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THEORETICAL AND EXPERIMENTAL STUDY ON LONG-TERM STRUCTURAL CHARACTERISTICS OF STEEL-CONCRETE COMPOSITE SLABS, PRESTRESSED IN BOTH DIRECTIONS

Gnida SOSSOU

Ph.D. in Civil Engineering "Reinforced and Prestressed Concrete Structures"

Lecturer in Civil Engineering; KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY; SCHOOL OF ENGINEERING ; DEPARTMENT OF CIVIL ENGINEERING; KUMASI, GHANA, WEST AFRICA.Tel/Fax: 233-51-60317; Tel/Fax: 233-51-60226; Telegram: KUMASITECH. E-mail: <gn459s@hotmail.com>.

SUMMARY: This theoretical and experimental study relates to the details of a unified design and tests procedure for analytical prediction of various durability and quality structural characteristics of stell-concrete composite slabs, prestressed in both directions. This analytical procedure is aimed to predict the quality, stiffness, strength, reliability and durability at the planning phase, the nonlinear creep behaviour of these said composite members. This present ongoing study is so actual, as it is recognised that little information is available on the time dependent factors like the matrix (concrete) creep, shrinkage and loss of stress, in relation to bi-directional prestressing of reinforced steel-concrete composite slabs, with high yield tendons, subjected to long-term service loads.

KEYWORDS: Bi-directional Prestressing, Creep and Shrinkage of the Concrete Matrix, Long-term Service Loads, Matrix Stress and Strain; Nonlinear Differential Equations.

INTRODUCTION

Today, the major concern for civil engineers and scientists in applied mechamics of steel-concrete composite structures, is the failure of the reinforced and prestressed steel-concrete composite to meet the design and service life of structures. This paper describes the present ongoing numerical and experimental analysis model used to evaluate the structural long duration flexural and nonlinear creep characteristics of reinforced steel-concrete composite slabs, prestressed in both directions. This present study, according to applied mechanics of reinforced and prestressed steel-concrete composite structures, has been based on nonlinear differential equations of the matrix creep theory which reflects the correlation between the matrix stress and strain by its modulus of elasticity, using the nonlinear strain function and the well-known geometrical preconditions of the theory of elasticity concerning thin plates with small flexural deformations. For structural and crack predictions, the well-known virtual work principles have been used to estimate (a) transient bi-directional strains due to the matrix creep and shrinkage, (b) the resulting time-dependent bi-directional stress redistributions, as well as (c) bi-directional displacement variations in the slabs and finally (d) bi-directional prestressing losses in the prestressed high yield tendons. The concrete shear stresses have been evaluated by the well-known principle of Juravsky. The finite-difference method based on the displacement formulation has been successfully used to solve the systems of nonlinear equilibrium differential equations.

A serie of full-scale test experiments with once evaluated strength parameters has been planned to be successfully used to provide encouraging support for the numerical evaluations said at above points (a) - (d) in addition to (e) calibrating the parameters likely to enable the estimation of the said time-dependent prestressing losses, (f) predicting the slabs sections' stiffness and strength by determining their long-term flexural and nonlinear creep capacity and hence, (g) devising a definition for structural durability and integrity, with regards to the matrix stress-strain relationship under prolonged service loads.

MAIN BASIC PRECONDITIONS

The main basic preconditions for the computation of the stress-strain states of the steel-concrete composite slabs have been listed in following forms:

1. CONCRETE MATRIX STATICAL MOMENTS

Applied influences and efforts have been reducted to medium-level surface of the composite slabs, which passes through in the middle of its thickness, and the computation of contructions is based on the conceptions of the medium-level surface unit for the two directions of the stress state, which are parallel to the coordinate axes. Accordingly, linear (refered to width unit) statical moments of the concrete matrix S_{bx} and S_{by} are equal to zero.

