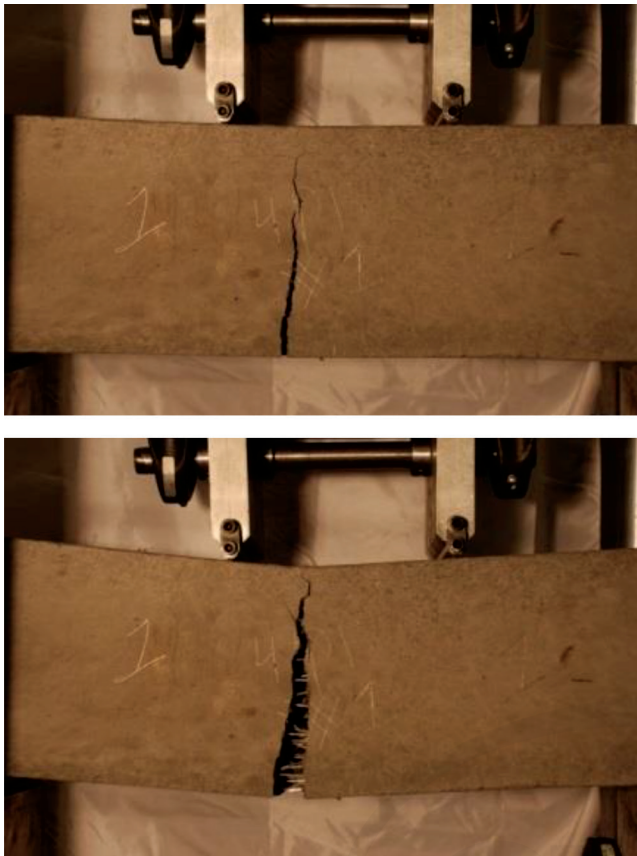


Fig. 3.2b—Crack control (bridging) in FRC beam under flexural loading. Note that in a standard test, the crack width is limited to approximately 0.12 in. (3 mm), whereas this beam was additionally loaded to show crack control at wide crack widths up to 1 in. (25 mm).

that they generate a post-cracking tensile/flexural strength in concrete, and this is true under both static and impact loads (Schrader 1981; Gopalaratnam and Shah 1986; Dey et al. 2014). As such, FRC is characterized by substantial ductility and toughness (Shah and Rangan 1970). The flexural toughness and post-crack residual strength of FRC depend on several factors, including fiber material, dosage, aspect ratio, geometry, bond characteristics, and concrete properties. The choice of fiber type may be affected by the long-term performance of FRC for certain applications. This includes the effect of sustained loads (creep) as well as environmental exposure resulting in corrosion. Steel fibers typically do not exhibit creep behavior under normal service conditions at temperatures below approximately 700°F (370°C). Synthetic fibers, however, are considered viscoelastic materials and are more susceptible to creep than steel fibers. If a relatively high stress level is maintained for considerable time, polymeric materials may behave viscously and will creep. For FRC elements with lower stress levels or structures with continuous support (such as slabs-on-ground or shotcrete), creep may not be a determining factor and synthetic macro-fibers may be used. For applications such as elevated slabs-on-pile without continuous support, only steel fibers have been used. The combined use of conventional steel rein-

forcement and fibers can considerably reduce the long-term deformations under sustained loads and the crack widths with a positive effect on the durability of concrete.

3.3—Standard test methods for FRC

If crack control under plastic shrinkage is the intended function of the fibers, ASTM C1579 can be used. The effectiveness of fibers in controlling the drying shrinkage (under restraint) and reducing the crack widths can be determined following ASTM C1581/C1581M. In these two tests, the effectiveness of fibers in reducing the crack width is determined and expressed in a percentage versus control (plain concrete). If higher levels of crack control and post-crack flexural capacity are expected from fibers, FRC beams or panels should be tested using ASTM C1609/C1609M and ASTM C1550. Equivalent European test methods are BS EN 14651:2005 and BS EN 14488:2006, respectively.

