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Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs

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Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs

Reported by ACI Committee 544

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Construction of slabs in areas with weak soil conditions has commonly used pile-supported slab structural design so that the adverse effects of soil-structure interaction in terms of differential settlement, cracking, or long-term serviceability problems are avoided. In this application, the construction of slabs on closely spaced pile caps (typical span-depth ratios between 8 and 30) is referred to as elevated ground slabs (EGSs). These slabs may be subjected to moderately high loading, such as concentrated point loading of up to 44 kip (150 kN) and uniformly distributed loadings of 1000 lb/ft² (50 kN/m²). The dynamic loadings may be due to moving loads such as forklifts, travel lifts, and other

material handling equipment. Fiber-reinforced concrete (FRC) has been successfully used to address the structural design of these slabs. Based on the knowledge gained, the area has been extended to a construction practice for slabs supported by columns as well. Applications are further extended to multi-story building applications. This report addresses the methodology for analysis, design, and construction of steel FRC (SFRC) slabs supported on piles or columns (also called elevated SFRC [E-SFRC]). Sections of the report address the history, practice, applications, material testing, full-scale testing, and certifications. By compiling the practice and knowledge in the analysis design with FRC materials, the steps in the design approach based on ultimate strength approach using two-way slab mechanisms are presented. The behavior of a two-way system may not require the flexural strength of conventional reinforced concrete (RC) because of redistribution, redundancy, and failure mechanisms.

Methods of construction, curing, and full-scale testing of slabs are also presented. A high dosage of deformed steel fibers (85 to 170

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lb/yd³ [50 to 100 kg/m³]) is recommended as the primary method of reinforcement. Procedures for obtaining material properties from round panel tests and flexural tests are addressed, and finite element models for structural analysis of the slabs are discussed. Results of several full-scale testing procedures that are used for validation of the methods proposed are also presented.

Keywords: ductility; durability; fiber-reinforced cement-based materials; fibers; flexural strength; jointless slab; moment-curvature response; plastic shrinkage; reinforcing materials; shrinkage; shrinkage cracking; slab-on-ground; slab-on-piles; steel fibers; steel fiber-reinforced concrete; toughness; yield line analysis.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

Steel fibers have been used for over 50 years as reinforcement in many applications, such as heavily reinforced sections, shear-critical regions, slabs-on-ground, and pavements. A potential area of use of steel fibers is in the construction of slabs in areas with weak soil conditions where adverse effects due to soil-structure interaction, such as differential settlement, cracking, or long-term serviceability problems, can be treated by considering the fiber reinforcement effectiveness. In these cases, pile-supported slab structural designs have been commonly used and fiber reinforcement has shown tremendous promise. The use of steel fibers as reinforcement in these cases is due to practicality of installation, enhanced control of shrinkage cracks, durability, toughness, and cost savings in labor and equipment. The pile-supported continuous slabs are used in factories (industrial facilities), warehouses, and basements.

where any area underneath the slab is not considered to give vertical support to the slab. The practice has also been extended to slabs supported by columns in the past 20 years. This report addresses the practice of using steel fiber-reinforced concrete (SFRC) in flat plates supported on piles, or columns.

Elevated steel fiber-reinforced concrete (E-SFRC) slabs are also used as floors of multi-story buildings, with the fiber reinforcement serving as the primary flexural reinforcement. The use of E-SFRC slabs (Di Prisco et al. 2004; Destrée 1995, 2000, 2004) can be categorized as follows:

- a) Pile-supported ground-level SFRC (G-SFRC) slabs
- b) Column-supported E-SFRC slabs

The design procedures proposed are different than the conventional reinforced concrete (RC) calculations because the residual tensile strength of FRC is directly used in the calculations. Currently, flexural design of SFRC slabs or elements of rectangular sections is not currently covered by ACI 318. The mechanical characteristics of SFRC, defined in terms of residual tensile strength, its ductility and strain capacity, and its constructibility attributes, could make it an alternative technology to conventional RC. A direct comparison of cross-sectional moment capacity of SFRC to RC can be found in Mobasher (2011) and

Soranakom and Mobasher (2008). While the efficiency of continuous reinforcing bars are superior to fiber-reinforced concrete (FRC) in terms of ultimate strength, proper design and understanding of structural behavior makes up for this disadvantage; the benefits of construction speed and efficiency are the beneficial aspects of the technology described herein. It is noted that the behavior of a two-way system may not require the flexural strength of conventional RC because of redistribution, redundancy, and failure mechanisms.

G-SFRC slabs contain no conventional reinforcement (as shown in Fig. 1.1a) because they are not likely to provoke a progressive collapse of the structural frame above them. E-SFRC slabs, however, contain a set of minimum continuity reinforcing bars—also referred to as anti-progressive collapse (APC) reinforcing bars—running in the bottom of the slab from column to column in both directions (as shown in Fig. 1.1b). The floor in Fig. 1.1b is cast as a part of a five-story structure with 50,000 ft² (4645 m²) total floor space in Mondragon, Spain, with a 27 ft (8.2 m) span, 11 in. (279 mm) thick slab, and UDL of 140 lb/ft² (6703 Pa) using 165 lb/yd³ (98 kg/m³) of undulated 140 ksi (965 MPa) steel fibers with a diameter of 0.05 in. (1.3 mm) and a length of 2 in. (50 mm). The continuity reinforcing bars are used in accordance with the design guidelines addressing progressive collapse (CSA A-23.2-04) and are also used in edge areas where the performance of the slab may be dominated by single-curvature bending (Baldridge and Humay 2003; Sasani and Sagioglu 2008; Udilovich et al. 2010; Hawkins and Mitchell 1979).

Several factors are considered in addressing the competitiveness of this construction approach with other alternatives such as post-tensioned or precast systems. Advantages of G-SFRC and E-SFRC slab systems primarily include the economic aspects, followed by the improved strength and ductility, increased speed of construction, reduction of joints, and shrinkage crack width control in continuous joint-free slabs. Historical development of G-SFRC and E-SFRC slab systems are presented first, and an overview of the current design methods and



Fig. 1.1a—Installation of G-SFRC slab (pile-supported ground slab) (courtesy of Bombardier Aerospace Inc.).



