The International Journal Of Engineering
And Science (IJES)
||Volume|| 2 ||Issue|| 1 ||Pages||360-366 ||2013||
ISSN: 2319 – 1813 ISBN: 2319 – 1805

Restrained Shrinkage Cracks in Composite Bridge Decks, Evaluation and Reduction Method

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Abstract

Paper presents an analytical method to estimate restrained shrinkage stresses in concrete bridge decks and a practical method to decrease these stresses. Proposed approach is based on flexure analysis of a composite beam's section assuming displacement and strain discontinuity condition and slip at interface of the deck and girder. The ratio of deck-to-girder stiffness strongly affects the final value of the restrained shrinkage stresses. Results indicate the strong possibility of cracks initiation in the deck because the level of restraint caused by the girders can range 60% of the full restraint. Presented analytical expression for the coefficient of restraint level can be used as a measure of cracking tendency of concrete. It is proposed to apply external forces to the girders at the beginning of the construction process to create an initial camber. In that manner, created stress pattern is of opposite sign to that caused by the restrained shrinkage. Camber is gradually relived during early stage of concrete maturing. Based on calculations, even half of tensile stress can be eliminated from the deck. This decrease of tension in the deck can prevent cracking.

***Keywords**: bridge decks, composite bridges, early cracking, restrained shrinkage.*

Date of Submission: 14,January, 2013 ⟷ Date of Publication: 05, February 2013

I Introduction

Reinforced concrete bridge deck slabs made composite with supporting steel girders are widely used structural systems in highway bridges. Current practice shows that service life of a reinforced concrete deck can be much shorter than the design life of the bridge [1]. Such situation can decrease desired reliability level and affect life-cycle cost of a bridge. The average life of a concrete deck slab is determined by many parameters including: material properties, design, construction and curing practice, ambient conditions during pouring process and concrete hydration, salt application, traffic volume, temperature changes, maintenance practice and many others [2], [3]. Observed deterioration scenarios indicate that degradation process of bridge decks is very often initiated by hydration heat and shrinkage cracks.

These early, small cracks develop in time due to freeze and thaw cycles, application of dynamic load and evolution of a restrained shrinkage [4]. These cracks can also initiate fatigue degradation of concrete and corrosion of reinforcing steel.In spite of many modifications to standards of bridge deck design made in the past three decades [3], early-age transverse cracks have continued to appear. According to the results of several studies, the leading cause of premature deck cracking is restrained shrinkage. Other design-, material-, and construction-related parameters also influence the transverse cracking. As a result of these studies practical improvements to bridge construction including low shrinkage mix design, better curing and minimizing deck restraint were recommended [1], [3].The development of simple and practical method for estimation of restrained shrinkage stresses in the bridge deck is presented in the first part of the paper. Proposed approach allows for derivation of closed form formulas, which can be easily implemented in the design process. Parametric study is required to identify the structural behavior related design factors and better understanding of theirs influence on the overall service life of the deck. An excellent study of the design factors, which affect transverse cracking of concrete bridge deck, is presented in [5]. Joining of the results of the mentioned work and Si Larbi, et al research [6], which is dedicated to the analysis of steel beam and concrete deck connections, further research was done. Correlation between the composite beam bending stiffness and the stiffness of connectors was used to develop a method for diminishing the restrained shrinkage effect in the bridge decks.The second objective of presented work is focused on the development of a practical method to limit the early-age restrained shrinkage cracks in deck slabs [7]. The idea of the proposed method is to create strains/stresses in the slab of the opposite sign to those caused by the restrained shrinkage, just at the beginning of the construction process. Shrinkage strains/stresses developing in the slab during the hydration process and concrete maturing will be suppressed by opposite values induced into the cross-section. The method involves creation of an initial camber in steel girders, and after the first period of rapid increase in shrinkage, its gradual release. In that manner, a large portion of the restrained shrinkage stresses can be compensated and early cracks in the deck slab can be substantially limited.