2. HYPOTHESIS OF STRAIGHT NORMALS

Has been succesfully assumed the hypothesis of straight normals according to which:

$$\varepsilon_x^c = \varepsilon_x + \Re_x z;\ \varepsilon_y^c = \varepsilon_y + \Re_y z;\ \gamma_{xy}^c = \gamma_{xy} + 2\Re_{xy} z, \qquad (1)$$

where $\varepsilon_x^c = \varepsilon_x^c(x,\ y,\ z,\ \phi)$; $\varepsilon_y^c = \varepsilon_y^c(x, y, z, \phi)$; $\gamma_{xy}^c = \gamma_{xy}^c(x,\ y,\ z,\ \phi)$ - normal and shear strains of the slab layer, separeted from the distance z at the medium-level surface;
$\varepsilon_x = \varepsilon_x\ (x, y, \phi)$; $\varepsilon_y = \varepsilon_y\ (x, y, \phi)$; $\gamma_{xy} = \gamma_{xy}\ (x, y, \phi)$ -suitable strains of medium-level layer of the slab; $\Re_x\ (x, y, \phi)$; $\Re_y\ (x, y, \phi)$; $\Re_{xy}\ (x, y, \phi)$ - flexural curvature and torsion of the slab;
ϕ - parameter of conditional time.

3. LINEAR GEOMETRICAL HYPOTHESIS

Has been respected the linear geometrical hypothesis:

$$\Re_x = -\frac{\partial^2 w}{\partial x^2};\ \Re_y = -\frac{\partial^2 w}{\partial y^2};\ \Re_{xy} = -\frac{\partial^2 w}{\partial x \partial y}\ , \qquad (2)$$

where w = w(x, y, ϕ) - deflections in the composite slab.

4. CHARACTERISTICS OF THE STEEL REINFORCEMENT

The steel reinforcement has been refered to elastic material and according to the law of Hooke we obtained:

$$\sigma_{e,x} = E_e \varepsilon_{e,x}\ ;\ \sigma_{e,y} = E_e \varepsilon_{e,y} \qquad (3)$$

with $\sigma_e = \sigma_e(x, y, z_e, \phi)$ - stresses in steel reinforcement, E_e – steel reinforcement modulus of elasticity, and $\varepsilon_e = \varepsilon_e(x, y, z_e, \phi)$ - relative steel reinforcement strain of the e-th layer of the slab. Steel reinforcement moduluses of each wire netting have been accepted like the same in all the both directions, so accordingly $E_{ex} = E_{ey} = E_e$.

5. JOINT DEFORMATION PRINCIPLE

The steel reinforcement and the concrete matrix deformed jointly, so:

$$\varepsilon^{c}(x, y, z_{e}, \phi) = \varepsilon_{e}(x, y, \phi) \qquad (4)$$

6. WIRE NETTING REINFORCEMENTS

It has been accepted that wire netting reinforcements do not resist to shear strains in the surface, and to torsional displacements out of the surface of the composite slab.

7. CONCRETE MATRIX DEFORMATION PROPERTIES

Elastical, creep and shrinkage deformations of the concrete matrix are isotropical and cannot be changed in depth of the composite slab. The coefficient of the matrix elastical shear strain ν and the coefficient of the matrix creep strain ν_c are accepted equally, so $\nu = \nu_c$

8. COMPOSITE SLAB LOADING

The uniformly distributed service load acting on the composite slab $q(x,y,\phi)$ has been submitted to the principle of dividing, so:

$$q(x, y, \phi) = g\,(x, y)\,\rho(\phi) \qquad (5)$$

where g - load intensity, and ρ - stretch time fonction.

9. UNIFORM STRESS STATE OF THIN CONCRETE MATRIX MEMBRANES

Deformation laws of thin isotropical concrete matrix membranes (Figure.1) in a uniform stress state have been presented in following forms:

$$\varepsilon_{x} = \varepsilon'_{x} + \varepsilon''_{x} = (\sigma_{x} / E_{0}) - \mu\,(\sigma_{y} / E_{0}) \qquad (6)$$
$$(x\,,\,y)$$

Here indexes x, y show the stress-strain directions which correspond to coordinate axes.