Fig. 1.1b—Construction and applications of E-SFRC slabs (courtesy of Primerks SIA) Document Sharing Hub

construction practices is presented. Existing standards and design methodologies are introduced and the effect of slab dimensioning, fiber dosage rate, and loading conditions are presented. Special construction provisions that deal with the criteria for progressive collapse failure and special provisions for reentrant corners, shrinkage restraint, shear wall restraint, and soil conditions are also discussed. Limitations of G-SFRC and E-SFRC slabs and areas of needed research are addressed in detail.

1.2—Scope

The design of steel fiber-reinforced concrete (SFRC) slabs-on-ground (G-SFRC) and elevated SFRC (E-SFRC) slabs in the past three decades has resulted in a significant practical and engineering experience that has not been documented before. This report addresses various aspects of analysis, design, and construction of elevated slabs using steel fibers as the primary reinforcement. The benefits of these systems are discussed in terms of reduction in the number of joints; shrinkage control enhancement; ductility; improvements in the architectural design; and reduction of drop panels and beams, which results in easier forming and setup and, ultimately, in an economic and sustainable system.

The design procedures address the material and structural ductility aspects and their effect on the two-way slab mechanism. Test methods that are applicable to design include the three-point bending test as a measure of material ductility, and simply supported round slab as a measure of material and structural ductility. The discussion of these tests is followed by the procedures to predict the behavior during full-scale structural testing. The design guides for strain-softening, deflection-hardening materials are also presented as the underlying basis for these systems.

The structural analysis approach to evaluate the nominal flexural strength of E-SFRC slabs is based on yield-line theory, and several cases of uniformly distributed loads, line, and point load are presented. Flexural strength calculations for failure patterns can be accomplished using the test data derived from both the three-point bending flexural test and/or a test on a continuously supported round slab. Design examples are presented in **Appendixes A** through **K** in support of the structural analysis approach and the flexural strength calculations.

Four full-scale tests of elevated slabs are presented and discussed. Experimental results and model-based computed values are compared using numerical examples for the verification of the design. Full-scale testing procedures are presented that show the ability of deflection hardening SFRC to produce multiple cracks under flexure and, hence, use of inelastic post-cracking properties in the design process are discussed.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_c = cross-sectional area, in.² (mm²)
 b = width, in. (mm)
 b_{col} = column width, in. (mm)

c = distance from extreme compression fiber to neutral axis, in. (mm)
 d = clear cover, in. (mm)
 f'_c = uniaxial concrete compressive strength, psi (MPa)
 f_y = yield strength, psi (MPa)
 L_{lin} = longitudinal bandwidth of a length, ft (m)
 L_n = effective length of span, ft (m)
 L_{rx} = distance between two adjacent negative yield lines in a panel parallel to the x-direction, ft (m)
 L_{ry} = distance between two adjacent negative yield lines in a panel parallel to the y-direction, ft (m)
 M_P^+ = positive bending moment resistance, ft-lb (Nm)
 M_P^- = negative bending moment resistance, ft-lb (Nm)
 M_u = bending moment ductility factor, ft-lb (Nm)
 P_{col} = column internal force, kip (kN)
 P_{max} = maximum load, kip (kN)
 P_{poi} = point load, kip (kN)
 q_{lin} = line load, kip/ft (kN/m)
 q_{sur} = uniform surface load, kip/ft² (kN/m²)
 R = radius of negative yield line, ft (m)
 t = slab thickness, in. (mm)
 W_G = self-weight of slab system per unit area, lb/ft² (kN/m²)
 x_{lin} = distance of from negative yield line at left extremity of each panel, ft (m)
 σ_{cy} = stress at yielding, psi (MPa)
 σ_{cu} = stress at nominal strength, psi (MPa)
 ϕ_h = ratio of negative to positive flexural capacities of the slab cross section
 ϕ_p = reduction factor

2.2—Definitions

ACI provides a comprehensive list of definitions though an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/store/productdetail.aspx?ItemID=CT13>. Definitions provided herein complement that resource.

bend-over point—tensile stress measured at the onset of first cracking (in a uniaxial tension test). This point is considered as tensile yield point or limit of proportionality.

crack bridging—ability of the fibers to extend from one face of a crack to the opposite side and transfer load during crack opening to the opposite face.

deflection hardening—multiple cracking accompanied by an increase in flexural strength after first cracking due to strain hardening of the bridging material.

deflection softening—flexural response with a primarily linear elastic ascending branch up to the first flexural cracking, followed by an immediate reduction in load with increasing deflection.

microcrack coalescence—process by which microcracks grow sufficiently to join together and form a larger, perhaps visible, macrocrack.

progressive collapse—failure of a primary structural element that results in the failure of adjoining structural elements leading to further structural failure.

stable crack propagation—crack extension caused solely by additional load on the specimen.

strain softening—process where unstable crack propagation directly follows crack initiation.

strain softening fiber-reinforced concrete—fiber-reinforced concrete composite with a primarily linear elastic ascending tensile stress-strain curve up to the same point representing both the first cracking and peak stress, followed by a reduction in stress as the strain is increased.

strain hardening fiber-reinforced concrete—fiber-reinforced concrete composite with a primarily linear elastic ascending tensile stress-strain curve up to the first cracking, microcrack coalescence, and a post-elastic portion characterized by an increase in the stress with a much lower effective stiffness (representing tension stiffening) up to the maximum stress.

structural integrity reinforcement—structural detailing that improves the redundancy and ductility in structures so that, in the event of damage to a major supporting element or an abnormal loading event, the resulting damage may be confined to a relatively small area and the structure will have a better chance to maintain overall stability.

unstable crack propagation—uncontrolled and dynamic expansion of a crack that is not solely dependent upon additional load on the specimen.

CHAPTER 3—HISTORICAL DEVELOPMENT OF SLABS-ON-GROUND AND ELEVATED STEEL FIBER-REINFORCED CONCRETE SLAB SYSTEMS

3.1—Historical background

More than 385 million ft² (35 million m²) of joint-free slabs-on-ground with a high dosage rate of steel fibers, without saw-cutting between construction joints, and 132 million ft² (12 million m²) of pile-supported ground or near-ground slabs have been successfully installed and used since 1995 (ACI 544.3R; Clarke 2007; Destrée 1995, 1998, 2000, 2001; Destrée et al. 2011; Alexandre and Bouhon 2010).