II Evaluation Of Restrained Shrinkage Stresses

Proposed approach is based on flexure analysis of composite beam's section assuming slip at the interface of concrete deck and steel girder. Special case of perfect connection, without a slip presented in [7], is a part of the general solution. An analytical method of evaluation of stresses, forces and moments in the deck and girder caused by the shrinkage straining in the deck is presented. The analysis of composite bridge cross-sections is limited to sections with vertical axis of symmetry. Following assumptions were adopted in the formulation of the problem: hypothesis of the plane cross-section, linear elastic constitutive relationships for concrete and steel, slip on studs and uniform distribution of shrinkage strains in the deck cross-section.

III Formulation Of The Problem

Typical composite cross-section of the deck and girder is shown in Fig.1, where basic notation used through the paper is explained. In Fig.1, c_D and c_G stand for the centers of gravity of deck and girder cross-sections considered separately. The coordinate system for analysis is located at the center of gravity of the girder's cross-section. Local coordinates for the deck are also used in calculations. Generally, subscript D refers to the deck and G to the girder.

The horizontal displacement in the deck and girder of the composite cross-section are defined using the plane section hypothesis,

$$u_D(x,z)=u(x)-zw'(x)-s(x), \qquad u_G(x,z)=u(x)-zw'(x), \tag{1}$$

where $u(x)$ is the horizontal displacement at the reference axis, $w(x)$ is the vertical displacement, and $w'(x)$ is the derivative of $w(x)$ with respect to x. The slip function is defined as the difference of horizontal displacements at the interface,

$$s(x)=u_G(x,-z_I)-u_D(x,-z_I), \tag{2}$$

where $z_I=z_{Gt}$ is the interface location in the assumed coordinates, see Fig .1. Based on Eq. (1) and Hooke's low for concrete and steel, longitudinal strains and stresses can be expressed as,

$$\varepsilon_D(x,z)=\varepsilon(x)+z\kappa(x)-s'(x), \qquad \varepsilon_G(x,z)=\varepsilon(x)+z\kappa(x), \tag{3}$$

$$\sigma_D(x,z)=E_D\left[\varepsilon(x)+z\kappa(x)-s'(x)-\varepsilon_S(x)\right], \qquad \sigma_G(x,z)=E_G\left[\varepsilon(x)+z\kappa(x)\right], \tag{4}$$

where notation $\varepsilon(x)=u'(x)$ and $\kappa(x)=-w''(x)$ is used for axial strain and curvature. In Eq. (4), $\varepsilon_S(x)$ is the shrinkage strain, which is assumed to be independent of z, but if generalization is required it can be also dependent on z. Integration of stresses, Eq. (4), over the cross-section leads to the resultant force and moment,

$$N(x)=N_D(x)+N_G(x)=B_D\left[\varepsilon(x)-H_C\,\kappa(x)-s'(x)-\varepsilon_S(x)\right]+B_G\varepsilon(x)=0, \tag{5}$$

$$\begin{aligned} M(x)&=M_D(x)-H_C N_D(x)+M_G(x)\\ &=D_D\kappa(x)-H_C B_D\left[\varepsilon(x)-H_C\,\kappa(x)-s'(x)-\varepsilon_S(x)\right]+D_G\kappa(x), \end{aligned} \tag{6}$$

where the notation for the axial and bending stiffness is used: $B_D=E_D A_D$, $B_G=E_G A_G$ and $D_D=E_D J_D$, $D_G=E_G J_G$, in which A_D, A_G denote area of each part (deck and girder), and J_D, J_G indicate moments of inertia with respect to the part's own centers of gravity. In the definitions of B_D and D_D, longitudinal reinforcement of the deck can be inserted. Solving Eqs. (5) and (6) for axial strain $\varepsilon(x)$ and curvature $\kappa(x)$ gives the results,

$$\varepsilon(x)=\frac{\beta}{1+\beta+\delta}\left[\frac{M(x)}{B_D H_C}\delta+s'(x)+\varepsilon_S(x)\right],\tag{7}$$

$$\kappa(x)=\frac{\delta}{(1+\beta+\delta)H_C}\left[\frac{M(x)}{B_D H_C}(1+\beta)-s'(x)-\varepsilon_S(x)\right],\tag{8}$$