Performing a direct tension test (static or fracture) is ideal and desirable for FRC; however, a proper tension test is extremely difficult for cement-based materials because of the potential slippage or crushing of concrete at the grips, or heterogeneous nature of FRC. As an accepted alternative, flexural tests are conducted and the results are used for back-calculating the tensile properties. These flexural tests are designed to obtain the complete pre- and post-crack response of FRC. All the existing design tools for FRC use the test parameters obtained from some type of a bending test. This document describes two test methods that are widely used for measuring the residual strength, the parameter that is implemented in FRC design: ASTM C1609/C1609M and BS EN 14651:2005.

3.3.1 ASTM C1609/C1609M: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)—This test measures the complete pre- and post-crack flexural response of FRC beams using accurate deflection to control the test (closed-loop control). The test is typically performed on 6 x 6 x 20 in. (150 x 150 x 500 mm) FRC beams with a span of 18 in. (450 mm). Two points of loading (four-point bending) are used until reaching a midpoint deflection of 1/150th of the span (L)—that is, 0.12 in. (3 mm). Figure 3.3.1 shows the schematics of a typical ASTM C1609/C1609M test and a beam subjected to flexure (bending). The following parameters are determined from the test and used in characterizing FRC, which includes the peak strength as well as the residual strength values at $L/600$ (0.03 in. [0.75 mm]) and $L/150$ (0.12 in. [3 mm]). Note that b is the width and h is the height of the beam. At least three replicate beams should be tested for determining these parameters, though testing six beams is recommended for achieving a representative average value for residual strength of FRC.

- a) P_P : peak flexural load (maximum load), lbf (kN)
- b) P_{600}^0 : FRC flexural residual load at a deflection of $L/600$, lbf (kN)
- c) P_{150}^0 : FRC flexural residual load at a deflection of $L/150$, lbf (kN)
- d) f_P : peak flexural strength, psi (MPa)

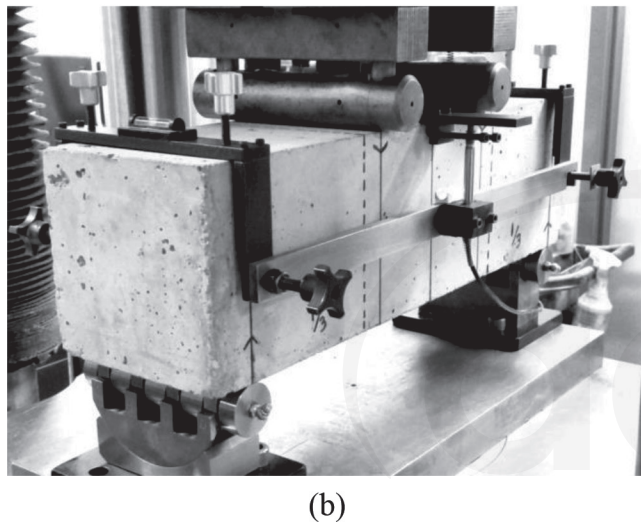
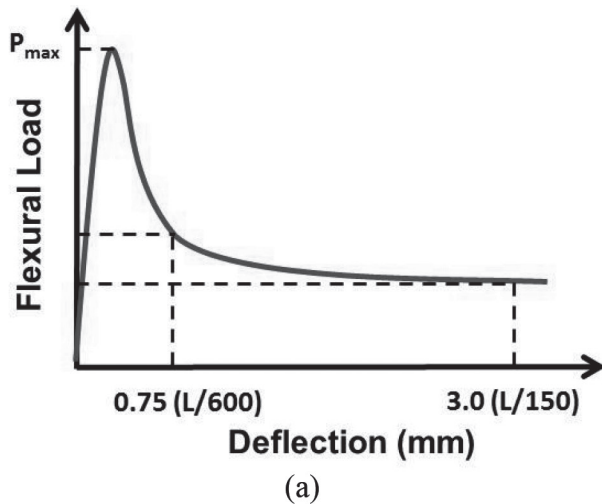


Fig. 3.3.1—(a) Schematics of a typical ASTM C1609/C1609M test result (strain-softening FRC); and (b) FRC beam under four-point flexural test. (Note: 1 in. = 25 mm.)