Considerable experience was gained in slabs-on-ground steel fiber-reinforced concrete (G-SFRC) during the 1980s (Sahloul and Destrée 1985). Various aspects of design and construction, such as fiber types, mixing of the fibers in concrete, use of automatic feeders, rheology control, pumping of SFRC materials, finishing of the slab to minimize the fiber protrusion, and design-simplified procedures have been addressed in previous work (Destrée 2004, 2008). Contraction joints (saw cuts) are therefore not required for bay sizes of up to 33,000 ft² (3000 m²) with up to 213 ft (65 m) between construction joints when special construction and quality control procedures are implemented (Destrée 1995, 2001; Destrée and Mandl 2008). Full-scale testing of slabs has shown that traditional elastic methods are overly conservative, as both first-visible crack and ultimate loading capacity were several times higher than the calculated values (Westergaard 1947; Ioannides et al. 1985; Destrée 1995, 2001, 2004, 2008; Destrée and Mandl 2008).

Full-scale testing procedures have also shown the ability of deflection-hardening SFRC to produce multiple cracks under flexure; hence the need to introduce inelastic post-cracking properties into the design process.

The first standard document for using G-SFRC was developed in 1992 (The Concrete Society 2003). It describes

a well-established design methodology in the United Kingdom resulting in an estimated 20 percent of industrial concrete slabs-on-ground to be designed as supported on piles (Dhir and Henderson 1999; Chandler and Neal 1988; Reddy 2003). After a decade of experience in G-SFRC and its successful design and implementation, design procedures were extended to column supported slabs. The natural extension of this design approach is to consider the case for a fully elevated slab. Experiments started in Belgium and Holland, where many industrial slabs are built on pile supports because shallow foundations are unable to offer bearing capacity (Destrée 2000, 2004).

Existing G-SFRC slab applications are in excess of 132 million ft² (12 million m²), with many of them in industrial applications that are subjected to dynamic loads from cranes and heavy forklift loads (Destrée 1995). Their resistance to dynamic loadings has been excellent. Dozens of buildings that used E-SFRC slabs have been completed since 2004 in several European countries.

Historical records and years of experience with pile-supported ground slabs subjected to severe traffic conditions, dynamic loadings, shrinkage, and creep have indicated no adverse effects. Durability aspects of SFRC have also shown no adverse effects to the concrete properties (Destrée 2008; Lie and Kodur 1995; Gambarova 2004; Kodur 1997; ACI 544.5R).

3.2—Advantages of G-SFRC and E-SFRC slab systems

There are numerous advantages of using the SFRC systems that make them sustainable products. These are defined in terms of several categories, including speed of construction, strength, ductility, shrinkage control in terms of crack width control, and long-term durability that ultimately leads to an economic and sustainable design.

3.2.1 Economic advantages—A key economic advantage is the reduction in construction time compared with the traditional installation of double layers of conventional reinforcing bars, stirrups, or other shear reinforcement. Time savings of several weeks for G-SFRC slab projects larger than 110,000 ft² (10,000 m²) can be obtained; however, the economic costs and actual savings are based on a collection of individual gains obtained and measured using appropriate construction estimating tools and evidenced by the field data that support the decisions made to use this construction methodology. Because the FRC can be directly pumped to elevated slabs, the use of cranes for lifting reinforcing bars is eliminated. The overall simplification of the jobsite significantly improves the physical and labor-intensive tasks that would be otherwise needed if reinforcing bars were to be placed. This simplification has the potential to improve safety on the jobsite. A reduction in personnel for placing and finishing may also occur when compared with the traditional RC structures. Moreover, as the requirements for concrete cover are eliminated in the FRC technology, an additional reduction in labor and material cost may occur. The SFRC may be somewhat thinner than the traditional slab only when design verifications for serviceability and ultimate limit states are assessed. Overall, the total cost saving in

construction can be as high as 30 percent compared with traditional methods of reinforced concrete slab construction.

3.2.2 Strength and ductility—The ductility of the slabs discussed herein is greater than comparable slabs that are reinforced using continuous transverse and longitudinal reinforcing bars. The analytical strength of the slabs calculated by means of standard rectangular stress block calculations tend to underestimate the experimental results. This suggests that the failure mechanisms may be governed by yield-line theory. The steel fibers with undulated, conical, or hooked ends provide improved mechanical bond and are shown to be able to provide sufficient structural capacity. Other conventional reinforcing bars are provided to reinforce the corners of lift shafts, staircases, manholes, and other reentrant corners.

3.2.3 Construction scheduling—E-SFRC slab systems have the same advantages as G-SFRC slab systems in addition to improving the architectural freedom to use creativity with non-orthogonal shapes of floor plans that may otherwise be quite difficult with traditional reinforcing bar layouts. Because drop panels and beams can be omitted, forming becomes easier and quicker. Savings in crane costs and scheduling time is obvious because only a small amount of reinforcing bar is needed to be lifted up to the floor level. If self-consolidating mixtures are used, installation does not require internal or poker vibrators, which may leave voids in concrete, and reduces noise pollution (Salehian and Barros 2015). Reduction of layers of reinforcing bars or reliance on welded wire reinforcement significantly improves mobility and safety of personnel.

3.2.4 Joint-free slabs—One of the principal advantages of using SFRC in slabs is to reduce the number of joints. G-SFRC slabs-on-piles typically span 7 to 13 ft (2 to 4 m) between piles, and are between 6-1/2 and 16 in. (165 and 410 mm) thick. In general, the pile spacing is a function of the pile loading capacity, whereas the span-depth ratio of the slab is between 8 and 20. The proximity of the piles enables the load distribution to take place such that the construction joint spacing is increased significantly. For example, in the case study discussed in 7.2.1, a 4800 yd² (4015 m²) project in a single bay without construction joints was erected.