where two non-dimensional parameters are used

$$\beta=\frac{B_D}{B_G},\qquad \delta=\frac{H_C^2 B_D}{D_D+D_G}.\tag{9}$$

Parameters, Eq. (9), measure the relative axial stiffness of the deck and girder, and relative bending stiffness of the composite section. Forces acting on the parts of composite cross-section can be expressed as (compare Fig. 1),

$$N_D(x)=-\frac{1}{1+\beta+\delta}\left\{\frac{M(x)}{H_C}\delta+B_D[s'(x)+\varepsilon_S(x)]\right\}=-N_G(x),\tag{10}$$

$$M_D(x)=\frac{D_D\delta}{(1+\beta+\delta)H_C}\left[\frac{M(x)}{B_D H_C}(1+\beta)-s'(x)-\varepsilon_S(x)\right]=\frac{D_D}{D_G}M_G(x).\tag{11}$$

Stresses, Eq. (4), in the deck and girder can be calculated using the following formulas,

$$\sigma_D(x,z_D)=-\frac{E_D}{1+\beta+\delta}\left\{\delta[1-\varsigma_D(1+\beta)]\frac{M(x)}{B_D H_C}+(1+\varsigma_D\delta)[s'(x)+\varepsilon_S(x)]\right\},\tag{12}$$

$$\sigma_G(x,z_G)=\frac{E_G}{1+\beta+\delta}\left\{\delta[\beta+\varsigma_G(1+\beta)]\frac{M(x)}{B_D H_C}+(\beta-\varsigma_G\delta)[s'(x)+\varepsilon_S(x)]\right\},\tag{13}$$

where $\varsigma_D=z_D/H_C$ and $\varsigma_G=z_G/H_C$ in local coordinates for each part of the composite cross-section. Strains can be calculated using Eq. (3).

The horizontal shear force $H(x)$ at the interface is linearly related to the slip defined by Eq. (2):

$$H(x)=K\,s(x),\tag{14}$$

where K is the interface stiffness expressed in N/m^2. Equilibrium consideration for a small segment of deck results in equation,

$$H(x)+N_D'(x)=0 \qquad \text{or} \qquad K\,s(x)+N_D'(x)=0.\tag{15}$$

Introducing Eq. (10) into Eq. (15), the differential equation for slip function can be obtain,

$$s''(x)-\frac{K}{B_D}(1+\beta+\delta)s(x)+\frac{\delta}{B_D H_C}M'(x)+\varepsilon_S'(x)=0.\tag{16}$$

Equilibrium equation for the composite beam states that $M'(x)=T(x)$, what implies in Eq. (16),

$$s''(x)-\alpha^2 s(x)+\gamma T(x)+\varepsilon_S'(x)=0,\tag{17}$$

where $\alpha^2=K(1+\beta+\delta)/B_D$ and $\gamma=\delta/(B_D H_C)$.

Knowing functions of shear force $T(x)$ and shrinkage strain (typically $\varepsilon_S(x)=\mathrm{const}$ is assumed), the differential equation (17) can be integrated for specific boundary valued problem. For a given load moment function $M(x)$ and the slip function $s(x)$, the deflection function $w(x)$, Eq.(8), can be obtained.

IV Analysis Of Shrinkage Inducted Stresses

In a case of no slip at the interface, $s(x)=0$, and no external load, $M(x)=0$, stresses in the top and bottom fibers of the deck and girder can be calculated using Eqs.(12) and (13). The results for the uniform distribution of shrinkage over the deck, $\varepsilon_S(x)=\varepsilon_S$, are:

$$\sigma_{Dt}=\frac{1+\varsigma_{Dt}\delta}{1+\beta+\delta}\sigma_S=\eta_{Dt}\sigma_S,\qquad \sigma_{Db}=\frac{1+\varsigma_{Db}\delta}{1+\beta+\delta}\sigma_S=\eta_{Db}\sigma_S,\tag{18}$$

$$\sigma_{Gt} = \frac{\varsigma_{Gt}\delta - \beta}{1+\beta+\delta} m\sigma_S, \qquad \sigma_{Gb} = \frac{\varsigma_{Gb}\delta - \beta}{1+\beta+\delta} m\sigma_S, \quad \text{and} \quad \sigma_S = -E_D\varepsilon_S \tag{19}$$

