

Effects of shrinkage, temperature and the degree of connection (N/N_f) on the behavior of steel-concrete composite beams

*Halima Aouad^a, Nacer Rahal^b, Houda Beghdad^c,
Mohamed Sadoun^d, Abdelaziz Souici^e,
Sara Zatir^f, Khaled Benmahdi^g*

^a Mustapha Stambouli University, Department of Civil Engineering, Mascara, People's Democratic Republic of Algeria, e-mail: aouadhal@gmail.com, **corresponding author**, ORCID iD:  <https://orcid.org/0009-0004-1999-1489>

^b Mustapha Stambouli University, Department of Civil Engineering, Mascara, People's Democratic Republic of Algeria + University of Sciences and Technology, Laboratory of Mechanical Structure and Construction Stability, Oran, People's Democratic Republic of Algeria, e-mail: n.rahal@univ-mascara.dz, ORCID iD:  <https://orcid.org/0009-0002-0400-8360>

^c Mustapha Stambouli University, Department of Civil Engineering, Mascara, People's Democratic Republic of Algeria, e-mail: houda.beghdad@univ-mascara.dz, ORCID iD:  <https://orcid.org/0009-0001-3548-5138>

^d Mustapha Stambouli University, Department of Civil Engineering, Mascara, People's Democratic Republic of Algeria, e-mail: m.sadoun@univ-mascara.dz, ORCID iD:  <https://orcid.org/0009-0008-2314-9402>

^e Mustapha Stambouli University, Department of Civil Engineering, Mascara, People's Democratic Republic of Algeria + University of Sciences and Technology, Laboratory of Mechanical Structure and Construction Stability, Oran, People's Democratic Republic of Algeria, e-mail: a.souici@univ-mascara.dz, ORCID iD:  <https://orcid.org/0009-0004-3845-7409>

^f University Tahri Mohamed of Bechar, Architecture and Urban Department, Bechar, People's Democratic Republic of Algeria, e-mail: zatir.sara@univ-bechar.dz, ORCID iD:  <https://orcid.org/0000-0002-6187-3441>

^g Mustapha Stambouli University, Department of Civil Engineering, Mascara, People's Democratic Republic of Algeria, e-mail: k.benmahdi@univ-mascara.dz, ORCID iD:  <https://orcid.org/0000-0002-8244-5817>

 <https://doi.org/10.5937/vojtehg73-50812>

FIELD: mechanics
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: Temperature and time-dependent effects such as concrete shrinkage and creep significantly affect the behavior of steel-concrete composite beams. Hence, taking into account the demands brought by these additional effects is necessary. This necessity has resulted in various theoretical and numerical research studies. This article proposes an analytical tool capable of predicting a new redistribution of stresses brought by the combined action of temperature and concrete shrinkage in composite steel-concrete beams in partial shear connection. In this work, the partial shear connection at the steel-concrete interface is taken into account according to the degree of connection (N/N_f).

Methods: This involves reformulating the model proposed in 2024 by Rahal et al analyzing the behavior of composite steel-concrete beams in full shear connection under the effect of temperature and concrete shrinkage. In this present study, the main contribution is the introduction of the effect of the connection degree (N/N_f) at the steel-concrete interface, thus leading to an analytical model capable of predicting additional stresses brought by shrinkage and temperature in composite steel-concrete beams in partial shear connection.

Results: When referred to the model proposed in 2024 by Rahal et al, the results from this current approach are satisfactory. They clearly show that the degree of connection significantly affects the forces brought about by the combined action of concrete shrinkage and temperature.

Conclusion: The results of the present approach and those of the existing model developed by Rahal et al are in good agreement. They clearly show the effect of concrete shrinkage and temperature as a function of the connection degree N/N_f on the behavior of composite steel-concrete beams.

Key words: degree of connection (N/N_f), shrinkage, time, steel-concrete interface.

Introduction

A composite steel-concrete beam consists of a steel beam on which a reinforced concrete slab rests. The connection at the steel-concrete interface is guaranteed by metallic elements called shear connectors (Dias & Karam, 2021). They are usually headed studs.

The advantages presented by this structural system such as: good seismic performance, speed and ease of construction, lightness, reduced construction cost and better ductility allow it to be widely used in civil

engineering (Bradford & Gilbert, 1992; Nie & Cai, 2003; Dias & Karam, 2021).

The behavior of steel-concrete composite beams is influenced by various factors, in particular the cracking of concrete under negative moment (Fan et al, 2010a, 2010b), the deformation capacity of shear connectors (Bradford & Gilbert, 1991; Al-deen et al, 2011a, 2011b) as well as the shrinkage and creep of the concrete slab (Amadio & Fragiocomo, 1997; Xiang et al, 2015). To this end, the justification of the resistance of this type of beam requires a precise prediction as a function of time to avoid possible cracking of concrete or exaggerated deflection (Kwak & Seo, 2000).

The time-dependent analysis of the behavior of composite steel-concrete beams has been the subject of much research. The first studies carried out began in the early 1970s (Roll, 1971). In the case of full shear connection at the steel-concrete interface, which ignores the relative slip between the two materials, several calculation approaches have been proposed (Souici et al, 2015; Partov & Kantchev, 2009, 2011, 2012, 2014; Tehami & Ramdane, 2009; Rahal et al, 2012). In this type of assembly, the long-term deflection will be obtained by analyzes of the cross section (Gilbert, 1989). Actually, partial shear connection, for which the relative slip at the steel-concrete interface must be taken into account, is widely applied (Wen et al, 2024). This relative sliding reduces the resistance of composite beams and considerably affects their behavior over time (Wen et al, 2024).

In the case of the partial shear connection at the steel-concrete interface, which takes into account the relative slip between the two materials, several calculation approaches have been proposed (Gara et al, 2010; Ranzi & Bradford, 2006; Sakr & Sakla, 2008; Newmark et al, 1951; Faella et al, 2010; Beghdad et al, 2017; Tarantino & Dezi, 1992).

Fire is a dangerous phenomenon for the safety of human lives because the mechanical properties of a composite beam deteriorate when exposed to a possible fire and consequently there may be the collapse of the construction or one of its components (Dias & Karam, 2021). In order to protect human lives, checking the resistance of a composite steel-concrete beam in a fire situation has become a necessity.

In the absence of external mechanical stress, concrete drying causes progressive shortening over time; this is called concrete shrinkage (Rahal et al, 2024). In addition, and due to a thermal gradient or temperature variations, a statically determinate composite beam undergoes deformations and displacements without the appearance of internal forces (Rahal et al, 2024). Concrete shrinkage and temperature produce stresses

that vary over time. Predicting the behavior of composite steel-concrete beams under the simultaneous effect of shrinkage and concrete temperature is extremely complex.

The calculation and design codes for composite steel-concrete beams do not provide methods for accurately estimating deformations caused by a shrinkage-temperature combination (Mark et al, 2010).