- e) f_{600}^D : FRC flexural residual strength at a deflection of $L/600$, psi (MPa)
- f) f_{150}^D : FRC flexural residual strength at a deflection of $L/150$, psi (MPa)
- g) T_{150}^D : FRC flexural toughness up to a deflection of $L/150$, lb-in. (joule)
- h) $R_{T,150}^D$: FRC equivalent flexural strength ratio at a deflection of $L/150$ (%), calculated as shown in Eq. (3.3.1a) from the toughness value (hence, subscript T). The term $R_{e,3}$ has also been used in the literature to represent this parameter, referring to 0.12 in. (3 mm) deflection.

$$R_{T,150}^D = \frac{150 \times T_{150}^D}{f_p \cdot b \cdot h^2} \quad (3.3.1a)$$

- i) $f_{e,3}$: FRC equivalent flexural strength at a deflection of $L/150$, psi (MPa), calculated as shown in Eq. (3.3.1b). This term is not directly defined in **ASTM C1609/C1609M**; however, it has been widely used in the literature, referring to 0.12 in. (3 mm) deflection.

$$f_{e,3} = f_p \times R_{T,150}^D \quad (3.3.1b)$$

The residual strength measured from this test is in flexure and proper conversion factors should be used to determine the residual strength in tension. This is further discussed in **Chapter 4**.

3.3.2 BS EN 14651:2005: Test and Design Methods for Steel Fiber-Reinforced Concrete—This test method was originally introduced by **RILEM TC 162-TDF (2003)**, and the test parameters are widely used for design in several design codes and specifications, especially when the design is based on a limited crack width. The test is performed on 6 x 6 x 22 in. (150 x 150 x 550 mm) FRC beams with a span of 20 in. (500 mm) and a small notch of 1 in. (25 mm) depth at the midspan. The notch is used as a crack initiator and the deflection and crack-mouth opening displacement (CMOD) are measured at the midspan during the test. The beam is tested under closed-loop control with one point of loading (three-point bending) until reaching a CMOD of 0.14 in. (3.5 mm). The parameter $F_{R,i}$ is the residual load at point i on the load-CMOD curve, and $f_{R,i}$ is the equivalent flexural residual strength. For example, $f_{R,3}$ is the residual strength at point $i = 3$, where the crack opening or CMOD is 0.1 in. (2.5 mm). In Eq. (3.3.2), L is the loading length (span), b is the width, and h_{sp} is the net height of the beam (total height – notch height). Figure 3.3.2 shows the schematics of a typical test for BS EN 14651:2005 and a beam under flexural (bending) test. A subscript i of 1, 2, 3, or 4 points out to crack opening or CMOD values of 0.02, 0.06, 0.1, or 0.14 in. (0.5, 1.5, 2.5, or 3.5 mm) that are used for specific crack width, desired in the design of a concrete member. At least three replicate beams should be tested for determining these parameters, though testing six beams is recommended for achieving a representative average value for residual strength of FRC.

- a) F_{max} : peak flexural load (maximum load), lbf (kN)
- b) $F_{R,i}$: FRC flexural residual load at point i , lbf (kN)
- c) $f_{R,i}$: FRC flexural residual strength at point i , calculated as shown in Eq. (3.3.2), psi (MPa)

$$f_{R,i} = \frac{3F_{R,i} \cdot L}{2b \cdot h_{sp}^2} \quad (3.3.2)$$

It should be noted that a modified version of this test has been conducted without a notch, where higher dosages of fibers were used, resulting in multiple cracks (strain-hardening).