3.2.5 Contraction joint reductions—The addition of steel fibers to concrete used in slabs helps control shrinkage and, thus, promotes the application of joint-free slabs (Silfwerbrand 2004; Bakhshi et al. 2012; ACI 544.5R). Contraction joints are specified in terms of aspect ratio according to ACI 224.3R, which also references ACI 302.1R and are typically used in large-size floor areas (bay sizes of up to 33,000 ft² [3065 m²]). Many of the long-term performance issues dealing with the maintenance of the joints are eliminated by reducing the overall number of joints. Typical SFRC contraction joint spacing has been used up to 150 ft (45 m), which is three times that of conventional practice. When compared with traditional methods, increasing the joint spacing becomes extremely important in cases where curling, joint movement, and corner cracks are dominant failure modes of the entire slab. When special construction and quality control procedures

are implemented, construction joints have been extended up to spacing of 213 ft (65 m).

For on-ground or near-ground slabs, starter reinforcing bar or connecting reinforcing bar projection out of the piles is usually not needed, and in most cases, drop panels can be eliminated. The installation can be accomplished using laser screed machines, as the concrete is often discharged from the truck mixer so that pumping is no longer needed. Bay areas of G-SFRC slabs that are larger than the conventional systems are possible because better shrinkage control due to the addition of fibers results in a reduced number of construction joints (Grzybowski and Shah 1990; Mangat and Azari 1988; Alexandre and Bouhon 2010). By using SFRC, additional savings are also obtained in the preparation of the drawings, as reinforcing bars do not need to be detailed or inspected (Destrée 2008; Destrée and Mandl 2008).

CHAPTER 4—CURRENT DESIGN METHODS AND CONSTRUCTION PRACTICES

4.1—Introduction

To verify the calculations of current design procedures that are primarily based on yield-line analysis of one- and two-way slabs, practicing engineers have relied on full-scale experimental tests on elevated slabs and large-scale round slabs. These tests, however, are costly and do not address all aspects of unique design equations. Ideally, it would be useful to use material property data in the development of standardized design procedures. During the past several years, a combination of small-scale flexural beam tests, round slab tests, finite element modeling, and full-scale testing of elevated slabs have been collectively used to address the mechanisms involved and present a comprehensive design methodology for elevated slabs based on post-cracking response and ductility of strain softening and strain hardening steel fiber-reinforced concrete (SFRC) (Mobasher 2011; Soranakom and Mobasher 2008; Mobasher et al. 2014; Salehian and Barros 2015). This report describes methodologies available to conduct a design and analysis approach; however, no standard code-approved procedure exists.

4.2—Existing standards and design methodologies

4.2.1 United Kingdom standards—The use of steel fibers as stand-alone reinforcement or in combination with traditional reinforcing bars in structural applications has been addressed by The Concrete Society (2007). Methods for determining section properties from small notched specimens in flexure are available; however, direct applications of these methods tend to underestimate the contribution of structural response to the overall behavior. Alternatively, steel fiber-reinforced concrete (SFRC) slabs can be designed following a method validated by experiments in which full-scale testing of slabs supported on piles, as well as testing of round indeterminate slabs in flexure, supply the resisting moment capacities (The Concrete Society 2003; CUR 2012; Mobasher 2011).

Table 4.3—Comparison of fiber, loading, and slab dimension parameters for G-SFRC and E-SFRC slabs (Destrée and Mandl 2008)

	G-SFRC	E-SFRC
Concrete type	Structural concrete $f'_c = 4000$ psi (27.6 MPa) $w/c = 0.50$	Structural concrete $f'_c = 4000$ psi (27.6 MPa) $w/c = 0.50$
Fiber parameters: type, strength, length, diameter, and shape	High-strength steel wire ASTM A820/A820M Type I Diameter = 0.04 in. (1 mm) IDEM Type: undulated $f_y = 218,000$ psi (1500 MPa)	High-strength steel wire ASTM A820/A820M Type I Diameter = 0.04 in. (1 mm) Fiber dimensions: 0.04 x 2.5 in. (1.0 x 60 mm) Type: undulated $f_y = 218,000$ psi (1500 MPa)
Dosage rate	66 to 83 lb/yd ³ (40 to 50 kg/m ³)	100 to 168 lb/yd ³ (60 to 100 kg/m ³)
Span	7 to 20 ft (2.1 to 6.1 m)	13 to 28 ft (4 to 8.5 m) span
Span-depth ratio	8 to 20	smaller than 30
Thickness	6.5 to 18 in. (165 to 458 mm)	6 to 12 in. (150 to 300 mm)
Slab size	147.6 x 147.6 ft (45 x 45 m) or more	98.4 x 98.4 ft (30 x 30 m) or more
Loading range concentrated load	44 kip (200 kN)	6 to 10 kip (27 to 45 kN)
Loading range distributed load	200 to 1000 lb/ft ² (10 to 50 kN/m ²)	80 to 160 lb/ft ² (4 to 8 kN/m ²)

4.2.2 Dutch standards—CUR (2012) is more specific to the design of SFRC pile-supported slabs. Small notched prismatic beam specimens tested in flexure are used to obtain post-cracking cross-sectional properties. The design calculations are conducted based on the post-cracking strength of the FRC specified; however, the analysis is conducted by means of elastic analysis. CUR (2012) mentions that a design method assisted by testing offers a viable solution and that nominal moments, as supplied by round indeterminate slab testing and by full-scale slab tests, are acceptable.

As an alternative approach, SFRC slabs can be designed based on an experimental validation with full-scale testing. In addition, test results of round indeterminate slabs in flexure can be used to provide the resisting moment capacity for design. These large-size specimen testing and full-scale slab testing procedures are costly and make the standardization of the methodology for design impractical.

Plastic analysis (Johansen 1962) and yield-line analysis of slabs (Kennedy and Goodchild 2004) are used to relate the section properties to the load-carrying capacity of the slabs.

4.3—Slab dimensioning, fiber dosage rate, and typical loading conditions

Table 4.3 presents a summary comparison of the fiber type, strength, length, diameter, dosage rate, typical slab dimensions, and loading conditions. Note that a high content of steel fibers (66 to 168 lb/yd³ [40 to 100 kg/m³]) made of undulated Type I (0.05 in. [1.3 mm] in diameter) normal-strength steel wire (123,000 psi [850 MPa]) or 0.04 in. (1 mm) diameter high-strength steel wire (210 ksi [1450 MPa]) is used as the primary reinforcement. Mixtures using high-range water-reducing admixtures (HRWRAs) to maintain a water-cement ratio (w/c) below 0.5 are necessary. The practical dosage of deformed steel fibers for slabs-on-ground or near-ground is 66 to 83 lb/yd³ (40 to 50 kg/m³) and that permits workability and pumping ability (Destrée 2001).

