Transverse cracking of composite bridge decks

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Abstract

Early age cracking of concrete bridge deck is a frequent problem for bridges worldwide. This work provides a framework for a thermo-hygro-mechanical mathematical model for the analysis of early age transverse cracking of the bridge deck. The model includes the determination of the temperature and moisture gradients in the deck slab, and the prediction of the thermal and drying shrinkage strains. These strains were superimposed with the strains from creep and mechanical loads and applied to an elasto-plastic damage approach to quantify the damage and stresses in deck slab. The model was implemented in finite element computer software to accurately predict the cracking and damage evolution in concrete bridge decks. Accurate prediction of crack tendency is essential for durability design of bridge decks, thus more sustainable bridges with increased usable life span and low life-cycle costs.

Keywords: transverse cracking, bridge deck, thermo-hygro-mechanical model.

1 Introduction

Bridges usually developed early cracking of their decks [1]. Early age cracks usually develop in the transverse direction of the traffic. The cracking could initiate almost immediately after construction and sometimes appear within a few months after deck is constructed. The problem of deck cracking is still significant, even after the adoption of high performance concrete (HPC) for bridge decks. In a survey conducted by New York Department of Transportation (NYSDOT), it was observed that 48% of an 84 bridge decks built in New York State between 1995 and 1998, using HP concrete, have developed transverse cracks [2].

Figure 1 shows the mechanism of the transverse cracking of a concrete deck slab. The composite action between the deck and the girders provides restraining

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to the deck. When concrete shrinks the external restraint from the girder as well as the internal restraints from the reinforcement and aggregates produce tensile stresses in the longitudinal direction of the deck. When these stresses reach the tensile strength of concrete (low at early ages), transverse cracks are developed in the deck starting from bottom and extended to the top surface. In continuous beams or in beams with fixed-end restraint, the negative moments result from mechanical loads produce tensile stress in the deck, which when combined with the shrinkage stresses aggravate the problem of deck cracking.

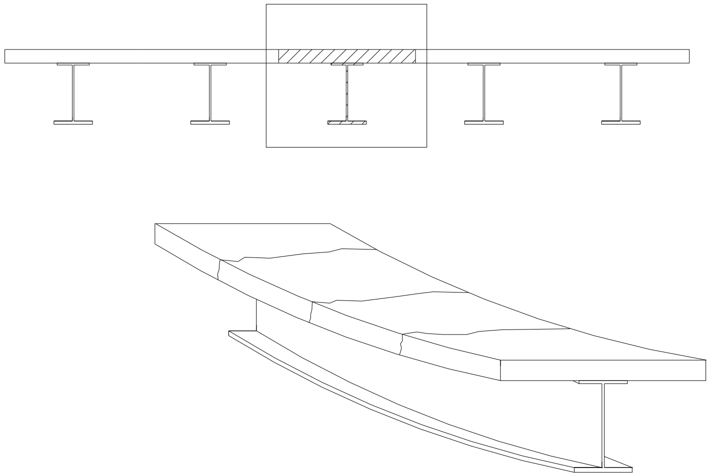


Figure 1: Transverse cracking of concrete.

Deck cracking has no immediate effect on the bridge safety, but it has detrimental effects on the long-term performance. Cracks interconnect the voids and the isolated microcracks in the concrete deck to form preferential pathways for the ingress of chlorides from deicing chemicals thus accelerate reinforcement corrosion. Fanous et al. [3] observed severe corrosion of black and epoxy coated rebars extracted from cracked location in different bridge decks. Also, leakage of water thorough cracks increases the degree of water saturation in the bridge substructure, therefore increases the risk of freeze-thaw damage. As a result, the bridge service life is reduced and maintenance and rehabilitation costs rise.

Bridge deck cracking occurs when restrained volumetric changes associated with moisture and temperature changes take place. Volumetric changes are mainly result from autogenous shrinkage, drying shrinkage, thermal shrinkage and creep. These major causes of concrete volume change with time depend primarily on the material properties and mix design, design details, construction practices, and environmental conditions. Concrete properties are the most important factors affecting transverse deck cracking since they control the shrinkage and thermal strains that cause stresses and control the relationship between strains and stresses. Understanding the concrete properties is central to reliably modeling the mechanisms contributing to the cracking of concrete decks. Experimental and analytical models have been developed to enable bridge designers to calculate shrinkage and thermal stresses in bridge decks [1, 4], so that they can evaluate and modify designs to reduce these stresses and the risk of transverse deck cracking. Furthermore, construction can affect transverse deck cracking. Careful construction practices are often required to reduce such a risk where the first large stresses in a concrete deck develop in the first 12 to 24 hours, when temperatures change rapidly from early hydration. The exposure to environmental conditions, e.g. ambient humidity and temperature has a major effect on transverse cracks.