Due to the lack of dedicated analytical methods for justifying the strength of steel-concrete composite beams taking both concrete shrinkage and temperature, the calculation and design codes for steel-concrete composite beams do not provide methods to estimate accurately the deformations caused by the shrinkage-temperature combination (Mark et al, 2010). Therefore, very simplified approaches based on approximate values of shrinkage and thermal effect are leading to unreliable results (Rahal et al, 2024). Faced with this insufficiency, the development and implementation of new calculation procedures leading to good approaches to correctly predict the effects of shrinkage and temperature has become necessary.

In this context, we seek through this article to propose an analytical, precise and simple approach in practical applications to predict the behavior of composite steel-concrete beams. In this new proposal, we will analyze the behavior of composite beams in partial shear connection at the steel-concrete interface under the shrinkage-temperature combination. This current contribution consists of enriching and expanding the model proposed by Rahal et al. (2024) in which full shear connection was used. In this approach the relative slip between the steel and the concrete was taken into account according to the degree of connection (N/N_f) defined by the European code Eurocode 4 (Hendy & Johnson, 2006). According to Eurocode 4 (Hendy & Johnson, 2006), if full shear connection is used, the connection degree is $N/N_f = 1$. On the other hand, in the case of partial shear connection, the connection degree is given as: $0.40 \leq N/N_f < 1$.

Theoretical bases

The total strain $\varepsilon(t)$ that develops in an uncracked, axially loaded concrete element is composed of four elementary strains (Kumar Mehta & Monteiro, 2005; Gilbert, 1989; Gilbert & Ranzi, 2011; Favre et al, 1996). It is evaluated as follows:

$$\varepsilon(t) = \varepsilon_{sh}(t) + \varepsilon_e(t) + \varepsilon_{cr}(t) + \varepsilon_T(t) \quad (1)$$

$\varepsilon_e(t)$: the instantaneous strain,
 $\varepsilon_{cr}(t)$: the strain of creep,
 $\varepsilon_{sh}(t)$: the deformation of shrinkage, and
 $\varepsilon_T(t)$: the thermal expansion.

In accordance with the irreversible theory of concrete (the rate of creep theory), the total deformation of an uncracked and axially loaded concrete specimen can be obtained by the expression below (Kumar Mehta & Monteiro, 2005; Gilbert, 1989; Gilbert & Ranzi, 2011; Favre et al, 1996):

$$\frac{d\varepsilon(t, \tau)}{d\varphi} = \frac{1}{E_c(\tau_1)} \frac{d\sigma_c(t)}{d\varphi} + \frac{\sigma_c(t)}{E_c(\tau_1)} + \frac{\varepsilon_{sh}(\infty)}{\varphi(\infty)} \quad (2)$$

φ : the shrinkage coefficient,
 E_c : the elastic modulus of concrete,
 σ_c : the stress applying to the concrete slab,
 τ_1 : the application time of the constraint, and
 t : the calculation moment.

Formulation of the proposed method

This study applies to the analysis of the elastic behavior of simply supported steel-concrete composite beams including both the shrinkage of concrete, the temperature and the degree of connection (N/N_f) at the steel-concrete interface.

In order to formulate the present analytical approach, we introduce the degree of connection (N/N_f) at the steel-concrete interface into the model proposed by Rahal et al. (2024). In this work, the figure (Figure 1) shows different forces loading the mixed steel-concrete cross section.

These forces are:

ΔT : the thermal gradient = $T_0 - T_1$,
 N_0 : the normal force applied externally, and
 M_0 : the externally applied bending moment.

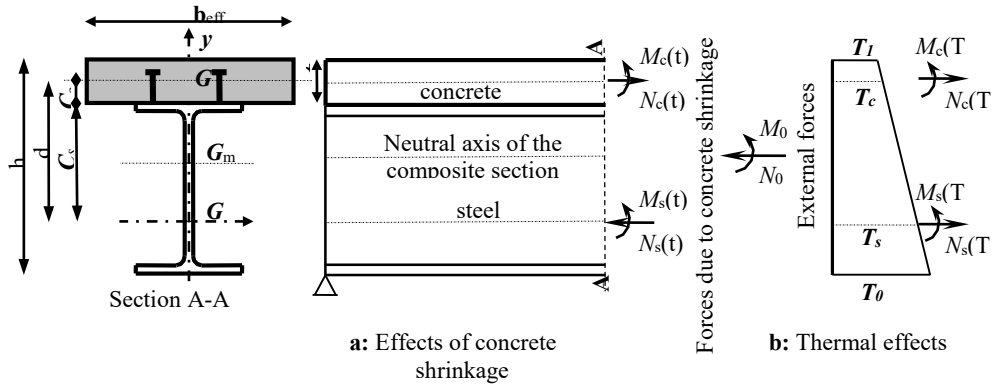


Figure 1 – Internal forces in a composite steel-concrete beam subjected to shrinkage and temperature (Rahal et al, 2024)

Thermal actions

Thermal actions can cause significant geometric changes in large buildings. These loadings can be: elongation when the structure is exposed to temperature or shortening when it is cooled (Gerhard, 1998; Beer, 2010). When a beam is exposed to thermal changes ΔT , it generates:

- thermal strains: $\varepsilon_T = \alpha \Delta T$ and

- thermal elongations: $\Delta_{LT} = \varepsilon_T L = \alpha \Delta T L$,

where α is the coefficient of thermal expansion ($^{\circ}\text{C}^{-1}$), ($= 1.2 \times 10^{-5}$ for steel and 1.0×10^{-5} for concrete),

L is the initial length of the bar, and

ΔT is the temperature variation ($^{\circ}\text{C}$).

When a beam is subjected to thermal effects, the temperature gradient ΔT develops a curvature and an axial deformation calculated respectively by the following relationships (Eqs. 3 and 4) (Gerhard, 1998; Beer, 2010):

$$\chi_T = \alpha_T \frac{\Delta T}{h} \quad (3)$$

$$\varepsilon_T = \alpha_T \Delta T \frac{d}{h} \quad (4)$$

In a composite steel-concrete beam, the bending moment acting on the cross section is the result of the four elementary forces ($M_s(t)$, $M_c(t)$, $N_s(t)$ and $N_c(t)$) applying the steel beam and the concrete slab individually. Hence, four equations are necessary to determine these four unknowns (Szabó, 2006). These four equations are obtained by kinematic analysis (two equations) and static analysis (two equations).

Static and kinematic study

From Figure 1, the static study will provide the following two equations

$$N_s(t) = -\alpha_s t_s - (\alpha_c t_c + N_c(t)) \left[\left(\frac{A_s}{A_m} - \frac{A_c C_c^2}{I_m} \right) \left(1 - \frac{N}{N_f} \right) - 1 \right] \quad (5)$$

$$M_s(t) = -\Delta T \left(\frac{\alpha_s}{h_s} + \frac{\alpha_c}{t_c} \right) - M_c(t) + [N_c(t) + \alpha_c t_c] a (1 - k) \quad (6)$$

with:

$$K = \left[\left(\frac{A_s}{A_m} - \frac{A_c C_c^2}{I_m} \right) \left(1 - \frac{N}{N_f} \right) \right]$$

$M_c(t)$: bending moment in the concrete slab due to creep,
 $M_s(t)$: bending moment in the steel beam,
 N : number of shear connectors in partial shear connection,
 $N_c(t)$: normal force in the concrete slab due to creep,
 N_f : number of shear connectors in full shear connection,
 $N_s(t)$: normal effort in the steel section,
 N/N_f : rate of shear connection in (%),
 t_c : thickness of the slab,
 A_c : area of the concrete slab,
 A_m : area of the composite beam,
 A_s : area of the steel beam,
 I_m : moment of inertia of the composite beam,
 α_c : thermal expansion coefficient of concrete, and
 α_s : thermal expansion coefficient of steel.

