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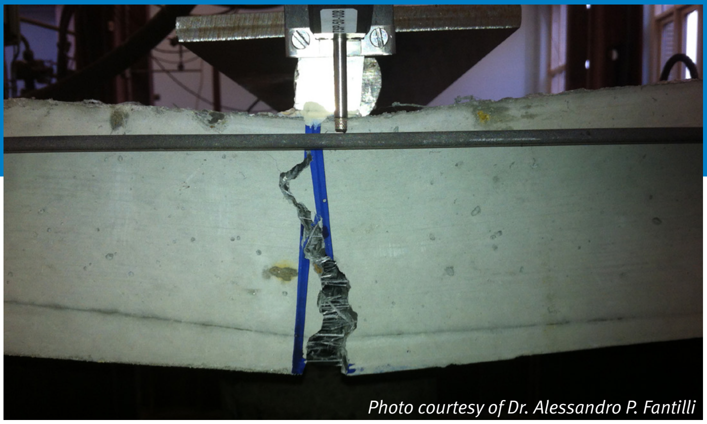
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Reduction of Crack Width with Fiber

Editors:
Corina-Maria Aldea and Mahmut Ekenel

SP-319

American Concrete Institute
Always advancing

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The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

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Preface

Fiber reinforcement is the most effective way of improving the resistance of concrete to cracking, but little is known of the extent of the reduction of crack width with fiber. The papers included in this special publication discuss the role of fiber reinforcement in reduction of crack width and lay the foundation for Life Cycle Engineering Analysis with fiber reinforced concrete.

Recognizing the reduction of crack width with fibers in cement-based materials, ACI Committee 544 Fiber Reinforced Concrete, together with 544F Fiber Reinforced Concrete Durability and Physical Properties sponsored two technical sessions entitled Reduction of crack width with fiber at the Fall 2016 ACI Convention in Philadelphia. Papers were presented by invited international experts from Belgium, France, Germany, Italy, Portugal, United Arab Emirates and the United States of America.

This Symposium Publication (SP) contains eleven papers which provide insight on the state of the art of the topic in the academia, in the industry and in real life applications. The topics of the papers cover the reduction of crack widths in steel reinforced concrete bridge decks with fiber, 15 years of applying SFRC for crack control in design from theory to practice, the effectiveness of macro synthetic fibers to control cracking in composite metal decks, conventional and unconventional approaches for the evaluation of crack width in fiber reinforced concrete (FRC) structures, reduction of water inflow by controlling cracks in tunnel linings using fiber reinforcement, a review of Engineering Cementitious Composites (ECC) for improved crack-width control of FRC beams, tailoring a new restrained shrinkage test for fiber reinforced concrete, a model to predict the crack width of FRC members reinforced with longitudinal bars, a probabilistic explicit cracking model for analyzing the cracking process of FRC structures, toughening of cement composites with wollastonite sub micro-fibers and self healing of FRC: a new value of “crack width” based design. The papers included in this publication have been peer reviewed by international experts in the field according to the guidelines established by the American Concrete Institute.

On behalf of ACI Committee 544 Fiber Reinforced Concrete and committee 544F Fiber Reinforced Concrete Durability and Physical Properties, the editors would like to thank all the authors for their contributions and the reviewers for their assistance, valuable suggestions and comments.

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Reduction of Crack Widths in Steel Reinforced Concrete Bridge Decks with Fiber Addition