3.4—Strain softening and strain hardening

Low to moderate dosages of fibers provide enough resistance for bridging one main crack in a tension or flexural test and the response is referred to as strain softening. During strain softening, the residual strength gradually declines as the beam deflection and crack width increase. Strain softening FRC has a post-cracking tensile stress that is lower than its ultimate tensile strength. With special fiber reinforcement that incorporates higher dosages and other mechanisms, and improved bond strengths, the fibers can

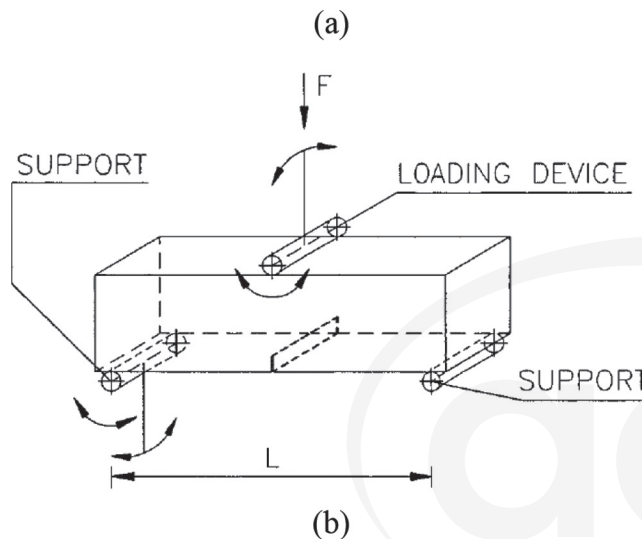
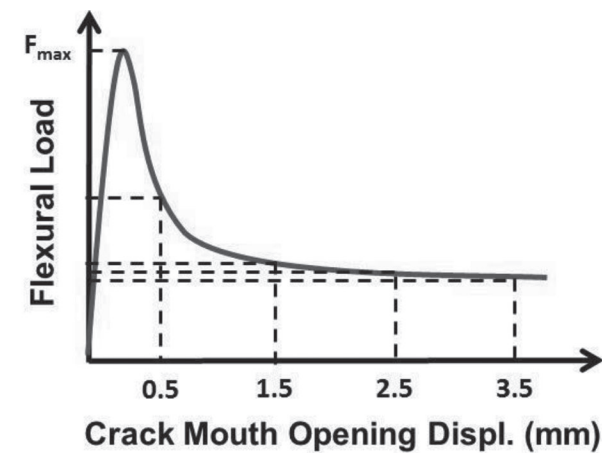


Fig. 3.3.2—(a) Schematics of typical BS EN 14651:2005 test results (strain-softening FRC); and (b) schematics of FRC beam under three-point flexural test. (Note: 1 in. = 25 mm.)

provide extra resistance for bridging several cracks and redistributing the stresses. This response is known as strain hardening. During strain hardening, the residual strength gradually increases as the deformations and crack widths get larger up to a point of failure. With the advancements of new generations of fibers and chemical admixtures, it is possible to produce strain-hardening FRC with post-cracking tensile stress that is higher than the cracking stress of concrete.

Two simplified stress-crack opening constitutive laws may be deduced from a uniaxial tensile test—plastic rigid behavior or linear post-cracking behavior (hardening or softening), as shown schematically in Fig. 3.4a. In these graphs, σ is the tensile stress, w is the crack width, and w_u is the ultimate crack width for a given design. With the assumption of rigid-plastic response, fibers are providing a constant residual strength after cracking, regardless of the crack width. In this model, f_{Ftu} represents the ultimate tensile residual strength. With the assumption of linear response, the residual strength provided by the fibers after cracking can either decrease (strain softening) or increase (strain hardening) as the crack grows. In this model, f_{Fts} represents the

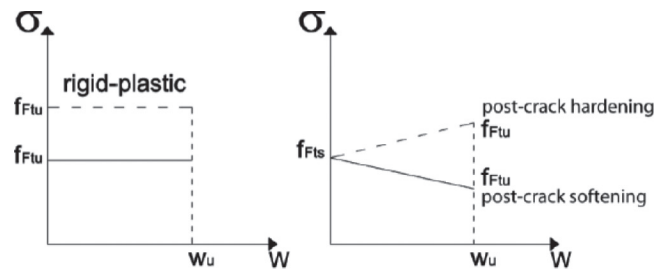


Fig. 3.4a—Simplified post-crack stress-crack width relationship for FRC, obtained from uniaxial test, showing softening and hardening behaviors (fib 2013).