Dimensionless parameters in Eqs. (18) and (19) are defined as follows:

$$m = \frac{E_G}{E_D}, \quad \varsigma_{Dt} = -\frac{z_{Dt}}{H_C}, \quad \varsigma_{Db} = \frac{z_{Db}}{H_C}, \quad \varsigma_{Gt} = -\frac{z_{Gt}}{H_C}, \quad \varsigma_{Gb} = \frac{z_{Gb}}{H_C}. \tag{20}$$

Stress, σ_S, is the hypothetical stress induced in the element if full constrain in the deck is applied. Non dimensional coefficients, η_{Dt} and η_{Db}, then can be understood as the portions of full constrain, which is caused by the girder and transferred to the deck by connectors. Cracking tendency of concrete used in bridge decks was indirectly tested on the ring test [1], in which 60-70% restrain level was achieved.Based on the obtained formulas, parametric study was performed to calculate restrained stresses and restrain coefficients in a typical deck slab supported on steel girders with different depth. In the performed study, the following dimensions were assumed: girder spacing, $G_S = 2.44, 3.05, 3.66\,\text{m}$ and the depth of deck $H_D = 20.3, 22.9, 25.4\,\text{cm}$. Three compressive strengths of concrete: $f_C' = 27.6, 31.0, 34.5\,\text{MPa}$ were selected what results in values for the modulus of elasticity, $E_D = 24.9, 26.4, 27.8\,\text{GPa}$ and tensile strength, $f_t = 2.62, 2.78, 2.93\,\text{MPa}$ with modulus of rapture, $f_r = 3.27, 3.47, 3.66\,\text{MPa}$. Free shrinkage of the deck concrete was assumed to be, $\varepsilon_S = -0.0003$, what reflects a typical short-term value of shrinkage. Depending on a concrete mixture design and curing condition, the "peak" shrinkage can vary in the range from $\varepsilon_S = -0.0002$ up to $\varepsilon_S = -0.0006$ [1] and [2]. The peak shrinkage here is understood as the maximum net strain developed in time being the difference of free shrinkage and creep. The full restrain stress, σ_S, then can vary as much as $5\text{ to }17\,\text{MPa}$, and for $\varepsilon_S = -0.0003$ and $E_D = 26.4\text{GPa}$ gives $\sigma_S = 7.9\text{MPa}$. Critical (sustainable by deck) value of restrain can be defined by the ratio, $\eta_t = f_t/\sigma_S$ or $\eta_r = f_r/\sigma_S$, for strain controlled loading. Assuming $\sigma_S = 7.9\text{MPa}$ and $f_t = 2.78\text{MPa}$, we can calculate $\eta_t = 0.35$ or $\eta_r = 0.44$, what measures the maximum allowable restrain level for the given material and free shrinkage magnitude. A good bridge deck design should then obtain less constrain than the critical value.

The typical proportioning of symmetrical I girder cross-section was adopted in the analysis. A simply supported beam of the span length, $L_S = 20H_G$, the flange width of $0.52H_G$ and its thickness of $0.042H_G$, and the web thickness of $0.025H_G$ were assumed for analysis. The modulus of elasticity for steel was $E_G = 200\,\text{GPa}$. In some cases, a non-symmetrical I girder was also analyzed. For this part of analysis, the assumed proportioning was: the top flange width of $0.5H_G$ and its thickness of $0.032H_G$, the bottom flange width of $0.6H_G$ and its thickness of $0.052H_G$, and the web thickness of $0.025H_G$.

