Simplified formulation to evaluate forces due to shrinkage in composite steel-concrete beams with full shear connection

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doi https://doi.org/10.5937/vojtehg72-46499

FIELD: materials, civil engineering
ARTICLE TYPE: review paper

Abstract:

Introduction/purpose: It has been known for a very long time that time-dependent effects such as creep and shrinkage of concrete considerably influence the behavior of composite steel-concrete beams. It is therefore *very important to take these effects into account when calculating the strength and safety of composite steel-concrete beams. To this end, many theoretical and numerical research studies have been established to control this phenomenon. Most of this research presents laborious processes and calculations requiring complex techniques.*

Methods: This model consists of combining the static equilibrium equations and the two compatibility relations, in curvature and in deformation, of the composite steel-concrete cross-section with the differential equation resulting from the creep rate theory (RCM). The idea of this work was to take this model and simplify it to avoid difficult mathematical transformations.

Results: The results from this simplified approach are very satisfactory when compared to those given by the analytical model.

Conclusion: To overcome an excessive number of calculations and various difficulties associated with analytical or numerical methods to estimate additional stresses brought by the shrinkage of concrete in composite steel-concrete beams, a simplified analytical methodology has been proposed here while ensuring desired safety. This work has tried to simplify an existing analytical model based on the theory of linear viscoelasticity established in 2012.

Key words: shrinkage, concrete, steel, time, simplified approach.

Introduction

Due to the complementary performance of steel and concrete, composite steel-concrete beams have become a very suitable structural system for the construction of buildings and bridges. To obtain a monolithic section, shear connectors must be arranged along the beam to connect the concrete slab to the steel beam. This process will lead to a structural system with significantly improved strength, stiffness, ductility, and fire protection (Nguyen & Hjiaj, 2016). Under the application of service loads, the steel beam deforms elastically. On the other hand, the concrete slab will undergo strong inelastic deformations over time, particularly shrinkage, creep, and aging of the concrete (Si & Au, 2011).

Due to the effects of concrete shrinkage and creep on the one hand and the steel-concrete interaction on the other hand, the accurate prediction of the service behavior of composite steel-concrete beams becomes highly complex.

In order to evaluate the structural behavior of composite steel-concrete beams, it is very important to predict the effects of concrete shrinkage and creep (Sun et al, 2019). Until now, despite numerous research studies carried out in this field, these two phenomena have not been mastered yet (Marí et al, 2010).

The shrinkage of concrete is, by definition, a physical phenomenon linked to various interdependent factors such as: temperature, type of cement, humidity and transverse dimensions of the element, etc. Total shrinkage includes autonomous shrinkage, drying shrinkage and plastic shrinkage (Aly et al, 2008). It affects the time-dependent behavior and reduces the volume of the concrete element. In the long term, it can cause a deformation of concrete structures or a redistribution of internal forces. When the ultimate tensile limit of concrete is reached, the durability and serviceability of concrete members will be affected (Sun et al, 2019). Shrinkage can also cause concrete cracking (Jason Weiss, 1998). If displacement is prevented or restricted, severe cracking of a concrete structure will occur (Au et al, 2007).

With the use of the theory of linear viscoelasticity, the time-dependent effects on the behavior of composite steel-concrete beams are the subject of many analytical and numerical research studies such as: Gilbert, 1989; Partov & Kantchev, 2012, 2014; Tehami & Ramdane, 2009; Rahal et al, 2012; Souici et al, 2015; Beghdad et al, 2017; Furtak, 2015; Ranzi et al, 2013; Dunwen et al 2019; Cao et al, 2018; Al-Deen et al, 2015; Ban et al, 2015; Huang et al, 2018; Huang et al 2019ab; and others.