The pile-supported slabs-on-ground steel fiber-reinforced concrete (G-SFRC) are generally subjected to concentrated,



Fig. 4.3—Construction of multi-story elevated slab for residential/office building (Destrée and Mandl 2008).

as well as uniformly distributed, loading of up to 1000 lb/ft² (50 kN/m²). Generally, these slabs are separated from the rest of the building and are not used to support columns, walls, and roof loads. Their span-depth ratios depend on the loading intensity and pile capacity.

The elevated SFRC (E-SFRC) application is a flat slab cast above columns and beams typically applied to condominium buildings, office towers, and schools where loading intensities are light to moderate. A typical example is shown in Fig. 4.3, where a 15-story high-rise condominium building under construction has E-SFRC flat plate slabs with a span-depth ratio of up to 30. The SFRC mixture for E-SFRC slabs are designed to be flowable or self-consolidating so that mechanical vibration during casting is not required because it may disrupt the random distribution of fibers. Mixtures containing deformed steel fibers can be designed to achieve similar performance such that the fiber dosage does not

impair the required workability, and pumping as high as 15 stories is possible.

4.4—Additional construction provisions

4.4.1 Criteria for anti-progressive collapse/structural integrity reinforcement—Elevated steel fiber-reinforced



Fig. 4.4.1a—Casting of E-SFRC slabs using SFRC.



Fig. 4.4.1b—Continuity or structural integrity reinforcement (SIR) reinforcing bar placement in elevated slab.

concrete (E-SFRC) slabs supported on columns aligned in orthogonal directions will form a regular two-dimensional (2-D) frame if steel bars are placed along the column alignment. These are referred to as structural integrity reinforcement (SIR) or anti-progressive collapse (APC) bars (Baldridge and Humay 2003; Sasani and Sagioglu 2008; Udilovich et al. 2010; Hawkins and Mitchell 1979; Mitchell and Cook 1984; Ghali and Tadros 1997; Blandford 1997). There is a clear need to better differentiate the role of these reinforcing bars in providing continuity among columns and serving to limit the extent of potential damage due to localized failure. The term “progressive collapse failure” is referred to as “the collapse of all or a large part of a structure precipitated by damage or failure of a relatively small part of it” (Post 2004). The goal of structural integrity also applies for detailing requirements by increasing the redundancy and improving the ductility of structures so that, in the event of damage to a major supporting element or an abnormal loading event, the resulting damage may be confined to a relatively small area and the structure will have a higher chance of maintaining overall stability (ACI 318).

As shown in Fig. 4.4.1a, all of the steel fiber-reinforced self-consolidating concrete is pumped and placed with the continuity SIR reinforcing bars used as the only continuous reinforcement as recommended by CAN/CSA-A23.3 and Hawkins and Mitchell (1979) as being mandatory to ensure integrity when column capacity diminishes due to an accident, explosion, or terrorist attack. The SIR reinforcement, as shown in Fig. 4.4.1b, consists of a set of at least two reinforcing bars placed at the bottom of the slab in both longitudinal and transverse (x- and y-) directions intersecting within the column core (as outlined in CAN/CSA-A23.3) as they follow the column grid.

The crack failure pattern obtained in experimental tests with E-SFRC prototypes and real-scale structures (Fig. 4.4.1c) demonstrate that the SIR can cross the failure cracks formed, offering resistance to the collapse of the panel.

Bar diameters are generally chosen in the range of 1/2 to 1 in. (12 to 25 mm), depending on loading intensity, thickness, and span. For example, an 8 in. (200 mm) thick office slab of 20 ft span has three bars of 0.64 in. (16 mm) while a 12

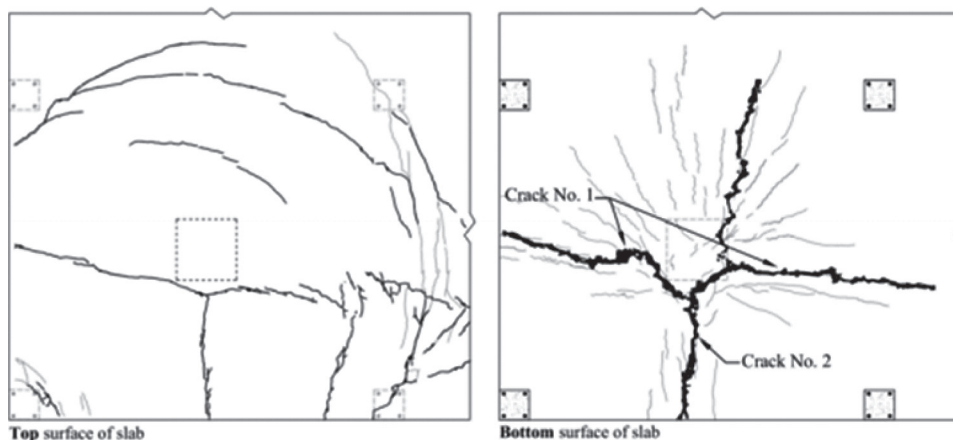


Fig. 4.4.1c—Crack patterns of E-SFRC slab's loaded panel (in its center) at end of test (Salehian and Barros 2015).

in. (300 mm) slab spanning 27 ft (8.2 m) has four bars of 1 in. (25 mm). The formula of CAN/CSA-A23.3 in Appendix J can be used to evaluate SIR. No other conventional bars are required except those used locally to prevent crack extension from lift shafts, staircases, manholes, and reentrant corners.