Previous studies have focused primarily on unveiling the extent and significance of cracking and trying to pinpoint possible causes. While there is agreement among researchers on the major causes, the relative contribution of each factor has not been completely determined and the problem of premature deck cracking still exists. The predominant reason for this is because most of the factors have simply been discussed qualitatively and there has been little quantitative analysis of these mechanisms. In the last few years, researchers have developed numerical models using finite element or finite difference methods to simulate real structures under different environmental conditions. Saadeghvaziri and Hadidi [5] studied the developed tensile stresses in bridge decks under the effect of many design factors, e.g. girder stiffness, deck thickness, girder spacing, relative stiffness of deck to girder, and amount of reinforcements; in their simulation, they assumed that the shrinkage strain is constant in value and over the deck depth.

2 Significance

The main objective of this research is to develop a mechanistic approach for the analysis of transverse cracking of composite bridge decks. This work will allow better understanding of the cracking mechanism and in turn help practical engineers to develop preventive and remedial strategies to eliminate or at least mitigate them. The FEM simulations will result in better-determined stresses and crack widths in the bridge deck structures subjected to the combined effects of hygro-thermal volume changes and load-induced cracking. Accurate prediction of crack tendency is essential for the reliability and long-term performance of newly constructed bridge decks at service load levels.

The report with recommendations that will result from the literature survey and parametric studies will provide engineers with the ability to analyze the impacts of the material properties and mix design parameters, structural design details, and construction practices on cracking of concrete bridge decks. This will enable engineers to develop materials and methods to construct bridge deck structures that can withstand a multitude of harsh environmental conditions at low life-cycle cost. These measures will result in more sustainable structures with increased usable life span and low life-cycle costs.

3 Formulation of computational framework

This section presents the framework for a mechanistic approach for the analysis of early age transverse cracking of the bridge deck and it is divided into four steps. First, mathematical models for the determination of the temperature and moisture gradients in the deck slab are descried. The temperature variation and moisture loss will be used to predict the thermal and drying shrinkage strains in bridge deck. Finally, these strains will be added to the strains from creep and mechanical loads and applied to an elasto-plastic damage approach to quantify the damage and stresses in deck slab.

3.1 Determination of the temperature and moisture gradients

The variation of the temperature over the bridge deck is governed by the heat transfer in concrete which can be described by the following equation

$$\rho c \frac{\partial T}{\partial t} = div\ [k\ \ grad(T)] + Q \tag{1}$$

where T is the temperature, ρc is the heat capacity, k is the thermal conductivity and Q is the rate of heat generation inside concrete as a result of cement hydration. A model for the heat of hydration generation of blended cement is described by Kishi and Maekawa [6], and it will used to calculate Q.

The moisture loss is governed by the moisture transport equation as follows

$$\frac{\partial w}{\partial t} = \frac{\partial w}{\partial H}\frac{\partial H}{\partial t} = div\ [D_H grad(H)] + G \tag{2}$$

where w is the moisture content, t is the time, H is the relative humidity, D_H is the moisture diffusion coefficient, $\partial w/\partial H$ is the moisture capacity and G is the rate of moisture loss due to hydration. The heat of hydration generation model mentioned above can be also used to determine G.

3.2 Prediction of the volumetric changes

The numerical solution of the equations above (Eq. (1) and (2)) results in temporal and spatial distribution of the temperature (T) and relative humidity (H) inside the concrete bridge deck. The volumetric changes in concrete are related to environmental factors including temperate and humidity variations. The environmental strain, ε_{ev} is the summation of the drying and thermal strains

$$\varepsilon_{ev} = \varepsilon_{sh} + \varepsilon_T \tag{3}$$

The thermal strain ε_T is a function of heating and cooling cycles and can be expressed in terms of temperature change as follows

$$\varepsilon_T = \alpha\ \Delta T \tag{4}$$

in which α is the coefficient of thermal expansion of concrete and ΔT is the temperature change.

The drying shrinkage strain is related to moisture loss and so it can be linked to the change in the relative humidity as follows

$$\varepsilon_{sh} = \beta \ \Delta H \tag{5}$$

where β is coefficient of shrinkage strain and can be calculated by a multiscale model [7].