Presentation of the idea

Based on the theory of linear viscoelasticity, Rahal et al (Rahal et al 2012) proposed an analytical model analyzing the behavior, over time, of composite steel-concrete beams subjected to concrete shrinkage. The process consists of combining the static equilibrium equations and the two compatibility relations, in curvature and in deformation, of the composite steel-concrete cross-section with the differential (constitutive) equation resulting from the creep rate theory (RCM). In this model:

1- to obtain the variation of the normal force $N_c(t)$ and that of the bending moment $M_c(t)$ brought by the shrinkage of the concrete, which solicit the concrete slab, it is compulsory to solve the system of two differential equations below:

$$\left(1+\frac{I_c}{n I_a}\right)\frac{dM_c(t)}{d\phi}-\frac{a.(1+n\rho)I_c}{n I_a}\frac{dN_c}{d\phi}+M_c(t)=0 \qquad (1)$$

$$\left(\frac{C_C}{I_C}-\frac{C_S}{n\,I_S}\right)\frac{dM_C(t)}{d\phi}+\left(\frac{1}{A_C}+\frac{1}{n\,A_S}+\frac{C_S}{n\,I_S}a\right)(1+n\,\rho)\frac{dN_C(t)}{d\phi}+ \\ +\frac{C_C}{I_C}M_C(t)+\frac{1}{A_C}N_C(t)=E_C\,\frac{\varepsilon_{sh\infty}}{\phi_\infty} \tag{2}$$

Its solution is as follows:

$$M_c(t)=C_1.a_{1(\lambda_1)}.e^{\lambda_1.\varphi}+C_2.a_{1(\lambda_2)}e^{\lambda_2\varphi} \tag{3}$$

$$N_c(t)=C_1.a_{2(\lambda_1)}.e^{\lambda_1.\varphi}+C_2.a_{2(\lambda_2)}e^{\lambda_2\varphi}+\frac{E_c}{A_6}\frac{\varepsilon_{sh\varphi}}{\varphi_\infty} \tag{4}$$

where C_1 and C_2 will be determined from the boundary conditions, and a_1 and a_2 will be determined from the geometric and mechanical characteristics of the composite cross-section.

The forces acting on the steel beam will be obtained by the static equilibrium of the cross-section.

A_c: the cross section area of concrete in the slab.
A_s: steel beam area.
ρ: Reinforcement percentage ($\rho = A_a/A_c$).
A_a: the area of the longitudinal reinforcement incorporated in the slab.
I_c: moment of inertia of the concrete slab.
I_s: moment of inertia of the steel beam.
a: distance between the neutral axis of the steel beam and that of the reinforced concrete slab.
b_{eff}: effective width of the reinforced concrete slab.
C_c: distance from the slab centre of gravity to the neutral fibre of the mixed section.
C_s: distance from the steel beam centre of gravity to the neutral fibre of the mixed section.
E_c: the modulus of tensile elasticity of concrete.
E_s: the modulus of tensile elasticity of steel.
n: equivalence coefficient ($n = E_s/E_c$).
$\varepsilon_{sh}(t)$: the deformation due to concrete shrinkage. It can be determined using calculation codes for concrete structures such as: EC2, ACI, fib model code, etc.
$M_c(t)$: bending moment in the concrete slab due to shrinkage.
$M_s(t)$: bending moment in the steel beam.
$N_c(t)$: normal force in the concrete slab due to shrinkage.
$N_s(t)$: normal force in the steel beam.

This work seeks to significantly simplify this formulation so that it can be easily used by engineers in design offices.

Formulation of the proposed approach

Figure 1 shows the different components of the cross-section, namely: the concrete slab, the steel beam, the reinforcement embedded in the slab, and the shear connectors. For the formulation of the present approach, Figure 1 shows various forces acting on the composite cross-section.

Static equilibrium equations

At any instant t, the static equilibrium gives the following system of equations:

$$\sum F/_{x} = 0 \Rightarrow N_s(t) + N_c(t) = N_0 \tag{5}$$

$$\sum M / Gs = 0 \Rightarrow M_s(t) - N_c(t) \times a + M_c(t) = M_0 \tag{6}$$

Under the effect of concrete shrinkage, the slab can therefore be subjected to a normal tensile force on its neutral axis. Based on Hook's law, this force can be obtained by the following relation (Eurocodes, 2006):

$$N_c(t) = \frac{1}{n_L} A_c\, E_c\, \varepsilon_{sh}(t) \tag{7}$$

The relation (Eq.7) is introduced into the static equilibrium equations (Eqs.5 and 6) of the model proposed by Rahal et al (Rahal et al 2012), therefore:

$$N_s(t) = -\frac{1}{n_L} A_c\, E_c\, \varepsilon_{sh}(t) + N_0 \tag{8}$$

$$M_s(t) = \frac{1}{n_L} A_c\, E_c\, \varepsilon_{sh}(t) \times a - M_c(t) + M_0 \tag{9}$$