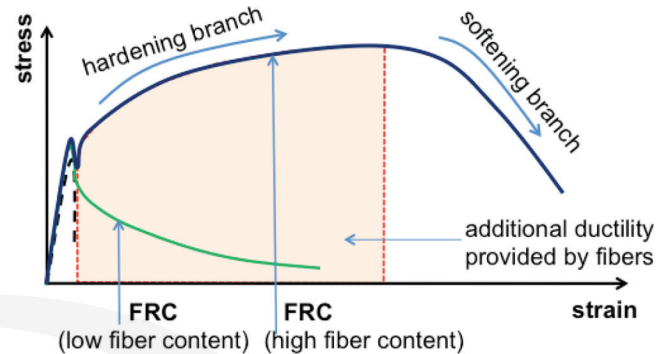


Fig. 3.4b—Fiber contribution to tensile/flexural performance, obtained from flexural test, showing softening and hardening behaviors.

serviceability residual strength, defined as the post-cracking strength for certain crack widths.

Figure 3.4b shows the flexural stress-strain curves for two different fiber dosages. The dotted line, which corresponds to the unreinforced concrete, shows a brittle failure once the cracking load is reached. The green line corresponds to FRC with relatively low fiber dosage; there is no such brittle failure, but once the first crack occurs, load-carrying capacity is gradually decreased (softening behavior). The blue line represents the behavior of FRC with relatively high fiber dosage; after the cracking load is reached, concrete will sustain the loads, and fibers make it possible to carry increasing loads (hardening branch) until a maximum stress value (ultimate load) is reached in the post-peak region, which is higher than the cracking load of concrete. After that, load-carrying capacity gradually decreases (final softening branch). Because of the contribution of fibers, the material is capable of absorbing a great deal of additional deformation energy (shaded region under the curve) compared to its unreinforced counterpart.

The frontier between softening behavior and hardening behavior depends on several factors, including fiber material, geometry, and dosage. In relation to that, [di Prisco et al. \(2009\)](#) have pointed out that, for the same fiber type, the residual strength depends significantly on the number of fibers crossing active cracks and on their orientation. Fibers are therefore to be selected based on the type of member and the load conditions. Curves in Fig. 3.4b illustrate FRC flexural response, but similar comparisons can be made in relation to its tensile behavior. However, the factors that affect FRC