Anil Patnaik, Prince Baah, Perry Ricciardi, and Waseem Khalifa

Synopsis: Bridge deck cracking is a common problem in the United States, and affects the durability and service life of reinforced concrete bridges. Physical inspections of three-span structural slab bridges in Ohio revealed cracks wider than ⅛ inch (3.2 mm). ACI 224R-01 recommends a maximum crack width of 0.007 inch (0.18 mm) for members exposed to de-icing chemicals. The primary objective of this study was to investigate the effects of fiber addition on crack resistance. In an attempt to minimize deck cracking, slab specimens with basalt MiniBar or polypropylene fiber were also investigated in the test program. Slab tests revealed that the specimens with longitudinal epoxy-coated bars developed first crack at smaller loads, exhibited wider cracks and a larger number of cracks, and failed at smaller ultimate loads compared to the corresponding test specimens with uncoated (black) bars. Test specimens with fiber exhibited higher cracking loads, smaller crack widths, smaller mid-span deflections and higher ultimate failure loads compared to identical specimens without fiber. Addition of fiber to concrete with no changes to internal steel reinforcement details is expected to reduce the severity and extent of cracking in reinforced concrete bridge decks demonstrating that fiber addition improves crack resistance of bridge decks.

Keywords: Bridge deck cracking; continuous span structural slab bridges; crack widths; epoxy coated bars; fiber reinforced concrete; load testing; deck slabs; crack resistance

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INTRODUCTION

Non-prestressed steel reinforced concrete solid structural slab bridges are commonly used by several Departments of Transportation (DOTs) in the United States. Structurally, a continuous deck slab runs parallel to the longitudinal axis of the bridge, and is supported by the abutments at the ends and piers at intermediate locations. The decks typically are between 11 inch (280 mm) and 27 inch (685 mm) in thickness.

One of the primary factors affecting concrete bridge durability is deck cracking. Cracks are caused primarily by low tensile strength of the concrete, volumetric instability, and/or deleterious chemical reactions. Crack openings and spacing are affected by bar size and the effective concrete area surrounding the bar (Soltani et al. 2013). Regardless of the causes, cracking on bridge decks is a serious concern, because cracks provide access to harmful, corrosive chemicals that deteriorate the reinforcing steel embedded within the concrete. Once chloride and other corrosive agents penetrate concrete, corrosion of the embedded steel can initiate and cause concrete spalling. Such deterioration can affect the shear and moment capacity of reinforced concrete bridge decks. Also, bridge deck cracks allow water and de-icing salts to flow down through the deck and can also damage to the substructure (Krauss and Rogalla 2003). According to a survey of 52 transportation agencies across North America, more than 100,000 bridges were found to crack early (McDonald et al. 1995), and in some cases, typically when concrete is just one month old (Patnaik and Wehbe 2015).

In 2002, corrosion of the reinforcing steel in concrete was estimated to have an annual direct cost to highway bridges of $8.3 billion. However, the indirect cost to users due to traffic delays and lost productivity was estimated to be ten times as much (Yunivich et al. 2002). Replacement costs for bridge decks are a significant portion of that direct cost (Virmani and Clemena 1998). Cracks frequently form relatively early in the life of concrete bridge decks, at times well in advance of a bridge being open to traffic, and sometimes immediately following construction (Schmitt and Darwin, 1995, Patnaik and Wehbe, 2015). Concrete bridge deck cracking is influenced by several conditions, including construction practices, concrete mix proportions, material properties, structural design, and loading levels (Ramakrishnan and Patnaik 2006; Cavaliero and Durham 2011).

The addition of fiber to improve cracking behavior of reinforced concrete is gaining some recognition. One of the important features of fiber reinforced concrete is the ability of the fiber to bridge across cracks. Fibers, when added to concrete, modify the cracking mechanism from macro cracking to micro cracking. The results are that crack widths are reduced, and the ultimate tensile cracking strain capacity of the concrete is increased. The mechanical bond between the embedded fiber and binder matrix redistributes the stresses. Additionally, the ability to modify the cracking mode results in quantifiable benefits. Reduced micro cracking leads to reduced permeability and increased surface abrasion resistance, impact resistance and fatigue strength (Adhikari and Patnaik 2012;

Patnaik et al. 2015). There are many different metallic and non-metallic micro or macro fiber available for use in fiber reinforced concrete.