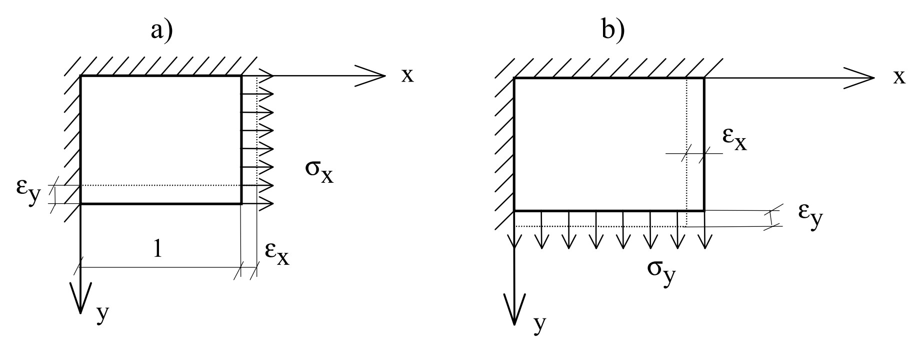

Figure 1. Force strains of concrete matrix membranes:
a) by the acting of the stresses σ_x
b) by the acting of the stresses σ_y

Using the aging theory with a constant concrete matrix modulus of elasticity, we obtained:

$$\sigma_x = E_0 \left[\varepsilon_x - e^{-\varphi} \int_0^{\varphi} f(\varepsilon_x)\, e^{\varphi}\, d\varphi \right] - \mu E_0 \left[\varepsilon_y - e^{-\varphi} \int_0^{\varphi} f(\varepsilon_y)\, e^{\varphi}\, d\varphi \right] \quad (x, y) \tag{7}$$

By deriving (7) according to φ, we obtained after cancellation:

$$\dot{\sigma}_x + \sigma_x = E_0 \{ \dot{\varepsilon}_x + \varepsilon_x - \mu (\dot{\varepsilon}_y + \varepsilon_y) - f(\varepsilon_x) - \mu f(\varepsilon_y)\} \quad (x,y) \tag{8}$$

with $$f(\varepsilon_x) = \varepsilon_x + \beta \varepsilon^2_x \quad (x,y) \tag{9}$$

where β - a fonction which regularize the nonlinear creep strains in due course.
Here and in the next formulas the functions' derivates have been presented by points.

Then, the arrangement of (9) into (8) gives after cancellation:

$$\dot{\sigma}_x + \sigma_x = E_0 \{ \dot{\varepsilon}_x - \beta \varepsilon^2_x - \mu (\dot{\varepsilon}_y + 2 \varepsilon_y + \beta \varepsilon^2_y)\} \quad (x,y) \tag{10}$$

10 STRESS-STRAIN RELATIONSHIPS

Normal stresses in the formula (10) have been presented like a sum of separeted force stresses (marked with single quotation comma) and spontaneous stresses (marked with double quotation comma):

$$\sigma_x = \sigma'_x + \sigma''_x \quad (x, y) \tag{11}$$

By arranging (11) into (10), taking into consideration the concrete shrinkage strain, we obtained:

$$\dot{\sigma}'_x + \sigma'_x = E_0 [(\dot{\varepsilon}_x - \dot{\varepsilon}_{sh,x}) - \beta (\varepsilon_x - \varepsilon_{sh,x})^2] ; \quad (x, y) \tag{12}$$

$$\dot{\sigma}''_x + \sigma''_x = - \mu E_0 [(\dot{\varepsilon}_y - \dot{\varepsilon}_{sh,y}) + 2 (\varepsilon_y - \varepsilon_{sh,y}) + \beta (\varepsilon_y - \varepsilon_{sh,y})^2] \quad (x, y), \tag{13}$$

and the examination has been done on uncracked composite slabs.

DESCRIPTION OF THE COMPOSITE SLAB ELEMENT

We have examined a multilayer composite slab element with one unity of dimension in the two directions and with a thickness δ (Figure 2), reinforced with many rows, total quantity of steel reinforcement rows $e = 1, 2, ..., s$, where e - ordinal number of the steel reinforcement.
From the total quantity s rows of the steel reinforcement, p rows were prestressed with ordinal number c ($c = 1, 2, ..., p$). Reinforcement wire nettings have been oriented parallel to coordinate

axes x and y. Linear areas of the reinforcement section $A_{e,x}$, and $A_{e,y}$ of a certain e-th layer, separated from the medium-level surface at distance z , have been refered to width unit, of the slab element [1,2,5,7,8].