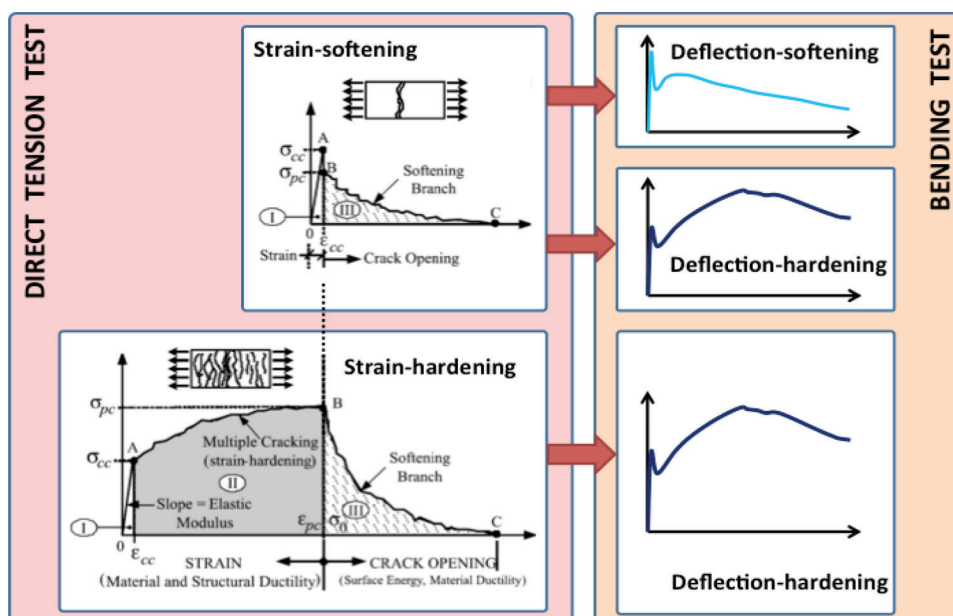


Fig. 3.4c—Different possibilities of FRC response in tension and flexure (Naaman 2007).

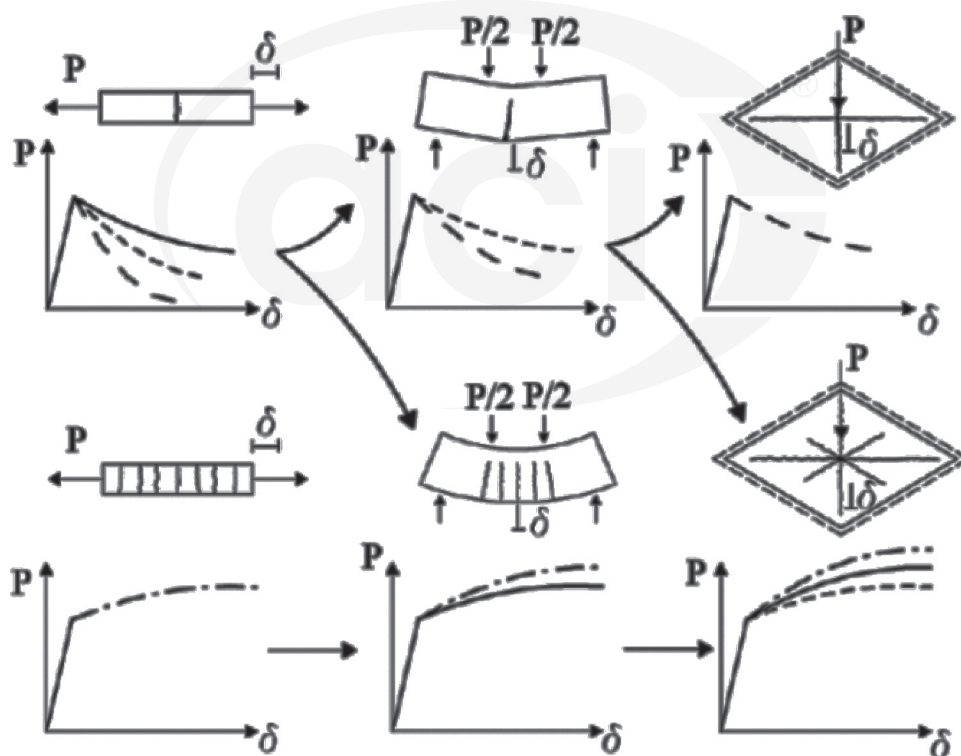


Fig. 3.4d—Schematics of strain softening and strain hardening in FRC under tension, flexure, and a system (Model Code 2010 [fib 2013]). The top three show strain-softening behavior; the bottom three show strain-hardening response.

presents a hardening flexural behavior does not necessarily imply tensile behavior to be hardening as well.

Under certain conditions, a bending-hardening response of a structure can be achieved even with a tension-softening or bending-softening material. This means that only structures with sufficient redistribution capabilities can be designed with softening materials in accordance with Model

Code 2010 (fib 2013). If system ductility cannot be proven for structures reinforced with fibers alone, Model Code 2010 (fib 2013) requires conventional reinforcement to achieve a ductile response of the structure. These are schematically shown in Fig. 3.4d for FRC under tension, flexure, and a system. The top three graphs show strain-softening behavior while the bottom three graphs show strain-hardening response for the three cases.