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

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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/ft^2 (50 kN/m^2). 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/yd^3 [50 to 100 kg/m^3]) 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.

CONTENTS

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.

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

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 ft^2 (4645 m^2) 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/ft^2 (6703 Pa) using 165 lb/yd^3 (98 kg/m^3) 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 Sagiroglu 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. 1.1b—Construction and applications of E-SFRC slabs (courtesy of Primekss SIA).

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} (mm^2)
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/ft^2 (kN/m^2)
R = radius of negative yield line, ft (m)
t = slab thickness, in. (mm)
W_G = self-weight of slab system per unit area, lb/ft^2 (kN/m^2)
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.