Engineering Structures 140 (2017) 286–297

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A simplified method for predicting early-age stresses in slabs of steel-concrete composite beams in partial interaction

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ARTICLE INFO

Article history:
Received 19 February 2016
Revised 15 January 2017
Accepted 22 February 2017

Keywords:
Steel-concrete composite beams
Partial interaction
Early-age concrete
Shrinkage

ABSTRACT

Thermal effects due to the heat produced by cement reaction and shrinkage deformations affecting concrete generally results in stresses that can lead to early age cracking in the concrete slab of composite beams. This work provides a simplified approach for determining the time evolution of stresses developing at early age in curing concrete slabs of composite beams. Specifically, the method generally used in practice and based on a simple sectional analysis is extended to the case of steel-concrete composite beams in partial interaction. The time evolution of the force-slip relationship characterising the shear connector response as a result of the concrete curing process is also taken into account by means of a simple assumption corroborated by some experimental results available in the literature. The results obtained by applying the two proposed methods are compared to those achieved by means of the general practice-oriented procedure. Different types of cement, featuring a variable time evolution of the hydration process, are taken into account. Moreover, the effect of different external temperature at casting is also considered. It is worth highlighting that the proposed method enhances the predicting capability of the current practical ones, with almost no increase in calculation effort.

1. Introduction

Hydration heat and shrinkage developing in concrete at early age, in the first days after casting, are often responsible for cracking phenomena occurring in the concrete slab of steel-concrete composite beams, mainly in bridges, but also in buildings [1]. Since these processes develop during the concrete setting and hardening phases, predicting early age cracking in steel-concrete composite beams is a rather difficult task, as material properties of concrete quickly evolve in time and, hence, the actual interaction between concrete slab and steel profile is also affected by the time evolution of concrete properties [2].

Although both refined theoretical models [3,4] and phenomenological numerical approaches [5] are currently available in the scientific literature for simulating the cement hydration reaction in early age concrete and predicting the resulting heat production and temperature development in time, modelling the cracking phenomena often observed in steel-concrete composite beams should also take into account the time evolution of shear connection stiffness and strength. This aspect can be simulated numerically by employing complex Finite Element procedures [6], but, as of today, few experimental results are available in the scientific literature for validating the aforementioned numerical simulations [7].

As a matter of fact, recommendations of current design codes about this topic are often based on simplistic, and sometimes ambiguous, assumptions. For instance, EN 1994-2 [8][9] states that short term elastic modulus and 20 K temperature difference between concrete slab and steel beam should be considered. Conversely, SETRA Guidance book for Eurocodes 3 and 4 [10] reduces the temperature difference to 10 K, but it gives no precise indication on the elastic modulus to be used.

However, it is worth highlighting that both recommendations assume complete shear interaction (namely, no interface slip occurrence) between concrete slab and steel profile from the very beginning of the setting and hardening phases: this is clearly inconsistent with both the common sense and the aforementioned experimental results obtained on shear connectors in curing concrete [7]. Therefore, further efforts are needed for taking into account the actual time evolution of shear interaction degree at early age of concrete.

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http://dx.doi.org/10.1016/j.engstruct.2017.02.058
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Analytical and numerical models capable to manage short- and long-term response of composite beams in partial interaction are available in literature [11–18]. Models taking into account uplift effect at the end of the beam are also proposed [19,20]. However, those models consider the evolution of creep and shrinkage deformations only, while neglecting time variability of connection stiffness. This aspect is not relevant when concrete mechanical properties are completely developed, but it acquires importance when early-age concrete phenomena are considered.

In bridge design, "young" concrete behaviour could be considered in order to define casting strategies aimed at limiting the development of cracks due to early-age endogenous deformations [21]. However, in this case the role of partial interaction is not taken into account.

This work aims at formulating a model capable to simulate the behaviour of concrete at early age in composite beams, taking into account all the aforementioned relevant phenomena, albeit in a reasonably simplified manner. In the proposed formulation, the time evolution of both relevant concrete properties (i.e. tensile and compressive strength, Young modulus, linear creep and shrinkage) and temperature resulting from the exothermic nature of the cement hydration reaction are determined by means of an accurate multiphysics model [22]. This type of models are often employed for determining the temperature development in massive concrete elements [23], but can also be utilised in predicting the hydration heat reaction and the resulting time evolution of temperatures within the slab of steel-concrete composite beams [24].