3.3 Quantifying the early age transverse cracking

In practice, bridges at early ages are exposed to the simultaneous actions of environmental and mechanical deteriorations. The development and coalescence of early age cracks due to the combined effect of environmental factors and traffic loads progress gradually and cause gradual strain softening in the stress strain relation. These microcracks result in a reduction of both strength and stiffness at the macroscopic material level. Damage mechanics not only captures the loss of strength, but also the deterioration of material stiffness. Therefore, it is realistic to use continuum damage theory, which has the ability to describe the tensile strain softening and stiffness deterioration rather than a sudden complete cracking [8]. A fully coupled hygromechanical model was developed by Ababneh et al. [9] and Sheban et al. [10]. This model can be extended to quantify the damage due to environmental loads including the creep effect, and the mechanical loads. In this model, an elastoplastic-damage approach was used to characterize the shrinkage-induced damage. Based on the small strain theory of plasticity, the strain tensor is additively decomposed into an elastic part ε_e and a plastic part ε_p. Considering the presence of environmental strain tensor ε_{ev}, the total strain tensor can be expressed as:

$$\varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_{ev} \tag{6}$$

The constitutive relation can then be written as:

$$\sigma = E{:}(\varepsilon - \varepsilon_p - \varepsilon_{ev}) \tag{7}$$

in which E is the elastic stiffness tensor.

The elastoplastic and damage models are coupled by exploiting the effective stress concept known from continuum damage mechanics [11]. The effective stress represents the redistributed stress over undamaged or effective area after the damage has taken place. Based on the scalar damage model the relation between the effective stress σ_{eff} and the nominal stress σ can be expressed as:

$$\sigma_{eff} = \frac{\sigma}{1-d} \tag{8}$$

where d is the damage parameter. It is assumed that $0 < d < d_{cr}$, where d_{cr} is the critical damage in which a complete local rupture takes place. In practice, a $d_{cr} = 1$ is usually employed.

Considering the undamaged elastic stiffness E_o, we have

$$\sigma_{eff} = E_o:(\varepsilon - \varepsilon_p - \varepsilon_{ev}) \tag{9}$$

and its corresponding time derivative takes the form:

$$\dot{\sigma}_{eff} = E_o:(\dot{\varepsilon} - \dot{\varepsilon}_p - \dot{\varepsilon}_{ev}) \tag{10}$$

From Eqs. (9), (10) and (11), the constitutive relation becomes:

$$\sigma = (1-d)E_o:(\varepsilon - \varepsilon_p - \varepsilon_{ev}) = E:(\varepsilon - \varepsilon_p - \varepsilon_{ev})$$
$$E = (1-d)E_o \tag{11}$$

Following the effective stress concept, it is logical to assume that the plastic flow takes place only in undamaged area [12]. Thus, the formulae from elastoplastic theory that are dependent on stress must be modified by substituting the effective stress in place of the nominal stress. The problem can then be solved by using standard elastoplastic theory. The elastoplastic behavior of concrete will be assumed to follow the pressure-sensitive Drucker–Prager criterion. The damage initiation and evolution can be characterized by a damage model developed by Mazars and Pijaudier-Cabot [13].

4 Simulation of bridge deck cracking

Ababneh et al. [9] and Sheban et al. [10] studied the drying shrinkage-induced damage in concrete structures, and they developed a finite element simulation program capable to estimate the stress and strain variations with time in bridge decks. This program can be used to study the effects of many parameters, e.g. concrete mixing ingredients, types and proportions, ambient dry environment, and support restraints. A concrete bridge deck 4″ [10 cm] in depth was simulated by this model. The concrete has an average compressive strength of 5000 psi [34.5 MPa] and is moist cured for 28 days before drying. The deck, which is initially saturated (H_{ini}=100%), is exposed to drying on the top and bottom surfaces (H_{env}= 50 %) after curing. Figure 2 shows the geometry and boundary conditions of the investigated structure where only one quarter of the deck is modeled by four-noded plane strain elements.