Kinematic analysis

In composite steel-concrete beams, the kinematic analysis results in the condition at the steel-concrete interface (Tehami & Ramdane, 2009; Partov & Kantchev, 2009, 2011, 2012, 2014; Rahal et al, 2012; Souici et al, 2015; Beghdad et al, 2017; Rahal et al, 2024). According to this characteristic, we can write the following two compatibility equations in curvature (Eq. 7) and in deformation (Eq. 8):

$$\chi(t) = \frac{M_c(t)}{E_c I_c} = \frac{M_s(t)}{E_s I_s} \quad (7)$$

$$\varepsilon_c(t) = \frac{N_c(t)}{E_c A_c} + \frac{M_c(t)}{E_c I_c} C_c = \frac{N_s(t)}{E_s A_s} + \frac{M_s(t)}{E_s I_s} C_s \quad (8)$$

I_s : moment of inertia of the steel beam, and
 I_c : moment of inertia of the concrete slab.

Curvature

In accordance with the irreversible law of concrete (the rate of creep theory), the first condition (Eq.7) can be transformed into a differential equation of the type of relation (Eq.2), so one can write:

$$\chi(t) = \frac{1}{E_c I_c} [dM_c(t) + M_c(t).d\varphi] = \frac{M_s(t)}{E_s I_s} \quad (9)$$

$$\chi(t) = \frac{1}{E_c I_c} [dM_c(t) + M_c(t).d\varphi] = -\frac{\Delta T}{E_s I_s} \left(\frac{\alpha_s}{h_s} + \frac{\alpha_c}{t_c} \right) + \quad (10)$$

$$\frac{1}{E_s I_s} [N_c(t) + \alpha_c t_c] a(1-k) - \frac{1}{E_s I_s} M_c(t)$$

$$\chi(t) = \frac{1}{E_c I_c} \left[\frac{dM_c(t)}{d\varphi} (1-k) + \Delta T \frac{\alpha_c}{t_c} + M_c(t) (1-k) + \Delta T \frac{\alpha_c}{t_c} \right] +$$

$$\frac{1}{E_s I_s} \Delta T \frac{\alpha_s}{h_s} + \frac{1}{E_s I_s} \Delta T \frac{\alpha_c}{t_c} + \frac{1}{E_s I_s} \frac{dM_c(t)}{d\varphi} (1-k) - \quad (11)$$

$$\frac{1}{E_s I_s} \frac{dN_c(t)}{d\varphi} a (1-k) - \frac{1}{E_s I_s} \alpha_c t_c = 0$$

$$\chi(t) = \left(\frac{1}{E_c I_c} + \frac{1}{E_s I_s} \right) (1-k) \frac{dM_c(t)}{d\varphi} + \left(\frac{1}{E_c I_c} + \frac{1}{E_s I_s} \right) \Delta T \frac{\alpha_c}{t_c} -$$

$$\frac{1}{E_s I_s} \frac{dN_c(t)}{d\varphi} a (1-k) - \frac{1}{E_s I_s} \alpha_c t_c + \frac{1}{E_c I_c} M_c(t) (1-k) + \quad (12)$$

$$\frac{1}{E_c I_c} \Delta T \frac{\alpha_c}{t_c} + \frac{1}{E_s I_s} \Delta T \frac{\alpha_s}{h_s} = 0$$

$$\chi(t) = \left(1 + \frac{I_c}{n I_s} \right) (1-k) \frac{dM_c(t)}{d\varphi} + \left(1 + \frac{I_c}{n I_s} \right) \Delta T \frac{\alpha_c}{t_c} -$$

$$\frac{I_c}{n I_s} a (1-k) \frac{dN_c(t)}{d\varphi} - \frac{I_c}{n I_s} \alpha_c t_c + M_c(t) (1-k) + \quad (13)$$

$$\Delta T \frac{\alpha_c}{t_c} + \frac{I_c}{n I_s} \Delta T \frac{\alpha_s}{h_s} = 0$$

α_c : steel-concrete equivalence coefficient ($n=E_s/E_c$).

Deformation

In accordance with the irreversible law of concrete (the rate of creep theory), the second condition (Eq.8) can be transformed into differential equations of the type of relation (Eq.2), so one can write:

$$\varepsilon(t) = \frac{1}{E_c A_c} [dN_c(t) + N_c(t).d\varphi] + \frac{C_c}{E_c I_c} [dM_c(t) + M_c(t).d\varphi] \quad (14)$$

$$-d\varepsilon_{sh}(t) = \frac{N_s(t)}{E_s A_s} - \frac{M_s(t)}{E_s I_s} C_s$$

$$\varepsilon(t) = \frac{1}{E_c A_c} \frac{dN_c(t)}{d\varphi} (k-1) + \frac{\alpha_c t_c}{E_c A_c} + \frac{1}{E_c A_c} N_c(t)(k-1) +$$

$$\frac{\alpha_c t_c}{E_c A_c} + \frac{C_c}{E_c I_c} (1-k) \frac{dM_c(t)}{d\varphi} + \frac{C_c}{E_c I_c} \Delta T \frac{\alpha_c}{t_c} +$$

$$\frac{C_c}{E_c I_c} (1-k) M_c(t) + \frac{C_c}{E_c I_c} \Delta T \frac{\alpha_c}{t_c} - \frac{d\varepsilon_{sh}(t)}{d\varphi} = - \frac{\alpha_s t_s}{E_s A_s} -$$

$$\frac{\alpha_c t_c}{E_s A_s} - \frac{1}{E_s A_s} \frac{dN_c(t)}{d\varphi} (k-1) + \frac{C_s}{E_s I_s} \Delta T \frac{\alpha_s}{h_s} + \frac{C_s}{E_s I_s} \Delta T \frac{\alpha_c}{t_c} +$$

$$\frac{C_s}{E_s I_s} (1-k) \frac{dM_c(t)}{d\varphi} - \frac{C_s}{E_s I_s} a(1-k) \frac{dN_c(t)}{d\varphi} - \frac{C_s}{E_s I_s} \alpha_c t_c$$

$$\varepsilon(t) = \left(\frac{C_c}{E_c I_c} - \frac{C_s}{E_s I_s} \right) (1-k) \frac{dM_c(t)}{d\varphi} + \left(\frac{C_c}{E_c I_c} - \frac{C_s}{E_s I_s} \right) \Delta T \frac{\alpha_c}{t_c} +$$