Since shrinkage does not depend on external loading, N_0 and M_0 are cancelled and what is obtained is:

$$N_s(t) = -\frac{1}{n_L} A_c\, E_c\, \varepsilon_{sh}(t) \tag{10}$$

$$M_s(t) = \frac{1}{n_L} A_c\, E_c\, \varepsilon_{sh}(t) \times a - M_c(t) \tag{11}$$

n_L: modular ratio for shrinkage.

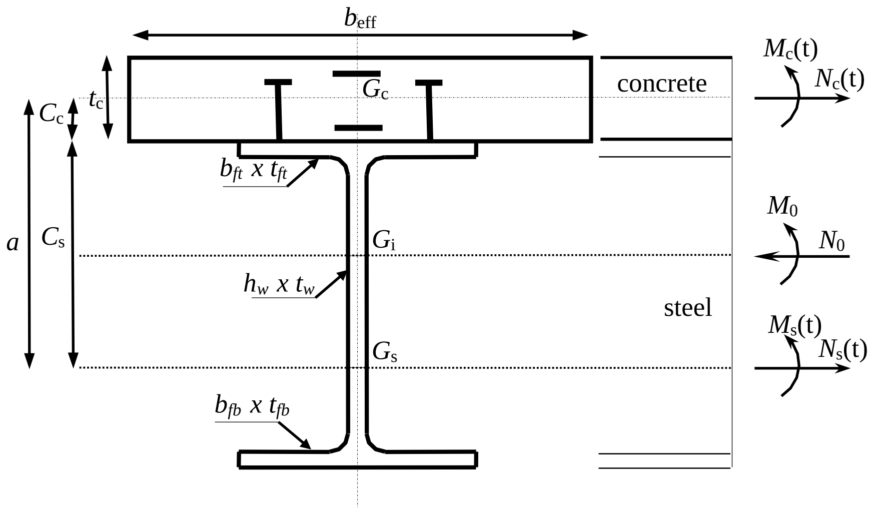

Figure 1 – Composite steel-concrete cross-section

Deformation compatibility

It is known that the curvature and the axial deformation of a beam are related to displacements by kinematic expressions (Nguyen & Hjiaj, 2016).

There are two equations (Eqs. 10 and 11) with three unknowns, $N_s(t)$, $M_c(t)$ and $M_s(t)$. From the first equation, $N_s(t)$ is obtained. It remains to find the expression of the bending moment $M_c(t)$ acting on the concrete slab and $M_s(t)$ acting on the steel beam.

To solve this problem, the compatibility of strains at the steel-concrete interface is exploited. This condition has been used by several researchers in the formulation of their models, such as: (Partov & Kantchev, 2012, 2014; Tehami & Ramdane, 2009; Rahal et al, 2012; Souici et al, 2015; Beghdad et al, 2017).

The deformation compatibility condition between steel and concrete was used by Rahal et al (Rahal et al 2012) in the model which is sought to be simplified. It translates into the following expression:

$$\varepsilon_C\left(t\right)=\frac{N_C\left(t\right)}{E_C\ A_C}+\frac{M_C\left(t\right)}{E_C\ I_C}C_C=\frac{N_S\left(t\right)}{E_S\ A_S}-\frac{M_S\left(t\right)}{E_S\ I_S}C_S \qquad (12)$$

In equation (Eq.12), Ns(t) and Ms(t) are replaced by their respective expressions (Eqs. 10 and 11); the expression of Mc(t) given by equation (Eq.13) is easily found:

$$M_c\left(t\right)=\frac{\left(A_c\,E_c\,\varepsilon_{sh}\left(t\right)\right)\left[\dfrac{a\,x\,C_s}{E_s\;I_s}+\dfrac{1}{E_s\;A_s}+\dfrac{1}{E_c\;A_c}\right]}{n_L\left[\dfrac{C_c}{E_c\;I_c}-\dfrac{C_s}{E_s\;I_s}\right]} \qquad (13)$$

Once $M_c(t)$ is known, it is very simple to calculate the expression of $M_s(t)$ by averaging the expression (Eq:11).