A new type of macro fiber known as MiniBars was recently made from basalt fiber and is gaining acceptance in the industry. The addition of fiber to concrete will also improve the bond strength between the reinforcing bar and the surrounding concrete (Banibayat and Patnaik 2014; Grace et al. 2011; Grace et al. 2012, Baah 2012). This is particularly useful for epoxy-coated bars (ECB) because these are demonstrated in this study to have larger cracking potential, maybe due to inferior bond strength. Patnaik (2011) and Patnaik et al. (2013) performed a comprehensive study on the mechanical and structural characterization of concrete reinforced with basalt MiniBars. Bagherzadeh et al. (2012) studied the influence of polypropylene fiber using different proportions and fiber lengths to improve the performance characteristics of the lightweight cement composites.

This paper presents the results of a recent bridge investigation on twelve, three-span continuous reinforced concrete structural slab bridges in Ohio. These bridges were carefully selected from the bridge inventory in the state. These bridges vary in terms of span lengths, roadway width, skew angle, deck thickness, number of lanes, reinforcement ratio, and geographic location within the state. The study focused on the wide transverse cracks primarily in the direction parallel to the intermediate pier supports. Section and crack width analyses for select bridges were performed to compare the field-recorded crack widths to the theoretical crack widths determined using the three most common equations for predicting crack widths. The Ohio Department of Transportation (ODOT) uses epoxy-coated bars (ECB) in bridge decks. An experimental program was set up, and tests were conducted to examine the flexural cracking behavior of laboratory-scale slabs representing the intermediate support region of typical bridge decks using both ECB and conventional uncoated reinforcing bars, commonly referred to in the construction industry as “black bars”. The effects of addition of fiber on concrete cracking were also investigated. Variables studied in the experimental investigations included type of bar (ECB or black), bar size, with or without fiber, and specimen preparation (precut or non-precut). DIC (Digital Image Correlation) was used to obtain crack width measurements for one bridge included in this study. DIC was also used in the field investigation to measure crack widening under both static and moving truck loads. Several DOTs routinely design, build, and maintain a large number of three-span continuous structural slab bridges. The sheer number of such bridges in the states necessitated a systematic study to determine the extent of the problem in structural slab bridge decks so that the causes of cracking can be identified and countermeasures established to minimize cracking in future bridge deck construction. Because several DOTs also use ECB in bridge decks, the need to investigate the effects of the ECB on cracking behavior of concrete was identified as an immediate need.

RESEARCH SIGNIFICANCE

One of the primary factors affecting concrete bridge durability is deck cracking. Despite significant research specifically studying the problem, cracking in reinforced concrete bridge decks is still a widespread concern in old and newly-constructed bridges. Previous research conducted by the authors focused mainly on shrinkage cracking of stringer supported bridge decks (Ganapuram et al. 2012; Patnaik and Wehbe 2015). However, limited research is available on the cracking behavior of structural slab bridge decks. This investigation addresses the cracking problems identified in continuous structural slab bridge decks with an emphasis on “non-shrinkage” cracks. To investigate a preventive measure to deck cracking, this study examines the effects of the addition of basalt MiniBar and polypropylene fiber to reinforced concrete on deck cracking. Addition of fiber to concrete without changing any steel reinforcing details is expected to cost-effectively reduce the severity and extent of cracking in reinforced concrete bridge decks.

Also, the effect of epoxy coating on bond and anchorage behavior of reinforcing bars has been studied by several investigators (Treece and Jirsa 1989). However, little research has been done on the influence of ECB on crack control (Mitchell et al. 1996). This study also addresses the effect of epoxy-coating on deck cracking.

The adequacy of merely satisfying the reinforcement spacing requirements given in AASHTO or ACI 318-14 to limit cracking below the ACI 224R-01 recommended maximum limit, even though all the relevant design requirements are otherwise met, is an important factor that remains to be fully understood.

ALLOWABLE CRACK WIDTH LIMITS

To minimize the adverse effects of cracks on reinforced concrete bridge decks, the design should ensure that the crack widths under normal service conditions are within recommended allowable limits. The cracking of a reinforced concrete slab at service loads should not impact the appearance of the structure or lead to corrosion of the embedded steel reinforcement. According to ACI Committee report 224, crack widths equal to or greater than 0.007 in. (0.18 mm) can reduce durability when bridge decks are exposed to de-icing chemicals (ACI 224R-01 2008). Similar limits are set for other exposure conditions (ACI 224R-01 2008). Crack widths in the range of 0.01 in.