$$\left(\frac{1}{E_c A_c} + \frac{1}{E_s A_s} + \frac{C_s a}{E_s I_s} \right) (k-1) \frac{dN_c(t)}{d\varphi} + \left(\frac{1}{E_c A_c} + \frac{1}{E_s A_s} + \frac{C_s a}{E_s I_s} \right) \alpha_c t_c +$$
(16)

$$\frac{C_c}{E_c I_c} (1-k) M_c(t) + \frac{C_c}{E_c I_c} \Delta T \frac{\alpha_c}{t_c} + \frac{1}{E_c A_c} (k-1) N_c(t) + \frac{1}{E_c A_c} \alpha_c t_c =$$

$$\frac{d\varepsilon_{sh}(t)}{d\varphi} - \frac{\alpha_s t_s}{E_s A_s} + \frac{C_s}{E_s I_s} \Delta T \frac{\alpha_s}{h_s}$$

$$\varepsilon(t) = \frac{1}{E_c A_c} \frac{dN_c(t)}{d\varphi} (k-1) + \frac{\alpha_c t_c}{E_c A_c} + \frac{1}{E_c A_c} N_c(t) (k-1) + \frac{\alpha_c t_c}{E_c A_c} +$$

$$\frac{C_c}{E_c I_c} (1-k) \frac{dM_c(t)}{d\varphi} + \frac{C_c}{E_c I_c} \Delta T \frac{\alpha_c}{t_c} + \frac{C_c}{E_c I_c} (1-k) M_c(t) + \frac{C_c}{E_c I_c} \Delta T \frac{\alpha_c}{t_c}$$
(17)

$$-\frac{d\varepsilon_{sh}(t)}{d\varphi} = -\frac{\alpha_s t_s}{E_s A_s} - \frac{\alpha_c t_c}{E_s A_s} - \frac{1}{E_s A_s} \frac{dN_c(t)}{d\varphi} (k-1) + \frac{C_s}{E_s I_s} \Delta T \frac{\alpha_s}{h_s} +$$

$$\frac{C_s}{E_s I_s} \Delta T \frac{\alpha_c}{t_c} + \frac{C_s}{E_s I_s} (1-k) \frac{dM_c(t)}{d\varphi} - \frac{C_s}{E_s I_s} \frac{dN_c(t)}{d\varphi} a (1-k) - \frac{C_s}{E_s I_s} \alpha_c t$$

The two equations (Eqs. 13 and 17) can be rewritten in the following simplified form:

$$A_1 \frac{dM_c(t)}{d\varphi} + A_2 \frac{dN_c(t)}{d\varphi} + M_c(t) = -K_1$$
(18)

$$A_3 \frac{dM_c(t)}{d\phi} + A_4 \frac{dN_c(t)}{d\phi} + A_5 M_c(t) + A_6 N_c(t) = E_c \frac{\varepsilon_{sh}(\infty)}{\phi_\infty} - K_2 \quad (19)$$

Additional forces

The general solution of the two differential equations (Eqs. 18 and 19) will give the expressions we are looking for to estimate the additional stresses brought about by the combined effect of concrete shrinkage and temperature. They are of the following form:

$$N_c(t) = C_1 \cdot a_1(\lambda_1) \cdot e^{\lambda_1 \cdot \phi} + C_2 \cdot a_2(\lambda_2) \cdot e^{\lambda_2 \phi} + K_1 \quad (20)$$

$$M_c(t) = C_1 \cdot a_1(\lambda_1) \cdot e^{\lambda_1 \cdot \phi} + C_2 \cdot a_2(\lambda_2) \cdot e^{\lambda_2 \phi} + K_2 \quad (21)$$

In the equations (Eqs. 18, 19, 20 and 21), the constants A_1 to A_6 , K_1 and K_2 are calculated according to: the geometric and physical characteristics of the mixed cross section, the thermal expansion coefficient of steel and concrete, the degree of connection (N/N_f) and the temperatures T_0 and T_1 . On the other hand, the two constants C_1 and C_2 are obtained using the boundary conditions.

Model validation

Our present formulation is validated by examining the composite beam treated in Eurocode 4 (Hendy & Johnson, 2006).

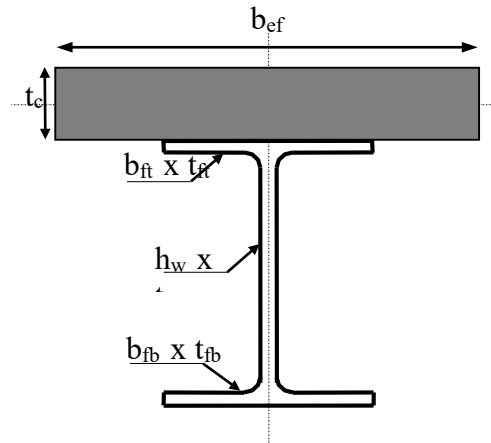


Figure 2 – Cross section characteristics

This example was also used by Rahal et al. (2024) to validate their model in the full shear connection. In this study, the shrinkage parameters are calculated according to Eurocode 2 (European Standard, 2004). The data to use is as follows:

$b_{eff} = 3100$ mm, $t_c = 250$ mm, $b_{ft} = 400$ mm, $t_{ft} = 20$ mm, $b_{fb} = 400$ mm, $t_{fb} = 30$ mm, $h_w = 1175$ mm, $t_w = 12.5$ mm. In this example, our beam is supposed to be subjected at time $t = 420$ days to a flame such that: $T_0 = 140$ °C and $T_1 = 100$ °C.

Results

The graphs of the figures (Figures 3 to 8) show the evolution as a function of time and the degree of connection (N/N_f) of the additional forces brought by the shrinkage of the concrete and the temperature and which request a mixed section steel-concrete in partial shear connection.