4.4.2 Special provisions for reentrant corners or shrinkage restraint—The slab-on-ground SFRC (G-SFRC) is generally built to have free contraction movement around manholes, columns, and at joints to better control shrinkage cracking. In the case of larger openings within a slab (Mota and Kamara 2006), an analysis of both strength and serviceability requirements are required. Alternatively, the amount of reinforcement that would have been used in the opening is recommended to be placed in the vicinity of the opening in both directions. Half of the interrupted reinforcement should be replaced on each side of the opening. The number of top or bottom reinforcing bars is calculated based on the resisting moment of fiber concrete missing in the opening. This number is calculated as in standard reinforced concrete without any influence of the fiber concrete. As a precautionary note, attention is needed when any opening is located within the column strip or within 10 times the slab thickness from a concentrated load or reaction area. Traditional reinforcing bars are added when the opening is within the critical perimeter around a column and additional shear/punching-out reinforcement is required and calculated without any influence of the fiber concrete.

4.4.3 Special provisions for shear wall restraint—In cases of significant restraint due to shear walls or multiple core walls, an analysis of both strength and serviceability requirements are needed to determine additional continuous reinforcement. To prevent crack extension from reentrant corners, reinforcement of as much as 0.25 percent of the slab section is used as top reinforcing bar or wire mesh, and installed in a strip width three times the depth of slab.

Experience has shown that for flat plates of less than 11,000 ft² (1022 m²) area with a square or rectangular length-width ratio smaller than 1.5, the restraint is not critical and can be addressed with additional steel fiber reinforcement.

4.4.4 Weak soil conditions and floor tolerance problems—Slabs-on-ground supported by a grid of ground piles are used for factory floors, warehouses, and basement slabs where the areas underneath the slab are not functional. Such applications are quite common for areas where soil-structure interaction may create differential settlement or long-term floor settlement tolerance problems. The piles in this case are necessary because the ground does not offer the required bearing capacity. In this case, a G-SFRC slab is designed as a structural slab without any ground support. A factor that should also be considered is that some types of soils are so weak that the plastic settlement under the slab will lead to loss of all contact over time. Some other soils that experience swelling pressures may affect the structural integrity of the slab. In cases where the soil is expansive, such as swelling clays, a G-SFRC slab is strongly recommended to be installed above the top level of the ground to alleviate the potential cracking problems.

4.5—Limitations and areas of needed research

4.5.1 Limitations of G-SFRC and E-SFRC slabs

4.5.1.1 G-SFRC limitations—Some of the limitations of slab-on-ground steel fiber-reinforced concrete (G-SFRC) slabs include a span-depth ratio smaller than 30 for general areas and less than 20 for areas where a void or a cavity underneath the slab is permitted. The general size of the spans is between 6.5 and 13 ft (2 and 4 m) with bay sizes of up to 33,000 ft² (3066 m²) with up to 213 ft (65 m) between construction joints. Mixture designs are also important to obtain a homogeneous and consistent mixture proportion and fiber distribution. In addition, methods of placement must address a uniform distribution and homogenized dispersion of the fiber through the mass (Destrée and Mandl 2008; Destrée et al. 2011).

4.5.1.2 E-SFRC limitations—Limitations of elevated steel fiber-reinforced concrete (E-SFRC) slabs include a span-depth ratio less than 30 and a maximum service unfactored dead load (UDL) of 167 lb/ft² (8 kN/m²). Slabs are considered two-way when the long span is less than two times the short span. Use of structural integrity reinforcement (SIR) reinforcing bars is mandatory for two-way slabs, as well as around openings in the slab and reentrant corners.

4.5.2 Research needs—The main purpose of this report is to present the application methods and design approaches for E-SFRC and G-SFRC slabs. Some of the needed areas of research in this subject include fire resistance, dynamic behavior, seismic lateral load design checks, and long-term behavior, mainly when these slabs are cracked. These areas have not been tested and are not included, considered, or discussed in this report. However, tests on the creep behavior of cracked SFRC have indicated that if instantaneous crack width is limited to 0.02 in. (0.5 mm) when permanent load is applied, stable crack width evolution is expected to occur (Abrishambaf et al. 2014a,b). Fatigue loading in cracked SFRC and moment redistribution capacity are additional areas deserving further research.

4.5.2.1 Fiber distribution—Further research is warranted to address the effect of rheology and casting method on the fiber distribution and observed differences between the positive and negative moment capacity as a quality control issue. If SFRC is self-consolidating, the geometry of the steel fibers on its orientation and distribution needs to be conveniently addressed because fibers tend to be oriented orthogonally to the concrete flux lines (Abrishambaf et al. 2013).

4.5.2.2 Seismic conditions—The process as described herein has been applied in areas where seismic considerations are not the primary design criteria. The results of two types of experimental investigations are described. The first one focuses on round indeterminate slab testing, also called large-scale tests, as opposed to standard small prismatic specimens tested in bending. The second focuses on full-scale testing of elevated slabs (Destrée 1995). Results are used to present a comprehensive design methodology for elevated slabs based on post-cracking response and ductility of slabs subjected to flexure.

More experience in the development of E-SFRC slabs is needed, however, especially in areas where there is potential for progressive collapse or seismic loading applications, where punching shear is the dominant mode of potential failure.

CHAPTER 5—MATERIAL AND STRUCTURAL DUCTILITY

5.1—Introduction

The objective of this chapter is to demonstrate that, given the available design methodologies based on testing flexural samples, large-scale panel tests, and full-scale field tests, a rational design basis for these types of slabs can be developed. The assumptions and methodologies regarding the measurement of material properties and the proposed design guides based on conventional limit analysis and two-way design of slabs are presented.

It is noted that the construction of the structures based on this approach have been primarily based on the back-calculation from round slab tests in addition to full-scale testing and small-scale notched beam specimens. The design methods described and developed for this document have been used in Europe and have had limited applications in construction projects in the United States and Canada.

A comprehensive procedure for the design of steel fiber-reinforced concrete (SFRC) slabs and derivation of their allowable moment capacities are presented first. The procedures use closed-form equations that relate the tensile and compressive response of fiber-reinforced concrete (FRC) to its flexural response (Soranakom et al. 2008b). This method is based on determining section properties derived from testing small notched beam specimens in flexure following RILEM TC 162-TDF (Barros and Antunes 2003).

CEB-FIP (2012) currently allows for the integration of a steel fiber contribution into the structural design. Many of the proposed methodologies presented in this report may be integrated with the material models and design procedures proposed in CEB-FIP (2012).