(0.254 mm) to 0.015 in. (0.381 mm) are acceptable from aesthetic considerations (ACI 224R-01 2008). Table 1 shows a summary of the maximum allowable crack widths, as suggested in ACI 224 report.

Table 1 − Allowable crack widths (ACI 224R-01, 2008)

Exposure Condition	Maximum Allowable Crack Width in. (mm)
Dry Air	0.016 (0.41)
Humidity, Moist Air, Soil	0.012 (0.30)
Deicing Chemicals	0.007 (0.18)
Sea Water	0.006 (0.15)
Water Retaining Structures	0.004 (0.10)

ACI 318−2014 CRACK CONTROL REQUIREMENT

Currently, the ACI 318-14 requirements are based on the belief that it can be misleading to calculate explicit crack widths, given the inherent variability in cracking. The three important parameters in flexural cracking are steel stress, cover, and bar spacing; of these, steel stress is the most important parameter. The design basis has been switched in recent years to the premise that crack width is not directly related to long-term durability, with cover depth and concrete quality being of greater importance. It can be misleading to use a design method that purports to effectively calculate crack widths. A re-evaluation of crack width data (Frosch 1999) provided a new equation based on the physical phenomenon for the determination of the flexural crack widths of reinforced concrete members. This study showed that previous crack width equations are valid for a relatively narrow range of covers up to 2.5 in. ACI 318-14 does not make distinction between interior and exterior exposure. The ACI 318-14 equation for determining the maximum spacing of flexural reinforcement closest to the tension face to affect adequate crack control is given below:

$$s = 15\left(\frac{40{,}000}{f_s}\right) - 2.5c_c \leq 12\left(\frac{40{,}000}{f_s}\right) \qquad (1)$$

Where: f_s = calculated stress in reinforcement closest to the tension face at service load, which is computed based on the unfactored moment. It is permitted to take f_s as $2/3f_y$; c_c = the least distance from surface of reinforcement to the tension face; and s = center-to-center spacing of flexural tension reinforcement nearest to the surface of the extreme tension face (in.)

AASHTO 2012 CRACK CONTROL REQUIREMENT

The American Association of State Highway and Transportation Officials (AASHTO 2012) equation for determining the maximum spacing of flexural reinforcement in the layer closest to the tension face to affect adequate crack control is given below:

$$S \leq \frac{700\gamma_e}{\beta_s f_{ss}} - 2d_c \qquad (2)$$

in which: $\beta_s = 1 + \frac{d_c}{0.7(h-d_c)}$ (3)

where γ_e is an exposure factor (equal to 1.00 for a Class 1 exposure condition or 0.75 for a Class 2 exposure condition); d_c = thickness of concrete cover measured from extreme fiber to the center of the flexural reinforcement located closest to the tension surface (in.); f_{ss} = the tensile stress in steel reinforcement at the service limit state (ksi); h = overall thickness or depth of the member (in.); and s = spacing of reinforcement.

FIELD INVESTIGATION

Twelve structural slab bridges with three sets of spans were studied during the field investigation. The three spans for the bridges investigated ranged from 24-30-24 ft (7.3-9.2-7.3 m) to 44-55-44 ft (13.4-16.8-13.4 m). The age of the bridge decks ranged from two to thirteen years. Crack patterns and maximum crack widths were recorded. With regard to the cracks on the top surface of the bridge deck, this study focused on the negative moment regions where cracks as wide as 0.03 in. (0.76 mm) to 0.125 in. (3.18 mm) were observed in the direction generally parallel to the intermediate pier supports. Design, material, and construction-related data are currently being collected for each bridge to determine if there is any correlation among these factors and the corresponding bridge deck cracking. The