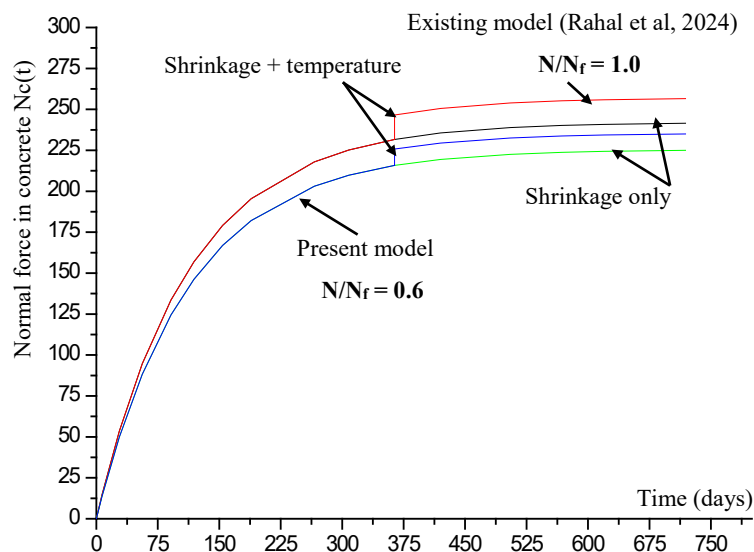


Figure 3 – Evolution in time of the normal force $N_c(t)$ in the concrete slab

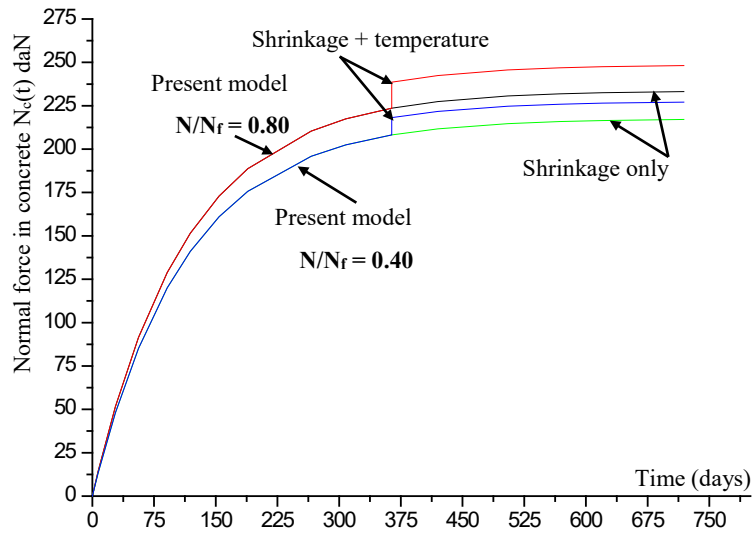


Figure 4 – Evolution in time of the normal force $N_c(t)$ in the concrete slab

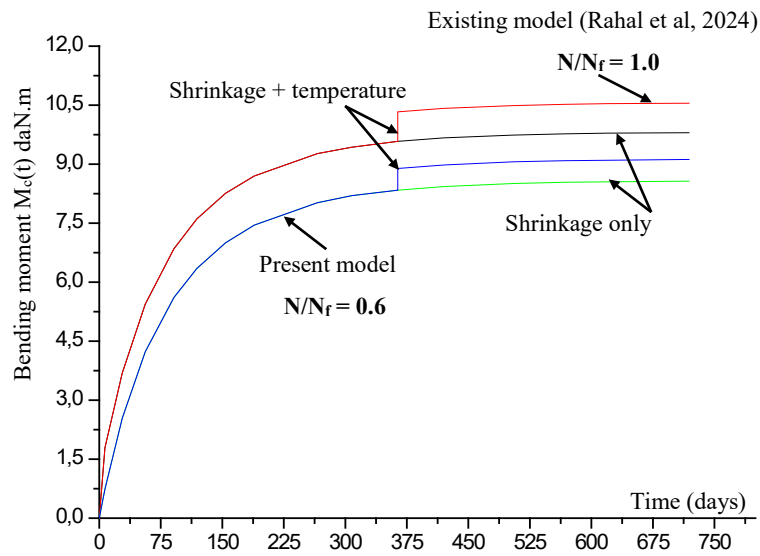


Figure 5 – Evolution in time of the bending moment $M_c(t)$ in the concrete slab

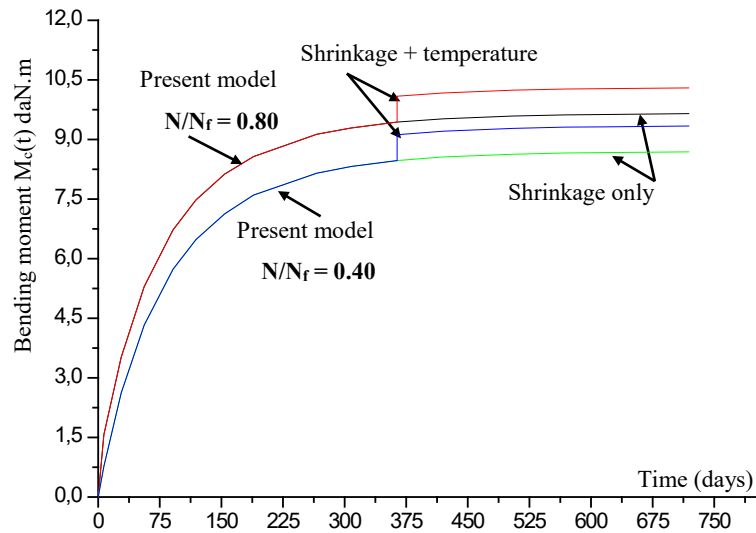


Figure 6 – Evolution in time of the bending moment $M_c(t)$ in the concrete slab

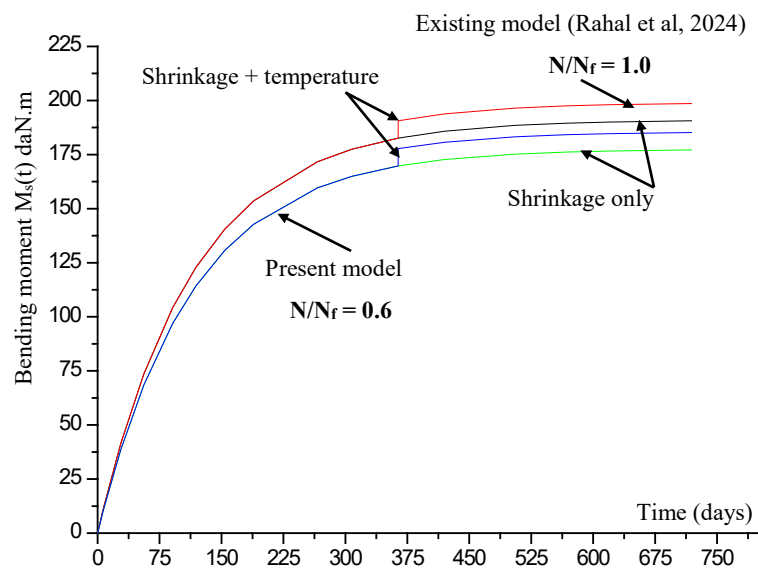
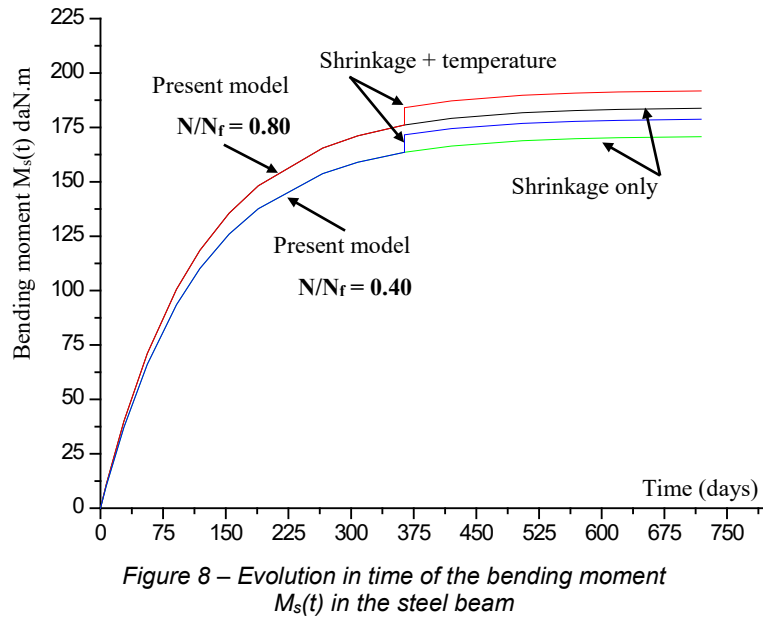


Figure 7 – Evolution in time of the bending moment $M_s(t)$ in the steel beam



Conclusion

The present study focuses on the analysis of the effect of concrete shrinkage on the behavior of composite steel-concrete beams in partial shear connection exposed to temperature.