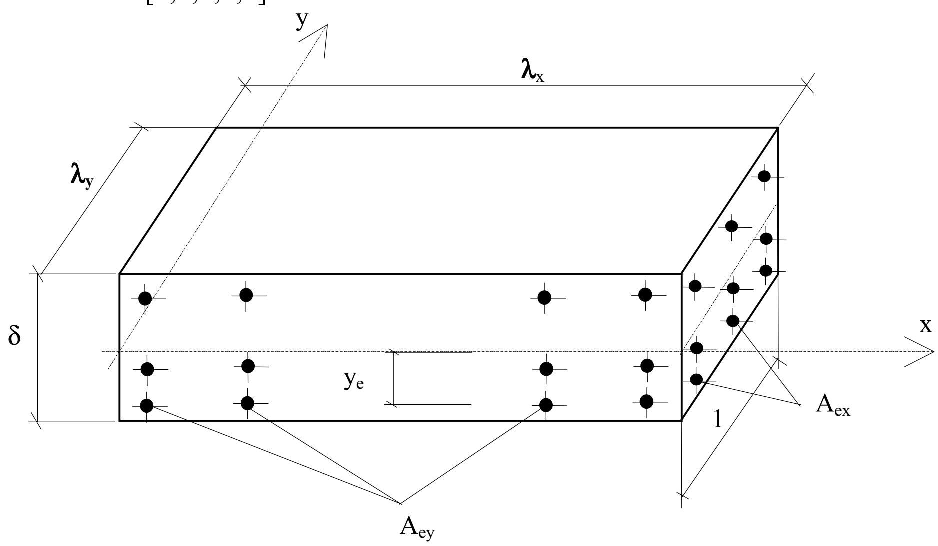

Figure 2. Multilayer reinforced steel-concrete composite slab element.

STRESS REDISTRIBUTION IN COMPOSITE SLAB ELEMENT AND ANALYSIS DETAILS

Before the transfer of the prestressing efforts to the composite slab element, in the e-th steel reinforcement row has been acting the initial controlled stress $\sigma_{e,contr.}$, without first losses, independing on deformation properties of the concrete.

At the moment of the transfer, taken like the beginning of time-dependent counting out, in the steel reinforcement and the concrete matrix were springing up elastoinstantaneous increases of stresses correspondingly σ_{e0} and $\sigma_0(y_e)$, where y_e - distance from the element center of reducted section to the axis of the e-th reinforcement row. At some time t these said elastoinstantaneous increases of stresses were changing and their current value became equal to $\sigma_e(t)$ and $\sigma(y_e,t)$, with the fact that stresses in steel reinforcement were increasing, but in concrete matrix reducing. After the moment of the trasfer the said initial controlled stress $\sigma_{e,contr.}$ has become equal to: $\sigma_{e,contr.} - \sigma_e(t)$.

According to Ukraine Codes of reinforced and prestressed concrete structures [6], stress losses due to concrete matrix shrinkage and creep in a certain e-th steel reinforcement row concern that part of stresses, which cannot supply themself with the action of certain effort P, applied with an eccentricity e_{0P} and which can annullify the stresses formed in the concrete matrix $\sigma(y_e,t)$ at the level of the same steel reinforcement row, at the calculation active time of the slab. In that way, the stresses $\sigma(y_e,t)$ have been provoked by the steel reinforcement prestressing efforts, by the concrete matrix shrinkage, by the composite slab weight and by the long term service loads on the slab.