Stresses in the top and bottom fibers of the decks cross section were computed. Basic results are shown in Fig.2 for the symmetrical girder and in Fig.3 for the non-symmetrical girder. These values can be treated as an upper bound for prediction of the tensile stresses caused by shrinkage. Results indicate the possibility of cracks initiation in the deck slab due to restrained shrinkage. The bottom part of the deck cross section is mostly exposed to cracking, Fig.2d and Fig.3a. The ratio of deck-to-girder stiffness (both axial and flexural) strongly affects the final value of the restrained shrinkage stresses. In general, deeper girder sections result in a higher tension, especially at the bottom of the deck. For the symmetrical girders with depth range of 60-180 cm, level of restraint caused by these girders ranges from 0.24 to 0.6 of the full restraint depending on a combination of parameters. The analytical expression for restraint level (coefficient η_{Db}) is given by Eq.(18), and can be used to measure cracking tendency of concrete in bridge decks. A nonlinear relationship between the depth of the girder and stresses at the top and bottom of the cross-section of the deck is obtained. If the critical restraint coefficient is about, $\eta_t = 0.35$, it indicates that in a case of girders with depth more than 120 cm cracking of the deck may occur.

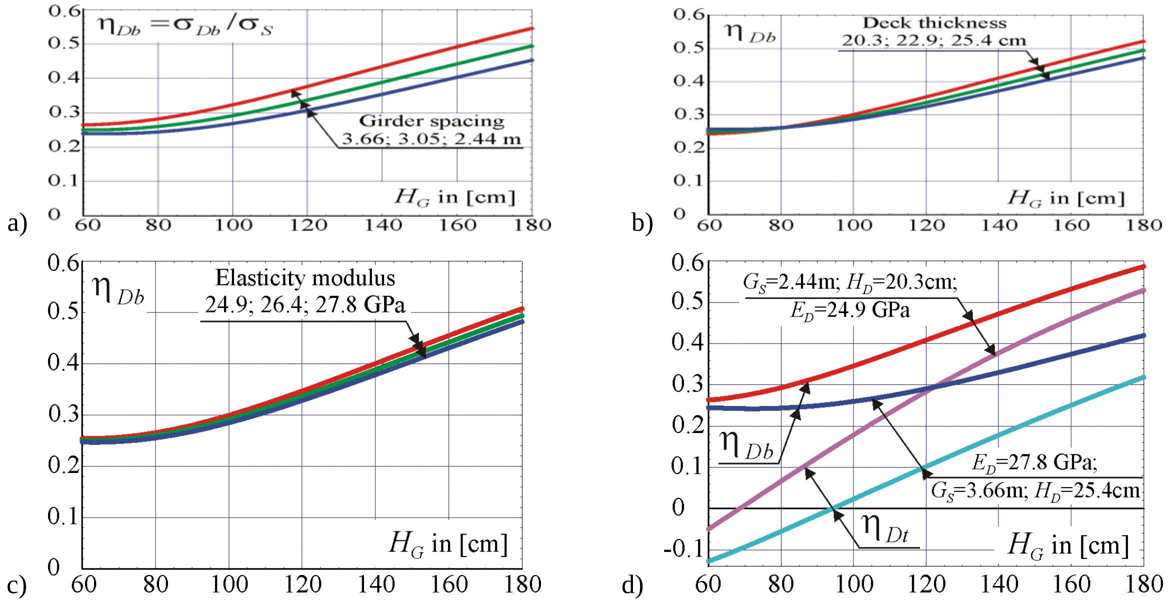

Fig.2. Restraint level of the free shrinkage at the bottom and top of the deck in a function of girder's depth. a) Girder spacing dependence for $H_D = 22.9\text{cm}$, $E_D = 26.4\text{GPa}$; b) Deck thickness dependence for $G_S = 3.05\text{m}$, $E_D = 26.4\text{GPa}$; c) Modulus of elasticity dependence for $H_D = 22.9\text{cm}$, $G_S = 3.05\text{m}$; d) Combination of the extreme values.