In this article, the main contribution lies in taking into account the effect of the connection degree (N/N_r) at the steel-concrete interface. This allows us to arrive at an analytical model capable of predicting the additional stresses brought by shrinkage and temperature in composite steel-concrete beams in partial shear connection. The present work is a continuation of that proposed by Rahal et al. (2024). The interest of this approach is to evaluate the new redistribution of constraints according to the degree of connection (N/N_r).

Previous studies clearly show that the bending stiffness of composite steel-concrete beams is reduced in the presence of sliding at the steel-concrete interface. The results obtained by our present approach (Figures 3 to 8) are clearly consistent with this conclusion because the introduction of sliding considerably changes the forces applying the steel beam and the concrete slab under the combined action of concrete shrinkage and temperature.

This research provides a simple and effective tool allowing the estimation, at any instant, of the forces ($N_c(t)$, $N_s(t)$, $M_c(t)$ and $M_s(t)$) which develop on the steel beam and the concrete slab and consequently the knowledge of the new redistribution of local stresses. If the beam is exposed to cooling, the values of temperatures T_0 and T_1 must be negative.

In perspective, future studies will be carried out on composite beams including, at the same time, the effects of concrete creep and temperature.

References

Al-deen, S., Ranzi, G. & Vrcelj, Z. 2011a. Full-scale long-term experiments of simply supported composite beams with solid slabs. *Journal of Constructional Steel Research*, 67(3), pp.308-321. Available at: <https://doi.org/10.1016/j.jcsr.2010.11.001>.

Al-deen, S., Ranzi, G. & Vrcelj, Z. 2011b. Full-scale long-term and ultimate experiments of simply-supported composite beams with steel deck. *Journal of Constructional Steel Research*, 67(10), pp.1658-1676. Available at: <https://doi.org/10.1016/j.jcsr.2011.04.010>.

Amadio, C. & Fragiocomo, M. 1997. Simplified Approach to Evaluate Creep and Shrinkage Effects in Steel-Concrete Composite Beams. *Journal of Structural Engineering*, 123(9), pp.1153-1162. Available at: [https://doi.org/10.1061/\(ASCE\)0733-9445\(1997\)123:9\(1153\)](https://doi.org/10.1061/(ASCE)0733-9445(1997)123:9(1153)).

Beer, G. 2010. *Baustatik: Von den Grundlagen bis zur Computerstatik (Textbook Series TU Graz)*. Verlag d. Technischen Universität Graz. ISBN: 978-3851251210.

Beghdad, H., Tehami, M. & Rahal, N. 2017. Shrinkage behaviour modelling of steel-concrete composite beams with varying degree of connection. *Asian Journal of Civil Engineering (BHRC)*, 18(8), pp.1271-1285 [online]. Available at: <https://ajce.bhrc.ac.ir/Volumes-Issues/agentType/View/PropertyID/9500> [Accessed: 02 May 2024].

Bradford, M.A. & Gilbert, R.I. 1991. Time-dependent behaviour of simply-supported steel-concrete composite beams. *Magazine of Concrete Research*, 43(157), pp.265-274. Available at: <https://doi.org/10.1680/mac.1991.43.157.265>.

Bradford, M.A. & Gilbert, R.I. 1992. Composite Beams with Partial Interaction under Sustained Loads. *Journal of Structural Engineering*, 118(7), pp.1871-1883. Available at: [https://doi.org/10.1061/\(ASCE\)0733-9445\(1992\)118:7\(1871\)](https://doi.org/10.1061/(ASCE)0733-9445(1992)118:7(1871)).

Dias, M.S.F. & Karam, V.J. 2021. Thermal analysis of steel and concrete composite beams cross sections in fire situations. *IBRACON Structures and Materials Journal*, 14(5), e14509. Available at: <https://doi.org/10.1590/S1983-41952021000500009>.

-European Standard. 2004. *EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings* [online]. Available at:

<https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.1.2004.pdf>
[Accessed: 02 May 2024].

Faella, C., Martinelli, E. & Nigro, E. 2010. Steel-concrete composite beams in partial interaction: Closed-form “exact” expression of the stiffness matrix and the vector of equivalent nodal forces. *Engineering Structures*, 32(9), pp.2744-2754. Available at: <https://doi.org/10.1016/j.engstruct.2010.04.044>.

Fan, J., Nie, J., Li, Q. & Wang, H. 2010a. Long-Term Behavior of Composite Beams under Positive and Negative Bending. I: Experimental Study. *Journal of Structural Engineering*, 136(7), pp.849-857. Available at: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000175](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000175).

Fan, J., Nie, X., Li, Quan & Li, Quanwang. 2010b. Long-Term Behavior of Composite Beams under Positive and Negative Bending. II: Analytical Study. *Journal of Structural Engineering*, 136(7), pp.858-865. Available at: [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000176](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000176).

Favre, R., Jaccourd, J.-P., Burdet, O. & Charif, H. 1996. *Dimensionnement des structures en béton : aptitude au service et éléments de structures*. Presses Polytechniques et Universitaires Romandes (PPUR). ISBN: 978-2-88074-330-7.

Gara, F., Ranzi, G. & Leoni, G. 2010. Short- and long-term analytical solutions for composite beams with partial interaction and shear-lag effects. *International Journal of Steel Structures*, 10(4), pp.359-372. Available at: <https://doi.org/10.1007/BF03215844>.

Gerhard, E. 1998. *Praktische Baustatik, Teil 2*. Vieweg+Teubner Verlag Wiesbaden. Available at: <https://doi.org/10.1007/978-3-663-11118-4>.

Gilbert, R.I. 1989. Time-Dependent Analysis of Composite Steel-Concrete Sections. *Journal of Structural Engineering*, 115(11), pp.2687-2705. Available at: [https://doi.org/10.1061/\(ASCE\)0733-9445\(1989\)115:11\(2687\)](https://doi.org/10.1061/(ASCE)0733-9445(1989)115:11(2687)).

Gilbert, R.I. & Ranzi, G. 2011. *Time Dependent Behaviour of Concrete Structures, 1st Edition*. CRC Press. Available at: <https://doi.org/10.1201/9781482288711>.

Hendy, C.R. & Johnson, R.P. 2006. *Designers' guide to EN 1994-2 Eurocode 4 : design of composite steel and concrete structures. Part 2, General rules and rules for bridges*. London, UK: Thomas Telford Ltd. ISBN: 978-0727731616.