At the moment τ, as the long term service loads were acting on the slab, so the application of these loads has changed stresses in the concrete matrix and the reinforcement to elastoinstantaneous quantities conformably $\sigma_e(\tau)$ and $\sigma(y_e,\tau)$, and the long duration of these said

loads can contribute to the fact that, stresses in the steel reinforcement have been increased, but in the concrete matrix theses stresses have been reduced, and just this positif effect can contribute to the increase of the efficiency of the use of these said composite slabs.
By applying to the slab element, the conditional effort P with an eccentricity e_{0P} at a certain moment of time t for the purpose to reduce the developped stresses $\sigma(y_e,\tau)$ to zero, we have changed the stress in steel reinforcement to the quantity $\alpha_e(\tau)\,\sigma(y_e,\tau)$, where $\alpha_e(\tau) = E_e/E(\tau)$ - elasticity moduluses ratio of the e-th steel reinforcement row and the concrete matrix, at the moment of time t. In that way, proper stresses in steel reinforcement will become equal to :

$$\sigma_{eP} = \sigma_{e,\,contr.} - \sigma_e(t) + \alpha_e(\tau)\,\sigma(y_e,\tau). \tag{14}$$

These same stresses can be presented in the following way:

$$\sigma_{eP} = \sigma_{e,\,contr.} - \sigma_{loss2e}(t) \tag{15}$$

where $\sigma_{loss2e}(t)$ - prestressing losses of the e-th steel reinforcement row at the application moment of the effort P. By equating expressions (14) and (15) we have obtained the formula for the evaluation of the generalized losses, using finite difference method for the evaluation of current stresses in the concrete and the e-th reinforcement row :

$$\sigma_{loss2e}(t) = \sigma_e(t) - \alpha_e(\tau)\,\sigma(y_e,\tau) \tag{16}$$

Thus, for the determination of prestressing losses in any e-th steel reinforcement row of the element, it is necessary to know the current initial stresses in the reinforcement and in the concrete matrix at the level of the same row, provoked by all of the long-term influences on the slabs. These said current initial stresses can be evaluated by creep computation of the slabs, using finite-difference method detailed in the work [3]. The conditional effort P which can generalize the effect of proper stresses and the eccentricity of his application e_{0P} can be evaluated by following formulas:

$$P = \sum_{e=1}^{s} (\sigma_{e,contr} - \sigma_{loss2e})A_e \;; \qquad e_{0P} = [\sum_{e=1}^{s} (\sigma_{e,contr} - \sigma_{loss2e})A_e y_e]/P \tag{17}$$

where A_e - section area of e-th steel reinforcement row.

In the composite slab were acting efforts with following linear values:
$N_x = N_x\,(x,y)$; $N_y = N_y\,(x,y)$; $N_{xy} = N_{xy}\,(x,y)$- normal and shear efforts on the medium-level surface of the slab.
$M_x = M_x\,(x,y)$; $M_y = M_y\,(x,y)$; $M_{xy} = M_{xy}\,(x,y)$ - flexure moments and torque relative to the medium-level surface of the slab.
Normal forces and flexural moments have been supported by the steel reinforcement (with index s) and the concrete matrix (with index b), and that's why following expressions have taken place [(x,y) - directions]:

$$M_x = M_{b,x} + M_{s,x} \;; \qquad N_x = N_{b,x} + N_{s,x} \qquad (x,y) \tag{18}$$

The displacement of the slab Δ has been determinated on the basis of virtual displacements principle by Juravskiy [1,3,5]:

$$\Delta = \sum_{i=1}^{n} \int_{0}^{\lambda_i} (M_1 \Re + N_1 \varepsilon)_i \, dx, \quad (x, y) \tag{19}$$

where i = 1, 2,..., n - quantity of homogeneous elements with a lengthwiseof λ_i;
M_1 and N_1 - efforts from generalized force unity, applyed in the place and to the direction of the unknown displacement;
$\Re$ and ε - components of deformations obtained by finite-difference method [1,3].

$$M_{b,x} = \int_{A_{b,x}} \sigma_{b,x}(z) \, z \, dA_{b,x} \; ; \qquad N_{b,x} = \int_{A_{b,x}} \sigma_{b,x}(z) \, dA_{b,x} \quad (x, y) \tag{20}$$

$$M_{s,x} = \sum_{e=1}^{s} \sigma_{e,x} A_{e,x} z_e \; ; \qquad N_{s,x} = \sum_{e=1}^{s} \sigma_{e,x} A_{e,x} \quad (x, y) \tag{21}$$

where A_b and A_e , (x,y) - linear sections areas of conformably active concrete matrix and e-th steel reinforcement row; s - quantity of steel reinforcement rows in the section.