These information are first employed for determining the time evolution of stresses within the concrete slab, by means of a practice-oriented methodology based on assuming complete shear interaction between concrete slab and steel profile, as generally accepted by codes and guidelines [9,10]. Then, an extension of the well-known Newmark's theory of steel-concrete composite beams in partial interaction [25] is considered for simulating the effect of interface relative displacements (slips) between the two connected parts of the composite beam. Specifically, the effects of shrinkage and, similarly, the consequences of thermal distortion developing in the concrete slab are included in this extension [26]. Moreover, the time variation of the interface shear stiffness is taken into account in an incremental application of the analytical solutions that can be derived by the scientific literature: this incremental solution scheme can also take into account the effect of creep on the resulting concrete behaviour [27]. All the analyses are referred to a steel-concrete composite beam assumed as a case-study described in the fourth section of the paper.

2. Shrinkage and thermal effects on composite beams

2.1. Time development of temperature

Shrinkage and thermal effects induced in concrete at early age as a result of the cement hydration reaction can be determined through advanced theoretical models capable of taking into account the effect of relevant factors, such as the type of cement (and, particularly, its reaction rate in adiabatic conditions) and the external ambient [22]: Fig. 1 reports relevant examples of typical time development of temperature simulated in concrete slab during the first six days of curing.

2.2. Early age properties of concrete

As it is well-known, the mechanical properties of concrete evolve in time during the cement hydration process. Model Code 2010 [27] proposes the following formulation describing the evolution of compressive strength f_{cm} and modulus of elasticity E_{cm}:

$$f_{cm}(t) = \beta_{cc}(t) \cdot f_{cm}(28) \quad (1)$$

$$E_{cm}(t) = [\beta_{cc}(t)]^{0.5} \cdot E_{cm}(28) \quad (2)$$

where $f_{cm}(28)$ and $E_{cm}(28)$ are the values of the two mechanical quantities at 28 days of curing and the function $\beta_{cc}(t)$ is expressed as follows:

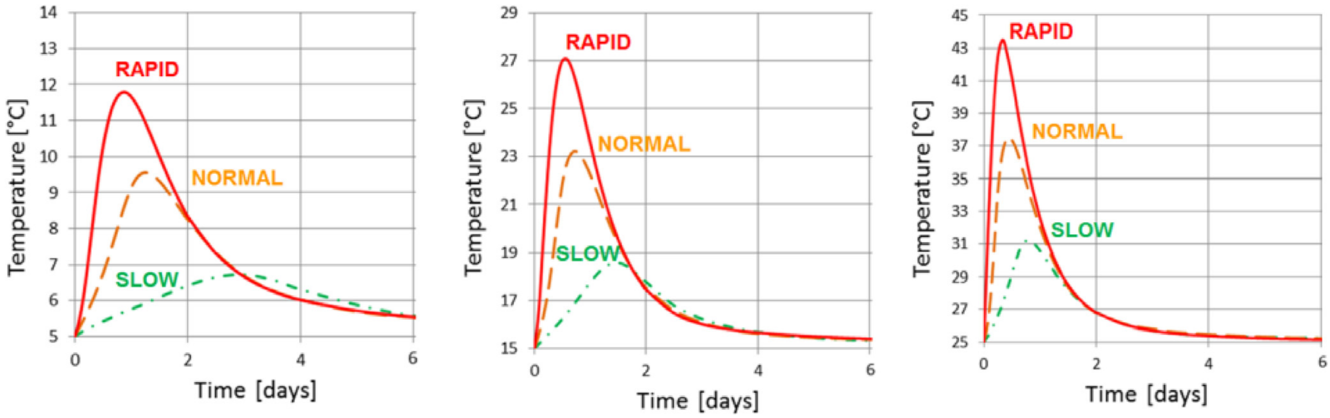
$$\beta_{cc}(t) = \exp\left\{ s \cdot \left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\} \quad (3)$$

The parameter s depends on the type of cement and the rate of its hydration reaction [27]. These formulations are not reliable in the very early age state (i.e.in the first 2 days of curing): possible empirical extensions are available in the literature for covering the whole hardening stage, from concreting time [24].

Moreover, the time development of shrinkage can be predicted through advanced theoretical models capable of simulating hydration reactions in concrete [4]. However, in the following, the time evolution of the imposed axial deformation of the slab due to shrinkage is simply denoted as $\varepsilon_S(t)$.

2.3. Modelling the interaction of shrinkage, thermal effects and creep: the classical Colonnetti method

Thermal effect and shrinkage trigger a viscoelastic response of the concrete. Due to the high thermal conductivity of steel, it is



a) T_{amb}= 5°C b) T_{amb}= 15°C c) T_{amb}= 25°C

Fig. 1. Time evolution of maximum temperature in bridge slab under isothermal boundary conditions at different ambient temperature.