Kumar Mehta, P. & Monteiro, P.J.M. 2005. *Concrete: Microstructure, Properties and Materials, Third Edition*. McGraw-Hill Professional . ISBN: 978-0071462891.

Kwak, H.-G & Seo, Y.-J. 2000. Long-term behavior of composite girder bridges. *Computer Structures*, 74(5), pp.583-599. Available at: [https://doi.org/10.1016/S0045-7949\(99\)00064-4](https://doi.org/10.1016/S0045-7949(99)00064-4).

Newmark, N.M, Siess, C.P. & Viest, I.M. 1951. Tests and analysis of composite beams with incomplete interaction. *Proceedings of the Society for Experimental Stress Analysis*, 9(1), pp.75-92.

Nie, J. & Cai, C.S. 2003. Steel-Concrete Composite Beams Considering Shear Slip Effects. *Journal of Structural Engineering*, 129(4), pp.495-506. Available at: [https://doi.org/10.1061/\(ASCE\)0733-9445\(2003\)129:4\(495\)](https://doi.org/10.1061/(ASCE)0733-9445(2003)129:4(495)).

Partov, D. & Kantchev, V. 2009. Time-dependent analysis of composite steel-concrete beams using integral equation of Volterra, according Eurocode 4. *Engineering Mechanics*, 16(5), pp.367-392 [online]. Available at: https://web.archive.org/web/20200321071535id_/http://www.engineeringmechanics.cz/pdf/16_5_367.pdf [Accessed: 02 May 2024].

Partov, D. & Kantchev, V. 2011. Level of creep sensitivity in composite steel-concrete beams according to ACI 209R-92 model, comparison with Eurocode-4 (CEB MC90-99). *Engineering Mechanics*, 18(2), p. 91-116 [online]. Available at: http://147.229.35.49/pdf/18_2_091.pdf [Accessed: 02 May 2024].

Partov, D. & Kantchev, V. 2012. Gardner&Lockman Model (2000) and its Application in Numerical Analysis of Composite Beams. *Procedia Engineering*, 40, pp.357-362. Available at: <https://doi.org/10.1016/j.proeng.2012.07.108>.

Partov, D. & Kantchev, V. 2014. Gardner and Lockman Model in Creep Analysis of Composite Steel-Concrete Sections. *ACI Structural Journal*, 111(1), pp.59-70. Available at: <https://doi.org/10.14359/51686430>.

Rahal, N., Souici, A., Beghdad, H., Tehami, M., Djaffari, D., Sadoun, M. & Benmahdi, K. 2024. Effects of shrinkage in composite steel-concrete beam subjected to fire. *Steel and Composite Structures*, 50(4), pp.375-382. Available at: <https://doi.org/10.12989/scs.2024.50.4.375>.

Rahal, N., Tehami, M., Souici, A. & Beghdad, H. 2012. Applying of Integral Equation of Volterra for Determining the Section Forces in Composite Beam, Regarding Shrinkage of Concrete. *Key Engineering Materials*, 498, pp.173-186. Available at: <https://doi.org/10.4028/www.scientific.net/KEM.498.173>.

Ranzi, G. & Bradford, M.A. 2006. Analytical solutions for the time dependent behavior of composite beams with partial interaction. *International Journal of Solid and Structures*, 43(13), pp.3770-3793. Available at: <https://doi.org/10.1016/j.ijsolstr.2005.03.032>.

Roll, F. 1971. Effects of Differential Shrinkage and Creep on a Composite Steel-Concrete Structure. *ACI Symposium Publication*, 27, pp.187-214 [online]. Available at: <https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/17182> [Accessed: 02 May 2024].

Sakr, M.A. & Sakla, S.S.S. 2008. Long-term deflection of cracked composite beams with nonlinear partial shear interaction: I — Finite element modeling. *Journal of Constructional Steel Research*, 64(12), pp.1446-1455. Available at: <https://doi.org/10.1016/j.jcsr.2008.01.003>.

Souici, A., Tehami, M., Rahal, N., Bekkouche, M.S. & Berthet, J.F. 2015. Creep effect on composite beam with perfect steel-concrete connection. *International Journal of Steel Structures*, 15(2), pp.433-445. Available at: <https://doi.org/10.1007/s13296-015-6013-6>.

Szabó, B. 2006. *Influence of shear connectors on the elastic behaviour of composite girders*. PhD thesis. Otaniemi, Espoo: Helsinki University of Technology [online]. Available at: <https://aaltodoc.aalto.fi/items/5856e568-6ec5-4a9e-8232-f2fd69723786> [Accessed: 02 May 2024].

Tarantino, A.M. & Dezi, L. 1992. Creep Effects in Composite Beams with Flexible Shear Connectors. *Journal of Structural Engineering*, 118(8), pp.2063-2080. Available at: [https://doi.org/10.1061/\(ASCE\)0733-9445\(1992\)118:8\(2063\)](https://doi.org/10.1061/(ASCE)0733-9445(1992)118:8(2063)).

Tehami, M. & Ramdane, K.-E. 2009. Creep behaviour modelling of a composite steel-concrete section. *Journal of Constructional Steel Research*, 65(5), pp.1029-1033. Available at: <https://doi.org/10.1016/j.jcsr.2009.01.001>.

Wen, C., Lin, Z., Xu, Z., Xu, C., Liu, X. & Yang, G. 2024. Time-dependent response of continuous steel-concrete composite beams under sustained loading. *Journal of Constructional Steel Research*, 213, art.number: 108339. Available at: <https://doi.org/10.1016/j.jcsr.2023.108339>.

Xiang, T., Yang, C. & Zhao, G. 2015. Stochastic Creep and Shrinkage Effect of Steel-Concrete Composite Beam. *Advances in Structural Engineering*, 18(8), pp.1129-1140. Available at: <https://doi.org/10.1260/1369-4332.18.8.1129>.

Efectos de la contracción, la temperatura y el grado de conexión (N/N_t) sobre el comportamiento de vigas mixtas acero-hormigón

Halima Aouad^a, **autor de correspondencia**, Nacer Rahal^{ab}, Houda Beghdad^a, Mohamed Sadoun^a, Abdelaziz Souici^{ab}, Sara Zatir^c, Khaled Benmahdi^a

^a Universidad Mustapha Stambouli, Departamento de Ingeniería Civil, Mascara, República Argelina Democrática y Popular

^b Universidad de Ciencias y Tecnología, Laboratorio de Estructura Mecánica y Estabilidad de la Construcción, Orán, República Argelina Democrática y Popular

^c Universidad Tahri Mohamed de Bechar, Departamento de Arquitectura y Urbanismo, Bechar, República Argelina Democrática y Popular

CAMPO: mecánica

TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: Los efectos dependientes de la temperatura y el tiempo, como la contracción y la fluencia del concreto, afectan significativamente el comportamiento de las vigas compuestas de acero y concreto. Por lo tanto, es necesario tener en cuenta las demandas que plantean estos efectos adicionales. Esta necesidad ha dado lugar a diversos estudios de investigación teóricos y numéricos. Este artículo propone una herramienta analítica capaz de predecir una nueva redistribución de tensiones provocada por la acción combinada de la temperatura y la contracción del hormigón en vigas compuestas de acero y hormigón en conexión de corte parcial. En este trabajo se tiene en cuenta la conexión de corte parcial en la interfaz acero-hormigón según el grado de conexión (N/N_t).