EXPERIMENTAL TESTING PROGRAM

The experimental programme consisted of casting twelve 180x180x5 cm pretensioned steel-concrete composite slabs with specified characteristic material properties of 40 MPa for the concrete matrix and E_{SP} = 190.5 GPa for the high-yield steel tendons with nominal diameter of 10 mm which will be contained in frames made of 5 mm bent mild steel mesh with E_S = 171 GPa.
The concrete matrix properties should be determined by testing 30 (number of) 100x100x400 mm prisms and 40 (number of) 100 mm cubes.
As above said at the concrete matrix age of 9 days with natural curing, all of the composite slabs, after the transfer of stresses from the prestressed steel tendons to the concrete matrix, will be pressed out by prestresing efforts and then will be taken away from the prestressing beds together with their deflection indicators, after cutting the steel tendons. Two of the composite slabs, marked S-1, after their pressing out by the prestressing efforts will be maintained in the laboratory without long-term loads. By them will be obtained the variations of the deformations in the prestressed steel tendons and in the concrete matrix, due to prestressing efforts and due to the shrinkage of the concrete matrix. Further, at the concrete matrix age of 36 days, 10 other slabs will be tested under long-term uniformly distributed statical loads, with different force intensities. At the matrix age of 365 days, all of the composite slabs will be tested under quasi-statical short-term successive loads up to their failure state. Parallel to all these said testings, as above said, will be also tested at different following concrete matrix ages of 9, 12, 15, 24, 36, 76, 118, 136, 200 and 365 days, concrete matrix prisms and cubes (3 prisms and 3 cubes at each above said concrete matrix age) for the determination of the concrete matrix physical properties, and for the evaluation of the creep and shrinkage behaviour of the concrete matrix.

During these creep tests, the specimens will be mounted on the loading frame which consisted of a hydraulic jack, a load cell, and a systhem of coil springs held in compression by a set of roads and plates. Theoretical data of deformations in the concrete matrix at upper facet of the slabs ε_b, increases of deformations in the prestressed reinforcement tendons $\Delta\varepsilon_{SP}$ and the flexures of the slabs Δ, calculated, using the finite-difference method with a step h = 0,3, then the experimental data of the same characteristics of the composite slabs, obtained by their deflection indicators will be presented in a table. It is hoped that they will show a satisfactory coincidence of theoretical and experimental data.

We hope to confirm at the end of the study that nonlinear concrete creep is able to contribute to the redistribution of stresses between the concrete matrix and the steel reinforcement with long duration efforts and service loads influences on the composite slabs. This said redistribution is able to provoke the accumulation of natural initial stresses in the steel reinforcement and the concrete matrix, which are equivalent to artificial initial stresses due to prestressing efforts in the steel reinforcement, and which can reduce losses and, like consequence, able to increase the exponents of the composite slabs' limit states, and all of these said positif effects could be able to contribute for reinforcement economies up to 15%.

APPLICATION

This proposed model can be used also for many other multilayer composite members, taking into consideration their physico-mechanical and thechnogical characteritics.

CONCLUSIONS

1. The value of shear matrix creep deformation exerts an essential influence on the redistribution of efforts in the composite slabs, which is very necessary and very important to take into account during the computation stage of the project at the planning phase, using for exemple the finite differente method with well explanations and all details in [3].
2. The nonlinear matrix creep is able to contribute to the above said positive redistribution of stresses between the matrix and the steel reinforcement with long duration efforts and service loads influences on the composite slabs. The consideration of this proposed design model and these said time-dependent effects could be able to increase the quality, the assurance by the durability of these said multilayer slabs used for different building structures, and ensure the economies of steel reinforcement up to 15 %.

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