In Fig.3, the results for non-symmetrical girder with depth range of 75 to 250 cm are shown. In Fig.3a, stresses at the top and bottom fibers of the deck for two limiting values of design parameters are shown. Curves in the figure indicate possible changes in shrinkage-induced stresses by selecting girder spacing, thickness of deck and modulus of elasticity of concrete. In Fig.3b, results for restrain coefficients are shown with the maximum allowable constrain for the given shrinkage strain. It is obvious that for high values of shrinkage there is no possibility to prevent deck from cracking. That is why, material design considerations are conducted for reducing the free shrinkage strain to an acceptable level. Basic conclusions drown from the research in this area can be found in [1], [2], and [3]. Despite of achievements in the mix design or structural design, the problem of an early-age cracking of bridge decks still exist.

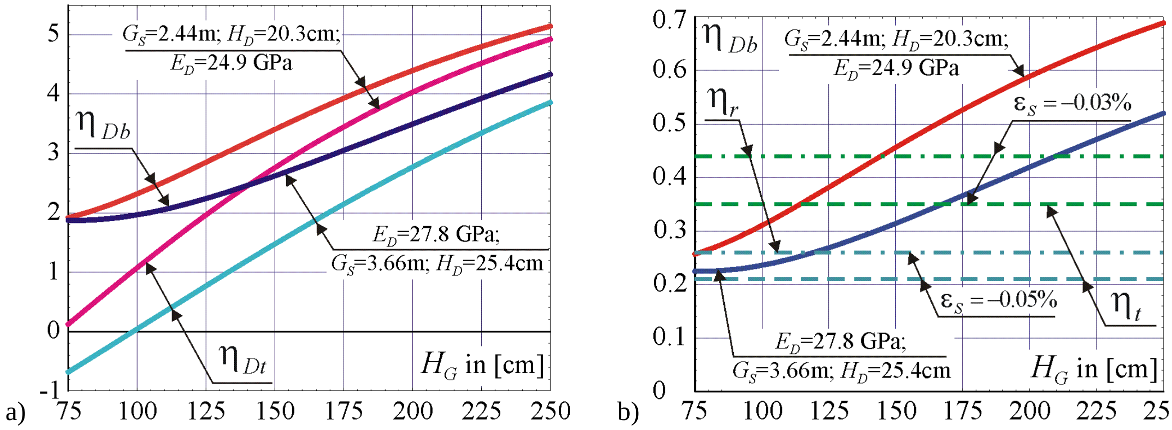

Fig.3. Restraint level of the free shrinkage in sections with non-symmetrical girder. a) Stresses at the top and bottom fibers of deck for $\varepsilon_S = -0.0003$; b) Restraint coefficient at the bottom of the cross-section and limits for two levels of maximum shrinkage strains.

Based on the performed parametric study, an additional technique to reduce unfavorable shrinkage effect should be proposed. Some researchers [5] advise using shoring as a helpful tool in diminishing the shrinkage effect. Another general idea is to make bridge superstructure more flexible

V Method to Reduce Shrinkage Effect

The development of a practical method to limit shrinkage cracks in bridge decks is the next part of presented research work. A general idea behind the method is to initially create stress pattern in the slab of opposite sign to that caused by restrained shrinkage. It is proposed to apply externally controlled forces to the girders to create the initial camber. In that manner, tensile stresses will be induced at the top part of the girders. After the first phase of concrete maturing, the camber will be gradually relaxed. A part of tension stress caused by shrinkage will be compensated by the composite action of bridge cross-section. As an example of application of compensating load simply supported beam (pin-roller) of a bridge is analyzed. Solution of Eq.(17) for the symmetrical girder 1.5 m deep and for shrinkage strain of $\varepsilon_S = -0.03\%$ is plotted in Fig.4. Three values of connector's stiffness were analyzed: flexible with $K = 2\,GPa$, semi-rigid with $K = 4\,GPa$, and rigid $K = 16\,GPa$, [6]. The effectiveness of proposed method depends on stiffness K and for the best results more flexible connectors should be used, [5].