Validation of the proposed approach

In order to validate the presented approach, the same composite beam used by Rahal et al (2012) and Beghdad et al (2017) will be used to validate their proposed models.

This beam was also analyzed (prediction of time-dependent effects) and dimensioned in accordance with Eurocode 4 (Eurocodes, 2006). In this example, the shrinkage parameters were calculated according to Eurocode 2 (Eurocodes, 1992).

The geometric and physical characteristics of the treated example are 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, A_c = 0.785 m^2, A_s = 0.0346875 m^2, A_a = 58.47 cm^2, ρ = 0.0074, I_c = 0.004223633272 m^4 , I_s = 0.0346875 m^2, C_c = 0.375 m,C_s = 0.451 m, a= 0.826m, E_c = 33x10^4 MPa, Es =2.1x10^5 MPa, HR = 70%, Grade of concrete = C30/37, and HR: relative humidity in %.

Results

The results obtained by this approach are compared to the existing model formulated by Rahal et al (Rahal et al 2012) and presented on the diagrams in Figures 2 to 6.

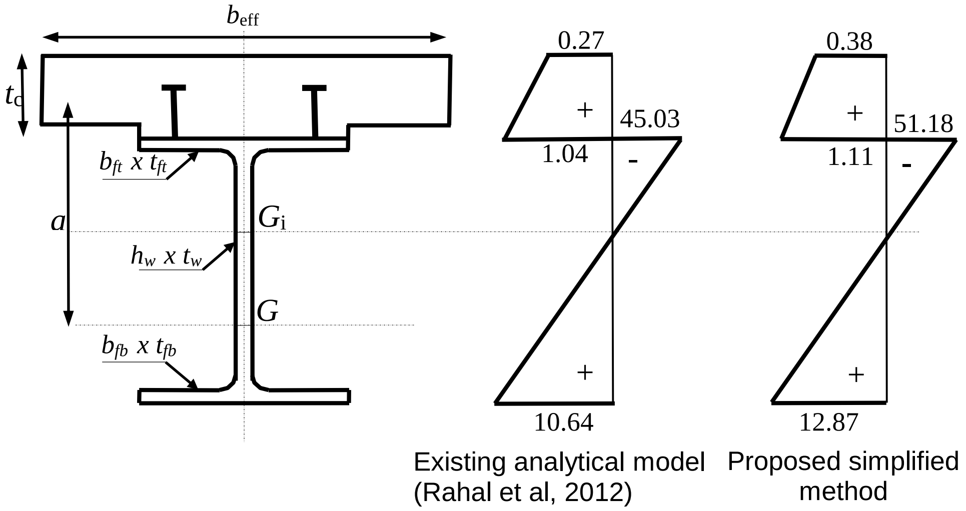

Figure 2 – Diagrams comparing the final stress (MPa) due to concrete shrinkage

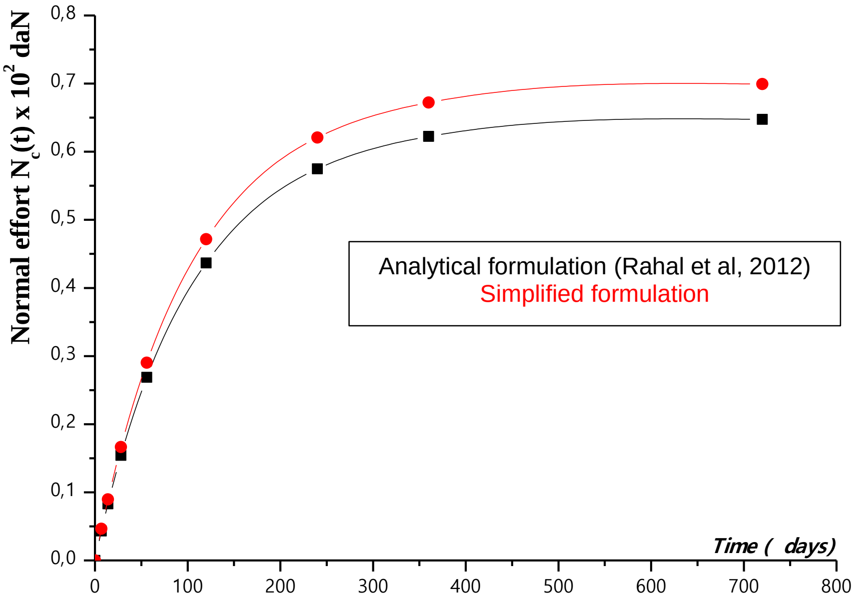

Figure 3 – Variation, in time, of the concrete slab normal effort $N_c(t)$

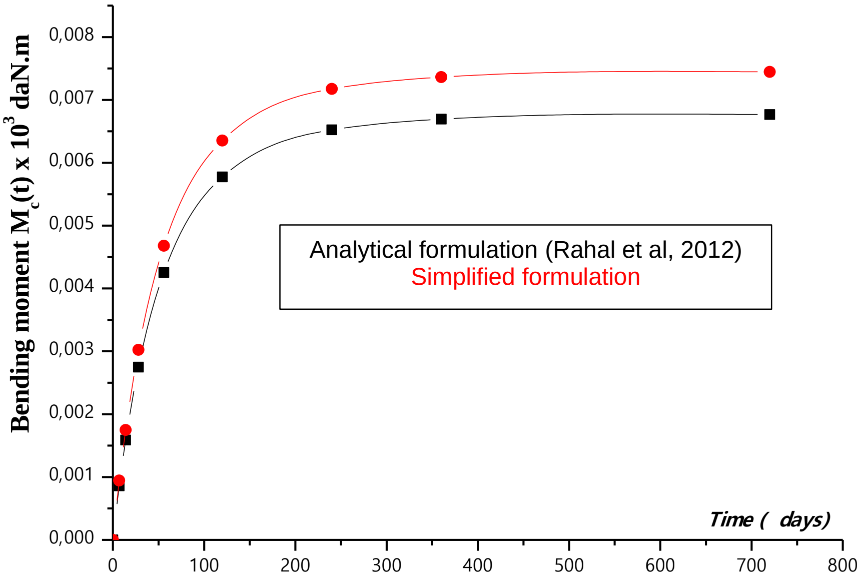

Figure 4 – Variation, in time, of the concrete slab bending moment $M_c(t)$

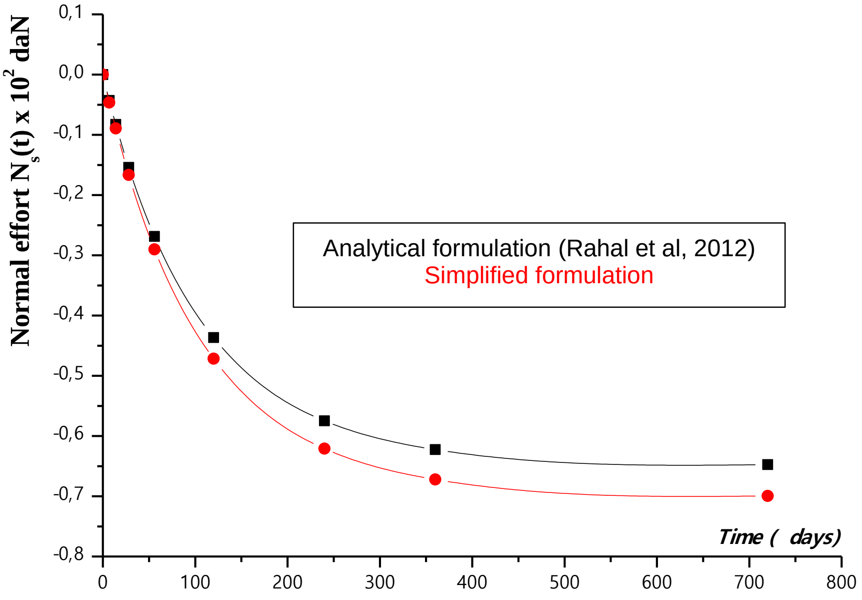

Figure 5 – Variation, in time, of the normal effort $N_s(t)$ recovered by the steel beam