Métodos: Se trata de reformular el modelo propuesto en 2024 por Rahal et al analizando el comportamiento de vigas compuestas de acero y hormigón en conexión de corte total bajo el efecto de la temperatura y la contracción del hormigón. En este presente estudio, la principal contribución es la introducción del efecto del grado de conexión (N/N_f) en la interfaz acero-hormigón, lo que lleva a un modelo analítico capaz de predecir tensiones adicionales provocadas por la contracción y la temperatura en vigas compuestas de acero y hormigón en conexión de corte parcial.

Resultados: Cuando se hace referencia al modelo propuesto en 2024 por Rahal et al, los resultados de este enfoque actual son satisfactorios. Muestran claramente que el grado de conexión afecta significativamente las fuerzas provocadas por la acción combinada de la contracción del hormigón y la temperatura.

Conclusión: Los resultados del presente enfoque y los del modelo existente desarrollado por Rahal et al concuerdan bien. Muestran claramente el efecto de la contracción del hormigón y la temperatura en función del grado de conexión N/N_f sobre el comportamiento de vigas mixtas de acero y hormigón.

Palabras claves: grado de conexión (N/N_f), retracción, tiempo, interfaz acero-hormigón

Влияние усадки, температуры и степени сцепления (N/N_f) на характеристики сталебетонных композитных балок

Халима Авед^а, **корреспондент**, Насер Рахал^{аб}, Хауда Бегдад^а, Мухамед Садун^а, Абдулазиз Соици^{аб}, Сара Затар^а, Халед Бенмахди^а

^а Университет Туши Мустафы Стамбули, строительный факультет, г. Маскара, Алжирская Народная Демократическая Республика

^б Университет естественных наук и технологий, Лаборатория машиностроения и прочности конструкций, г. Оран, Алжирская Народная Демократическая Республика

^в Университет Тахри Мохаммед Бешар, департамент архитектуры и урбанизма, г. Бешар, Алжирская Народная Демократическая Республика

РУБРИКА ГРНТИ: 67.09.33 Бетоны. Железобетон. Строительные растворы, смеси, составы

ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Эффекты, зависящие от температуры и времени, такие как усадка бетона и ползучесть, существенно влияют на поведение сталебетонных композитных балок. Следовательно, необходимо учитывать требования, связанные с этими дополнительными эффектами, которые являются

предметом многих теоретических и численных исследований. В данной статье представлен аналитический инструментарий, обеспечивающий возможность прогнозирования нового перераспределения нагрузок, вызванных совместным действием температуры и усадки бетона в композитных сталебетонных балках при частичном сдвиговом соединении. В исследовании учитывается частичное сдвиговое соединение в интерфейсе сталь-бетон в зависимости от степени сцепления (N/N_f).

Методы: В связи с вышеизложенным необходимо откорректировать модель, предложенную в 2024 году Рахалом и соавторами для анализа поведения композитных сталебетонных балок при полном сдвиговом соединении под воздействием температуры и усадки бетона. Главный вклад данного исследования заключается в учете влияния степени сцепления (N/N_f) в интерфейсе сталь-бетон, что позволяет создать аналитическую модель, способную прогнозировать дополнительные нагрузки, возникающие в результате усадки и температуры в композитных сталебетонных балках при частичном сдвиговом соединении.

Результаты: Данный подход дал лучшие результаты по сравнению с моделью, предложенной в 2024 году Рахалом и соавторами. Они недвусмысленно показывают, что степень сцепления существенно влияет на усилия, вызываемые совместным действием усадки бетона и температуры.

Вывод: Результаты настоящего подхода и результаты существующей модели, разработанной Рахалом и соавторами, не противоречат друг другу. Они наглядно показывают влияние усадки бетона и температуры в зависимости от степени сцепления N/N_f на поведение композитных сталебетонных балок.

Ключевые слова: степень сцепления (N/N_f), усадка, время, интерфейс сталь-бетон.

Утицај скупљања, температуре и степена спрезања (N/N_f) на понашање спрегнутог челично-бетонског носача

Халима Авед^а, **аутор за преписку**, Насер Рахал^{а,б}, Хауда Бегдад^а, Мухамед Садун^а, Абделаиз Соици^{а,б}, Сара Затар^б, Калед Бенмахди^а

^а Универзитет „Мустафа Стамболи“, Одсек за грађевинарство, Маскара, Народна Демократска Република Алжир

^б Универзитет природних наука и технологије, Лабораторија за машинске структуре и стабилност конструкције, Оран, Народна Демократска Република Алжир

^в Универзитет „Тахри Мохамед Бешар“, Одељење за архитектуру и урбанизам, Бешар, Народна Демократска Република Алжир

ОБЛАСТ: механика

КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Температура и ефекти зависни од времена, као што су течњење и скупљање бетона, знатно утичу на понашање спрегнутих носача од челика и бетона. Стога је неопходно узети у обзир захтеве ових додатних ефеката који су предмет различитих теоријских и нумеричких истраживања. У овој студији предлаже се аналитички алат способан да предвиди нову прераспodelу напона проузроковану комбинованим деловањем температуре и скупљања бетона у спрегнутим челично-бетонским носачима у парцијалном смичућем споју. Такође, узима се у обзир парцијални смичући спој на интерфејсу челик-бетон према степену спрезања (N/N_f).

Метод: Преформулисан је модел који су Рахал и сарадници предложили 2024. године анализирајући понашање спрегнутих челично-бетонских носача у пуном спрезању под утицајем температуре и скупљања бетона. Главни допринос ове студије представља увођење утицаја степена спрезања (N/N_f) на интерфејсу челик-бетон. Тиме се долази до аналитичког модела способног да предвиди додатна напрезања услед скупљања и температуре у спрегнутим челично-бетонским гредама у парцијалном смичућем споју.

Резултати: У односу на модел који су Рахал и сарадници предложили 2024. године, испоставило се да су резултати приступа из студије задовољавајући. Они јасно показују да степен спрезања значајно утиче на силе настале комбинованим деловањем скупљања бетона и температуре.

Закључак: Резултати наведеног приступа добро се слажу са резултатима постојећег модела који су развили Рахал и сарадници. Јасно се показује утицај скупљања бетона и температуре у функцији степена спрезања (N/N_f) на понашање спрегнутих челично-бетонских носача.

Кључне речи: степен спрезања (N/N_f), скупљање, време, интерфејс челик-бетон.

Paper received on: 02.05.2024.

Manuscript corrections submitted on: 27.01.2025.

Paper accepted for publishing on: 28.01.2025.

© 2025 The Authors. Published by Vojnotehnički glasnik / Military Technical Courier (www.vtg.mod.gov.rs, vtg.mo.ynp.spb). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/3.0/rs/>).