The comparison results of the deck simulation are shown in Figure 3 for two cases: case I, where the effect of damage on moisture diffusivity is ignored, and case II, where the full coupling between damage and moisture diffusion is considered. It is clear that in case I, the rate of drying process is slower than case II, and case II reaches equilibrium with the environment faster. In the latter case, the drying process generates damage in the concrete, which accelerates the drying process as shown in Figure 3a. The damage parameter, *d* versus drying time for the bridge deck is shown in Figure 3b for both cases. The state of damage in concrete in case II accelerate and increase earlier and faster, and its value is higher than the damage in case I where no coupling between the damage and the diffusion process is assumed. Therefore, ignoring the effect of damage

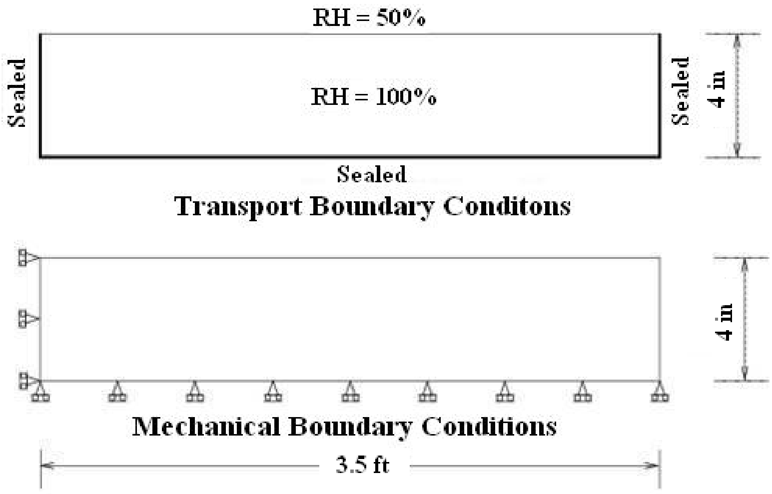
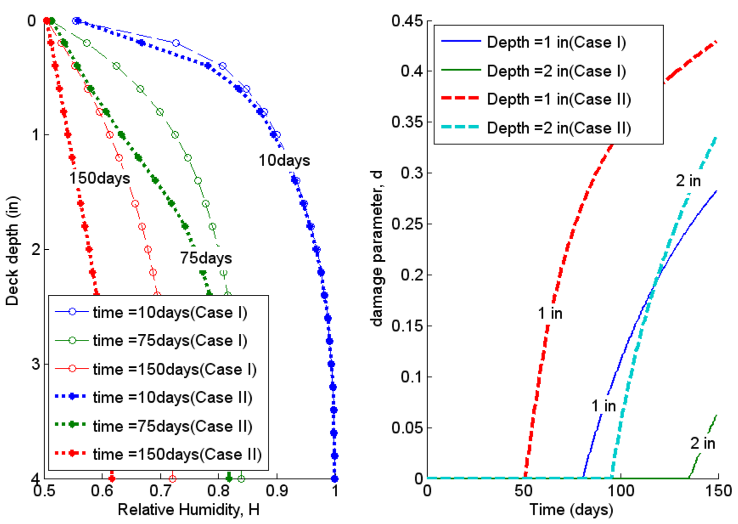


Figure 2: Boundary conditions for the concrete bridge deck.



a. Humidity profiles b. Damage evolution

Figure 3: Humidity profiles and damage versus drying time for the bridge deck.

on the moisture diffusion process yields an overestimation of the relative humidity in concrete and a lower estimation of concrete damage states.

This simulation demonstrated that the fully coupled hygromechanical model can capture the concrete structural behavior under drying conditions. This model can be used to analyze different types of concrete structures, and with some modifications, e.g. the effect of thermal stresses and stress relaxation, the computer program can be used for analysis of early age transverse cracks in composite bridge decks.

Ongoing research at Jordan University of Science and Technology seeks to develop a finite element analysis (FEA) based software to investigate the causes of transverse concrete deck cracking, quantitatively predict the tendency of a deck to crack and predict the crack sizes. To isolate the effects of individual parameters that have a potential impact on transverse deck cracking, computational software is developed, by means of which parametric studies will be conducted using finite element analysis of the complete bridge system. The information will then be used to make recommendations relative to design and construction practices to reduce the potential for transverse cracks in composite bridge decks.

5 Summary and conclusions

This paper provided a computational framework for the analysis of early age transverse cracking in composite bridge decks. A fully hygro-thermal-mechanical model for the prediction of early age transverse cracks was formulated. The model involves the formulation of the governing coupled heat and moisture transport equations, the quantification of the induced thermal and hygral damage by elasto-plastic damage model and modeling the coupling between damage and transport phenomena. The simulation of the bridge deck demonstrated that the fully coupled hygromechanical model can capture the concrete structural behavior under drying conditions. Ongoing research at Jordan University of Science and technology seeks to modify the computer software by implementing the hygro-thermal- mechanical model developed in this study.

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