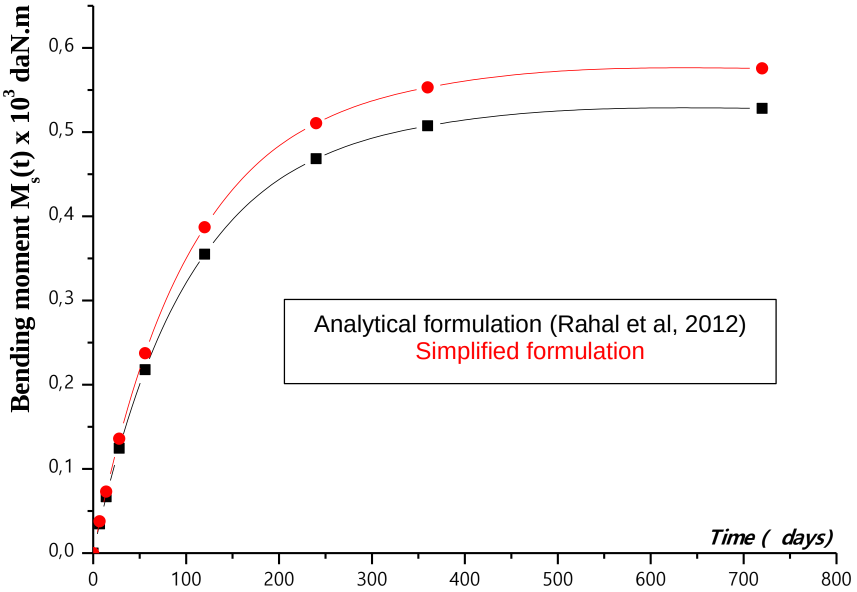

Figure 6 – Variation, in time, of the moment $M_s(t)$ recovered by the steel beam

Conclusion

The work presented in this article consists of simplifying an existing analytical model based on the aging theory of concrete. The use of the analytical model requires laborious efforts, and several constants must be calculated to determine additional stresses brought by shrinkage of concrete in composite beams. Due to these difficulties, it seemed very logical to simplify it and make it applicable with a minimum of effort while ensuring the desired security.

The approach applied here is very simple for practical use through the direct application of the developed expressions. By referring to the existing analytical model, the presented approach does not require, as the procedure shows, neither complicated mathematical calculations to be made nor constants to be determined.

The main advantage of this simplified formulation is its compatibility with any code or regulation for the calculation of composite steel-concrete structures used in the world. This possibility is clear in equation (Eq.7), in which it is enough to calculate the value of the specific deformation of the shrinkage $\varepsilon_{sh}(t)$ by the calculation regulation to be used such as: EC2, ACI, fib model code, etc.

It is clear that at any time t, the results obtained by applying the simplified approach formulated here (Figs. 2 to 6) are completely comparable to those resulting from the existing analytical model.

This idea can be further expanded to the case of composite beams in partial connection under the effect of concrete shrinkage as well as to the case of composite beams in full and partial connection under concrete creep.

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Formulación simplificada para evaluar fuerzas por contracción en vigas compuestas de acero y hormigón con conexión total a cortante

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CAMPO: materiales, ingenieria civil
TIPO DE ARTÍCULO: artículo de revisión

Resumen:

Introducción/objetivo: Se sabe desde hace mucho tiempo que los efectos dependientes del tiempo, como la fluencia y la contracción del hormigón, influyen considerablemente en el comportamiento de las vigas mixtas de acero y hormigón. Por lo tanto, es muy importante tener en cuenta estos efectos al calcular la resistencia y seguridad de las vigas mixtas de acero y hormigón. Para ello se han establecido numerosas investigaciones teóricas y numéricas para controlar este fenómeno. La mayor parte de estas investigaciones presentan procesos y cálculos laboriosos que requieren técnicas complejas.

Métodos: Este modelo consiste en combinar las ecuaciones de equilibrio estático y las dos relaciones de compatibilidad, en curvatura y en deformación, de la sección compuesta acero-hormigón con la ecuación diferencial resultante de la teoría de la velocidad de fluencia (RCM). La idea de este trabajo era tomar este modelo y simplificarlo para evitar transformaciones matemáticas difíciles.