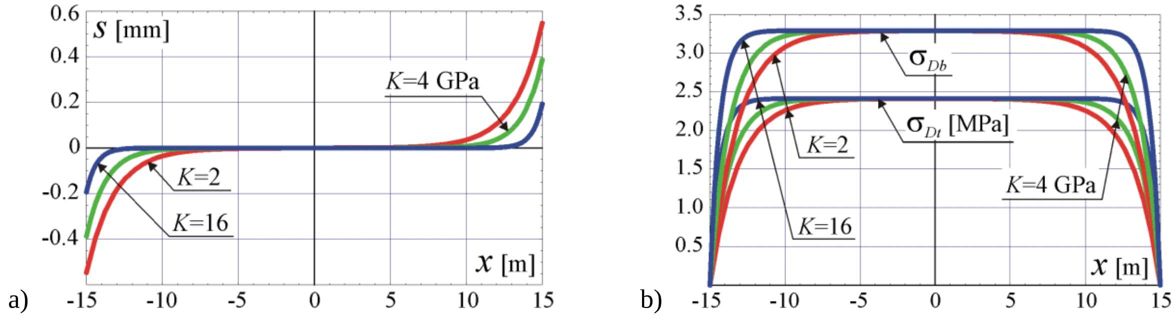

Fig.4. a) Slip at the interface for flexible, semi-rigid and rigid connectors; b) Stresses at the top and bottom of the cross-section in deck due to shrinkage straining.

Two external forces are used to control the camber, which are spaced symmetrically in the distance of L in a beam of $L_S = 2L = 30\,m$ total span length. The value of applied load is estimated as (weight of the deck), $P = q_D L$, where $q_D = A_D \gamma_D$, and $\gamma_D = 25\,kN/m^3$ is the unit weight of concrete. Location and value of the applied forces as well as stiffness of connectors should be carefully selected not to cause the uplift of the beam. The superposition of results for shrinkage straining and compensating load using the assumed data is presented in Fig.5. Stresses after relaxing of pre-cumbered beam are shown in Fig.5a for no slip connection and in Fig.5b with flexible connectors. When rigid connection is used the effect of applied load is small close to the supports, but for flexible one the method is effective over the whole beam. Based on the results, even one third of tensile stress can be eliminated from the deck during the early stage of concrete maturing. This decrease of tension in the deck will be sufficient in most cases to prevent cracking.

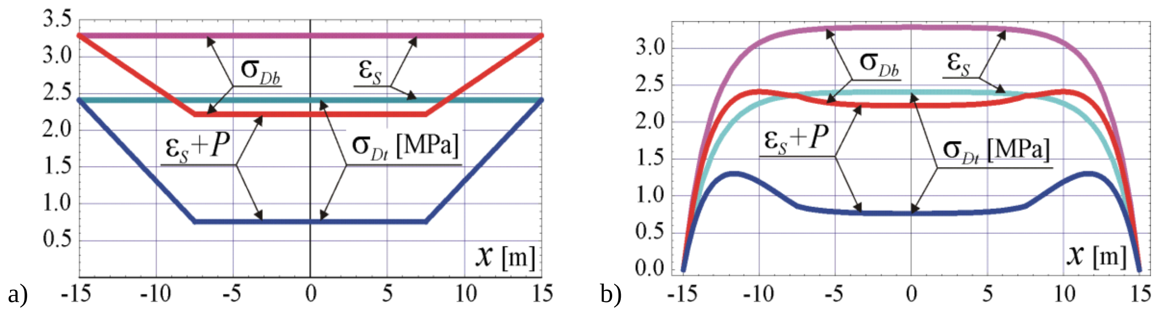

Fig.5. Corrected stresses at the top and bottom of the cross-section in deck. a) In case of no slip connection; b) For flexible connectors.

VI Conclusions

A simple way of evaluation of stresses, forces and moments in the deck and girder caused by the shrinkage straining in the deck is developed. Performed, parametric study quantifies possible changes in structural design to reduce vulnerability of bridge decks to pre-mature cracking. A method of controlled compensating forces for reduction of the restrained shrinkage is proposed. The method can be effectively applied to prevent cracking of concrete bridge decks especially in cases of deep steel girders or high levels of shrinkage of concrete.

VII Acknowledgements

The research reported in this paper was sponsored by the National Science Foundation under Grant No. ID 0408840 what is gratefully acknowledged.

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