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Reliability analysis of concrete deck overlays

L. Orta [a,b,*], F.M. Bartlett [a]

[a] The University of Western Ontario, Department of Civil and Environmental Engineering, 1151 Richmond Street, London, Ontario N6A 5B9, Canada
[b] Tecnologico de Monterrey, Campus Guadalajara, Department of Civil Engineering, Ramon Corona #2514, Zapopan, Jalisco 45201, Mexico

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ABSTRACT

Bridge decks are subjected to deterioration due to chloride ingress or other factors. Concrete overlays are used to replace the unsound concrete or to extend the life span of new concrete bridge decks. Overlay shrinkage is restrained by the substrate beneath leading to premature ingress of chlorides, corroding the steel reinforcement and producing delamination or spall of the concrete. This investigation quantifies the probability of the overlay cracking using mechanical strains as the main random variable. The analytical prediction of the time-dependent mechanical strains considers shrinkage strains from diffusion theory, tensile creep strains and the principle of superposition. Different overlay thicknesses, two types of substrates (concrete slabs and composite steel beams), and the impact of either not having or applying a water-proofing membrane are considered. Statistical parameters are computed from testing by others and testing conducted at Western University in Canada. Latin Hypercube sampling and Monte Carlo simulation is used to compute the probability of cracking. Analysis is performed for a fifty year lifetime of the overlay. Probability curves in time are presented and some recommendations about inspections are provided.

1. Introduction

Concrete bridges are vital infrastructure for the continuous development of nations. In Canada and the United States, for example, bridge infrastructure is aging and billions of dollars are spent on bridge rehabilitation [1–3]. Concrete bridge decks are particularly susceptible to deterioration and represent a main concern for transportation agencies like the Federal Highway Administration (FHWA) in the United States or the Ministry of Transportation of Ontario (MTO) in Canada (Personal communication, MTO 2006). Concrete bridge decks deteriorate rapidly due to wearing, freeze–thaw cycles, moisture and temperature cycles and the presence of chlorides [4]. In particular, concrete bridge decks in provinces and states with cold climates are subjected to large concentrations of chlorides from de-icing salts during winter seasons.

An overlay is a concrete slab cast on top of existing [5,6] or newly constructed bridge decks [3,7]. For newly constructed bridges, decks are protected using concrete overlays to delay the ingress of de-icing chemicals. For existing deteriorated bridge decks, concrete overlays are used to extend the lifetime of the bridge either by placing the overlay over the existing deck or, more commonly, by removing deteriorated concrete from the top surface of the deck and restoring the original geometry using the new concrete overlay, as shown in Fig. 1.

In either case, the overlay may crack because its shrinkage is restrained by the older substrate beneath. Early cracking of the overlay leads to premature ingress of chlorides into the concrete, corrosion of the reinforcement, delamination, and concrete spalling. Such early cracking may make the wearing surface unserviceable and, in some cases, may compromise the structural safety of the bridge.

An overview of the problem is presented schematically in Fig. 2. Four main components feed the analysis: material properties, environmental conditions, structural system characteristics and construction practices. The numerical analysis determines the internal stresses and strains in the overlay and substrate. These results are enhanced by accounting for the statistical characteristics of the input variables to compute the statistics of maximum internal stresses and mechanical strains, to finally compute the probability of cracking.

The material properties box includes the prediction of: the tensile strength of concrete; creep strains using a suitable compliance function; and the free shrinkage strains due to drying and autogenous shrinkage. The environmental conditions feed the free shrinkage strains box because the environmental humidity controls the rate of free shrinkage, and so the boundary conditions, at the

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[*] Corresponding author at: Tecnologico de Monterrey, Campus Guadalajara, Department of Civil Engineering, Ramon Corona #2514, Zapopan, Jalisco 45201, Mexico. Tel.: +52 (33) 3669 3000x2471.

E-mail address: luis.orta@itesm.mx (L. Orta).

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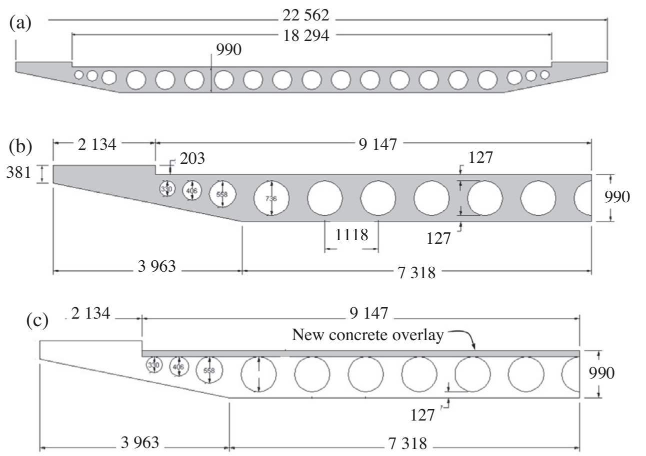

Fig. 1. Typical post-tensioned voided-slab bridge: (a) cross section; (b) half of the cross section before rehabilitation; and (c) half of the cross section after rehabilitation. Dimensions in millimeters.

drying faces of the overlay and substrate. The structural system box defines the substrate as either a solid concrete slab or a steel/-concrete composite system. Finally, the construction practices feed the analysis tool with necessary information about curing time, steel reinforcement in the overlay and the possible application of an impermeable water-proofing membrane.

The analysis tool uses all these input variables to compute the internal stresses and strains at discrete points in time across the depth of the overlay and substrate. The computation of mechanical strains are described in Orta and Bartlett [8].