Resultados: Los resultados de este enfoque simplificado son muy satisfactorios en comparación con los dados por el modelo analítico.

Conclusión: Para superar un número excesivo de cálculos y diversas dificultades asociadas con los métodos analíticos o numéricos para calcular las tensiones adicionales provocadas por la contracción del hormigón en vigas compuestas de acero y hormigón, se ha propuesto aquí una metodología analítica simplificada que garantiza al mismo tiempo la seguridad deseada. Este trabajo ha intentado simplificar un modelo analítico existente basado en la teoría de la viscoelasticidad lineal establecida en 2012.

Palabras claves: retracción, hormigón, acero, tiempo, enfoque simplificado.

Упрощенная формула для оценки усилий, возникающих при усадке композитных сталебетонных балок с полным поперечным соединением

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РУБРИКА ГРНТИ: 67.09.33 Бетоны. Железобетон. Строительные растворы, смеси, составы
ВИД СТАТЬИ: обзорная статья

Резюме:

Введение/цель: Давно известно, что зависящие от времени явления, такие как ползучесть и усадка бетона, существенно влияют на поведение композитных сталебетонных балок. Поэтому весьма важно учитывать эти явления при расчете прочности и безопасности композитных сталебетонных балок. Многие теоретические и численные исследования направлены на контроль этих явлений. В большинстве исследований представлены сложнейшие процессы и расчеты, которые предполагают сложную технику.

Методы: Данная модель сочетает в себе уравнения статического равновесия и два соотношения совместимости кривизны и деформации сталебетонной композитной балки в *поперечном сечении с дифференциальным уравнением, полученным из теории скорости ползучести (CRM). Цель данной статьи заключается в упрощении данной модели во избежание сложных алгебраических преобразований.*

Результаты: Результаты упрощенного подхода оказались весьма удовлетворительными, особенно по сравнению с результатами аналитической модели.

Выводы: Во избежание большого количества вычислительных операций и различных трудностей, сопровождающих аналитические или численные методы при оценке дополнительных напряжений, вызванных усадкой бетона в сталежелезобетонных композитных балках, в данной статье предлагается упрощенный аналитический метод, обеспечивающий при этом необходимую безопасность. Была предпринята попытка упростить существующую аналитическую модель, основанную на теории линейной вязкоупругости из 2012 года.

Ключевые слова: усадка, бетон, сталь, время, упрощенный подход.

Поједностављена формулација за процену сила насталих скупљањем у спрегнутим гредама од челика и бетона с потпуним смичућим спојем

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ОБЛАСТ: материјали, грађевинарство
КАТЕГОРИЈА (ТИП) ЧЛАНКА: прегледни рад

Сажетак:

Увод/циљ: Познато је да појаве зависне од времена, попут пузања и скупљања бетона, знатно утичу на понашање композитних греда од челика и бетона. Због тога је веома важно да се узму у обзир приликом израчунавања снаге и сигурности композитних греда од челика и бетона. Многа теоријска и нумеричка истраживања имају за циљ контролисање ових појава. У већини тих истраживања *заступљени су компликовани процеси и израчунавања који захтевају сложене технике.*

Методе: Овај модел комбинује једначине статичке равнотеже и две релације компатибилности, по закривљености и по деформацији, попречног пресека композитне греде од челика и бетона са диференцијалном једначином насталом као резултат теорије брзине пузања (CRM). Идеја је да се овај модел поједностави како би се избегле компликоване математичке трансформације.

Резултати: Резултати поједностављеног приступа су веома задовољавајући у поређењу са резултатима аналитичког модела.

Закључак: Да би се избегао велики број рачунских операција и различите тешкоће које прате аналитичке или нумеричке методе при процени додатног напрезања услед скупљања бетона у композитним гредама од челика и бетона, овај рад предлаже поједностављену аналитичку методологију уз обезбеђивање захтеване сигурности. Покушано је поједностављивање постојећег аналитичког модела заснованог на теорији линеарне вискоеластичности из 2012. године.

Кључне речи: скупљање, бетон, челик, време, поједностављени приступ.

Paper received on: 12.09.2023.
Manuscript corrections submitted on: 07.06.2024.
Paper accepted for publishing on: 08.06.2024.