It is essential that material properties of the mixtures be determined and verified to be able to develop fiber strengthening and ductility improvements. A deflection hardening behavior in flexure is necessary to develop multiple cracks (Soranakom et al. 2008b). There are two main ductility aspects in the design of FRC structures in terms of material-level and structural-level ductility. To differentiate between the two ductility levels, consideration of the two competing mechanisms must be done at the material level.

5.2—Material ductility

For plain concrete, or concrete with low fiber contents, initiation of the tensile crack may result in localization of deformations such that, as soon as cracks form, they tend to open and propagate. Under these circumstances, the material is defined as tensile strain-softening in uniaxial tension and viewed as brittle for structural applications. As the fiber content increases, however, propagation of newly-formed cracks require a much higher level of energy than what it took to create them. Under these circumstances, multiple



Fig. 5.2—Distributed cracking under full-scale elevated slab subjected to concentrated load (location: Tallinn, Estonia, 2007) (photo by courtesy of X. Destrée).

cracks are formed, and localization will occur at higher stress and strain levels. In such a case, the material is described as tensile strain-hardening.

In a typical bending test on small fiber-reinforced concrete (FRC) beams, failure generally occurs due to weakness in tension and the response of the beam could be either deflection softening or deflection hardening, depending on the effectiveness of the fibers in the concrete. Such behavior is relevant for FRC structural slabs for which a material with tensile strain-softening behavior may exhibit a deflection-hardening behavior. In deflection-hardening two-way slabs, diffuse crack pattern has been formed in the slab's bottom surface, where high tensile strains have occurred (refer to Fig. 5.2).

5.3—Structural ductility

The second mode of ductility is due to the structural aspect of load redistribution due to the support redundancies in the structural system. In this case, the geometry and degree of indeterminacy of structure play a dominant role in its response. For a statically determinate simply-supported beam, the first crack that localizes into a yield line serves to form a collapse mechanism. If the degree of structural indeterminacy increases due to the redundancy of the support conditions, which is the case of continuous beams and joint-free slabs, then a minimum number of yield lines are needed to initiate a collapse mechanism. Under these circumstances, the degree of structural indeterminacy increases the load-carrying capacity. Small notched or unnotched beam specimens that fail at a single failure plane may not appropriately represent the failure mechanisms occurring in a steel fiber-reinforced concrete (SFRC) slab because multiple cracking and load redistributions cannot be replicated in statically determinate test samples.

5.4—Two-way slab mechanism

The structural slab behavior results from the two-way bending action with moments m_x , m_y , and m_{xy} interacting

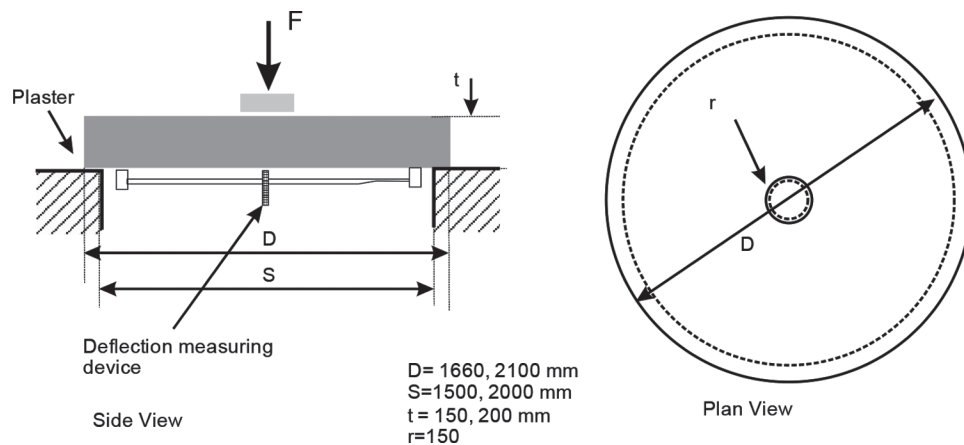


Fig. 5.5.2a—Schematics of round slab testing (Espion 2004). (Note: 1 mm = 0.04 in.)

together with potential membrane and arch actions. Slabs with two lateral dimensions that are much larger than the thickness are quite appropriate for fiber reinforcement because the fiber orientation tends to become preferential in the plane.

5.5—Test methods applicable to design

5.5.1 Three-point bending test as measure of material ductility—The greater the fiber dosage rate and concrete matrix strength, the more likely the material will exhibit strain-hardening behavior and the higher the potential is for multiple cracking, as long as fiber pullout mechanisms are preserved. This effect is also compounded in specimens that provide a high degree of indeterminacy.

5.5.2 Round slab testing as a measure of material and structural ductility—New approaches are needed to capture and differentiate between the structural and material interactions. For example, ductile behavior is observed from the test results of an indeterminate round slab where multiple cracking is possible. Steel fiber-reinforced concrete (SFRC) slabs loaded under a center-point loading that results in a two-dimensional (2-D) deformation pattern show far lower variability in results than one-way prismatic beam tests that have a determinate geometry and one-way action (Parmentier et al. 2008).

Quasi full-scale tests of SFRC round slabs with net diameters of $S = 5$ ft (1.5 m) and 7 ft (2.1 m) with a thicknesses of $t = 6$ in. (150 mm) and 8 in. (200 mm), respectively, were conducted (Destrée 1998). Figure 5.5.2a represents the geometry and the loading mode of a round indeterminate panel specimen. The round plate is simply supported along its perimeter, as shown in Fig. 5.5.2b. A load-deflection diagram is recorded during the test, where the first cracks at a load level of 11 kip (50 kN) become quite visible (minute cracks of 0.004 in. [0.1 mm] opening). Crack initiation is followed by a slight increase in the rate of deflection and formation of yield lines.

Note that the sample is supported continuously along its perimeter, as shown in Fig. 5.5.2b. It is a structural test that has been used for more than 20 years in the development of laboratory-based properties for both slabs-on-ground SFRC (G-SFRC) and elevated SFRC (E-SFRC) slab



Fig. 5.5.2b—Test setup for round slab test on simple supports.

applications. Its main advantage is to allow detection of a multiple-cracking pattern that is not observable in small beam specimens. This test is similar to the ASTM C1550 test method but with different boundary conditions and specimen dimensions. The ASTM C1550 test conducted on three equidistant supports results in three cracked sectors along the radial direction. The material test on the round indeterminate panel is not comparable to the prismatic specimens in standard bending tests.