2. Reliability analysis

This section presents the computation of the probability of occurrence and the conditional reliability for cracking of concrete overlays due to restrained shrinkage. The conditional reliability is the probability of cracking during the remaining lifetime of the overlay given that an inspection at time t shows no cracks. The results quantify these two probabilities for an overlay subjected to restrained shrinkage during its intended life span of 50 years.

The cross sections considered are shown in Fig. 3: overlays cast on concrete substrates and overlays cast on composite steel members [8]. The total depth of the deck is ℓ_y and the overlay depth is ℓ_{ny}.

Additionally, the impact of either applying a water-proofing membrane four days after the end of moist curing, in accordance with current MTO practices [5], or having no membrane was investigated. For the case of overlays on concrete substrates seven nominal thicknesses for the overlay were investigated: 70, 100, 150, 200, 250, 500 and 630 mm. The total thickness of the overlay and substrate was held constant at 700 mm. The first three correspond to typical thin overlays, the fourth and fifth correspond to medium thick overlays and the last two correspond to cases where the substrate represents a stay-in-place precast panel used to form the underside of a cast-in-place slab. For the case of overlays on composite systems five nominal overlay thickness reflecting a range from thin overlays to full-depth replacement were investigated: 70, 100, 150, 200 and 250 mm. In each case the total deck thickness of the overlay and the concrete substrate was maintained at 250 mm, so the thickest overlay represents the case of complete slab replacement with the overlay drying at its top and bottom surfaces. The application of a water-proofing membrane, currently recommended by different organizations [9,5], is intended to protect the overlay from the ingress of chlorides and help to prevent cracking.

2.1. Limit state function

A model to define the limit state of cracking in overlays cannot be verified by field investigation because cracking is not visible due to the presence of the asphalt layer and the waterproofing membrane. A limit state equation is therefore derived by comparing the cracking strain to mechanical strain demands $\varepsilon_{m1}(t)$ and $\varepsilon_{m2}(t)$ due to restraint of the overlay shrinkage. Mechanical strain $\varepsilon_{m1}(t)$ is the maximum strain across the thickness of the overlay, ℓ_{ny}, computed at any time t as:

$$\varepsilon_{m1}(t) = \max[\varepsilon_m(y,t)] \; 0 \leqslant y \leqslant \ell_{ny} \tag{1}$$

where $\varepsilon_m(y,t)$ is the mechanical strain at depth y and time t. Mechanical strain $\varepsilon_{m2}(t)$ is the mechanical strain at mid-depth of the overlay, $y = \ell_{ny}/2$, computed at any time t as

$$\varepsilon_{m2}(t) = \varepsilon_m(\ell_{ny}/2, t) \tag{2}$$

Cracking is defined as the state where the maximum mechanical strain, $\varepsilon_{m1}(t)$, has exceeded the cracking resistance, ε_{cr}, and the mechanical strain at mid-depth, $\varepsilon_{m2}(t)$, equals or exceeds half of the cracking resistance.

The selection of $\varepsilon_{cr}/2$ as the cracking limit for $\varepsilon_{m2}(t)$ is somewhat arbitrary, but it reflects the likelihood of a full depth crack occurring when a crack initiates at the top or bottom of the overlay and can propagate through a region of moderately large tensile stresses.

The limit state function $g(t)$ is defined as:

$$g(t) = \varepsilon_{cr} - \varepsilon_D(t) \tag{3}$$

where $\varepsilon_D(t) = \min\{\max[\varepsilon_{m1}(t); 2\varepsilon_{m2}(t)]\}$, $g(t) < 0$ denotes cracking of the overlay, $g(t) > 0$ denotes no cracking and $g(t) = 0$ corresponds to the limit state.

Function $g(t)$ represents the state where the maximum mechanical strain, $\varepsilon_{m1}(t)$, has exceeded the cracking resistance and the mechanical strain at mid-depth, $\varepsilon_{m2}(t)$, equals or exceeds half of the cracking resistance. The rationale for these criteria can be explained by reference to Fig. 4, which shows a typical case of the temporal variation of the mechanical strain demands and resistance over the lifetime of the overlay. The top curve labeled $\varepsilon_{m1}(t)$ denotes the maximum mechanical strain in the overlay and the bottom curve labeled $\varepsilon_{m2}(t)$ represents the mechanical strain at mid-depth. At time t_0, drying commences and mechanical strains $\varepsilon_{m1}(t)$ grow rapidly at the top or bottom face of the overlay [8]. At time t_1 the maximum strain $\varepsilon_{m1}(t_1)$ reaches the cracking strain ε_{cr} but the strain at mid-depth $\varepsilon_{m2}(t_1)$ is much less than ε_{cr}, so it is assumed that only microcracking occurs locally at the location of the maximum strain demand. At time t_2, the mid-depth strain $\varepsilon_{m2}(t_2)$ reaches half of ε_{cr}: cracking is deemed have occurred and the analysis is terminated. Thus the time of cracking for the time-histories of mechanical strain demands shown in Fig. 4 is t_2.

2.2. Cracking strength of concrete

The statistical characteristics for the cracking strain ε_{cr} are considered time independent and are computed by fitting a lognormal distribution to the data from Zheng et al. [10], Tia et al. [11] and testing at the University of Western Ontario (UWO).

Results for all cylinders tested at the University of Western Ontario are shown in Table 1. Each cylinder had a diameter of 102 mm and a length of 203 mm. The cylinders were cured for 3 days and then exposed to drying. The splitting strength $f_{sp}(t)$, the compressive strength $f_c(t)$ and the modulus of elasticity $E_c(t)$ tests were performed following standard ASTM C496 [12], ASTM