The test results of two-way action of an indeterminate round slab are influenced by the friction at the supporting rim. Because of its large size (span of 5 ft [1.52 m] and thickness of 6 in. [150 mm]), the test slab is not used for quality control. It can, however, be correlated to prismatic tests in bending in terms of stresses, curvatures, crack opening, and standard deviation when both types of tests are conducted together. More discussions about prismatic specimens in bending and round indeterminate panels are found in detail in Appendixes A through K.

5.3.3 Full-scale structural testing—Full-scale structural testing is discussed in detail in Chapter 7 and is verified by the design procedures used in the design and analysis of the G-SFRC and E-SFRC slabs.

CHAPTER 6—DESIGN GUIDES FOR TENSILE STRAIN SOFTENING, DEFLECTION HARDENING MATERIALS

6.1—Structural analysis

The proposed method of approach is based on [Johansen's \(1962\)](#) yield-line theory to evaluate the load-carrying capacity of an elevated steel fiber-reinforced concrete (E-SFRC) slab. According to yield-line theory, the ultimate load of a slab system is obtained by postulating a collapse mechanism, which is compatible with the boundary conditions. Slab sections are assumed to be sufficiently ductile to allow plastic rotation to occur at critical section along yield lines. Large-scale round slab and full-scale testing have verified that SFRC slabs with a fiber dosage rate of 135 to 168 lb/yd³ (80 to 100 kg/m³) are capable of forming nominal moments with a large rotation capacity in zones designated as yield lines ([Silfwerbrand 2004](#); [The Concrete Society 2003, 2007](#); [Dhir and Henderson 1999](#); [Destrée 2001](#); [CUR 2012](#); [Gesund and Kaushik 1970](#); [Gesund and Dikshit 1970](#); [Salehian and Barros 2015](#)). The yield patterns as observed under full-scale testing are circular and pass by the supporting columns while remaining parallel to the walls or fixed-beam supports. Nominal moments develop along the yield lines where the moments are maximum. Between the yield lines, the moments are smaller and the deformations are assumed negligible.

These observations, which are necessary for the application of yield-line analysis, have been verified using the finite element method ([Soranakom et al. 2008a](#)). A procedure that relates three distinct load conditions of uniform surface load (q_{sur}), line load (q_{lin}), and point load (P_{poi}) to the nominal flexural strength M_p and geometry of the slab can be expressed using an ultimate design approach as

$$h[q_{sur}, q_{lin}, P_{poi}]_{ult} = \phi_p f(M_p) \quad (6.1a)$$

where h represents the failure mode in terms of the maximum concentrated or distributed load, geometry, and potential failure mechanism as it relates to the function $f(M_p)$, which incorporates the nominal bending capacity.

Uniformly distributed load is obtained from the combination of self-weight of the slab, W_G , and live load, q'_{ult} , from the following equation

$$q_{sur} = \lambda_{DL} W_G + \lambda_{LL} q'_{ult} \quad (6.1b)$$

where λ_{DL} and λ_{LL} are load factors for the corresponding load cases (values should be in agreement with the design codes). The load factors in consideration of the ultimate strength approach are defined as $\lambda_{DL} = 1.2$, $\lambda_{LL} = 1.6$ in the present case, and a strength reduction factor of ϕ_p may be used depending on the applicable codes, such as ACI 318.

The line load addresses the influence of walls or similar elements on the slab's load-carrying capacity and can be taken into account from the following equation

$$q_{lin} = \lambda_{LL}(\gamma_w, h_w, t_w) \quad (6.1c)$$

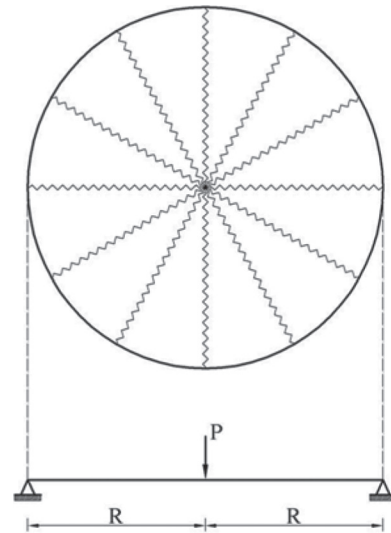


Fig. 6.2—Fan pattern of yield lines for case of center-point load of simply-supported round slab.

where γ_w , h_w , and t_w represent the specific weight of the material, the height, and the thickness of the wall or similar elements, respectively. The point load consists of a weight W applied in a relatively small area on the slab.

The design value of point load can be obtained from the following equation

$$P_{poi} = \lambda_{LL} W \quad (6.1d)$$

Because the values of loads in a design process are generally known, Eq. (6.1a) determines the nominal moment that a cross section must resist.

6.2—Approaches to evaluate nominal flexural strength of E-SFRC slabs

To evaluate M_p , two approaches are proposed. The first approach is based on the post-cracking residual strength concept of fiber-reinforced concrete (FRC) to obtain the resisting moment ([Soranakom and Mobasher 2007b](#)), where M_p can be determined from a straightforward process (refer to [Appendix H](#)). The influence of the parameters that define the post-cracking stress-strain tensile behavior on the crack width of FRC was numerically investigated by [Taheri et al. \(2012\)](#).

The second approach to determine M_p is based on the results obtained from round slab tests and applying the yield-line theory. Using the maximum load P_{max} , determined from experimental tests of a steel FRC (SFRC) round slab simply supported in its contour, the yield-line theory can be applied to obtain M_p from P_{max} .

The round slab test with its contour continuously supported (Fig. 6.2) can provide design-applicable data for E-SFRC slabs. Adopting a loading configuration consisting of a center-point load and measuring the applied load, P_{max} is obtained. Applying the yield-line theory for this type of structure ([Johansen 1962](#)), the nominal moment can be calculated from P_{max} (refer to [Appendixes A and B](#))