Effects of concrete hydration on composite bridges

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Summary

A detailed study of the causes of transverse cracking in concrete slabs of composite bridges has been carried out in order to understand better the most important parameters which reduce the effective tensile strength of deck slabs. Site measurements and laboratory tests have enabled the behaviour of concrete slabs to be followed from the moment they were placed. The results of measurements have demonstrated the important influence of concrete hydration on the tensile stress in the slab. A criterion for evaluating the risk of cracking in young concrete has been established on the basis of subsequent numerical simulations.

1. Introduction

Over the past 15 years, steel-concrete composite bridge construction in Switzerland and its neighbouring countries has evolved with a view to reducing labour costs at the expense of increasing the quantity of steel. For example, thicker steel webs are used in order to reduce the number of stiffeners to a minimum. Deck slabs are now placed without special provisions using travelling formwork and allowing composite action to be initiated at the time of concrete setting. In such bridges, transverse cracks often develop shortly after casting the deck slab, in particular at or near to internal supports. These cracks are normally between 0.1 and 0.2 mm wide, and are therefore not easily visible unless water has passed through them before the application of a waterproof membrane, in which case deposits can be visible on the deck soffit. Raising then lowering supports in order to introduce compression in the slab over supports after casting is used in some cases and longitudinal post-tensioning is often considered to be too expensive. The alternative is to increase the quantity of reinforcement over internal supports.

The importance of these transverse cracks is open to discussion. The structural safety is in no way compromised; even much wider cracks would not lead to significant damage to the main beams. It is interesting to note that in European countries, cracks of the order of 0.2 mm wide are allowed even in humid environments with the presence of de-icing salts. This is possible due to the use of well detailed waterproofing systems which are carefully installed and subsequently ensure the durability of a structure. However, there is a need to understand better the causes of these transversal cracks in order to be able to develop methods to reduce them. It is therefore concluded that there is a need to study the behaviour of concrete deck slabs from the moment the concrete is placed [1]. Similar research carried out in France also points to this stage of construction as being of interest [2].

2. Behaviour of young concrete

In order to study phenomena associated with young concrete in the case of deck slabs, it is important to understand the behaviour of concrete during hydration. The following can be observed [3,4]:

- An increase in temperature of between 15 and 30 °C during the first 12 to 25 hours followed by a cooling period of between 180 and 150 hours. These values vary as a function of the type of concrete, the slab geometry, the ambient temperature and the curing conditions.
- The development of the mechanical properties of the concrete as a function of the degree of hydration $\alpha(t)$ (= total heat produced up to time t / total heat that will ever be produced). The main point to note is that the elastic modulus is not the same during the heating and cooling periods.

If the deck slab and steel beams act compositely from the moment that the concrete is poured, then this composite action prevents the expansion of the concrete during the heating period as well as its contraction during the cooling period. This restraint can be represented by the ratio β of the cross sectional areas of the steel beams A_a and the concrete slab A_c :

$$\beta = \frac{A_a}{A_c} \qquad (1)$$

The restraining action of the steel beams on the concrete slab can be modelled by simply assuming constant but different values for the elastic modulus of the concrete during the heating and cooling periods. For the structural system illustrated in Figure 1, the concrete slab at Section 2 is in compression during the heating period and passes into traction during the cooling period. A resultant tensile stress remains in the slab at the end of the cooling period due to the difference between the two values of elastic modulus [5]. For the case shown in Figure 1, the resultant tensile stress in the deck slab at the internal support is between 0.9 and 1.5 N/mm^2, which is significant when compared to the tensile strength of young concrete.

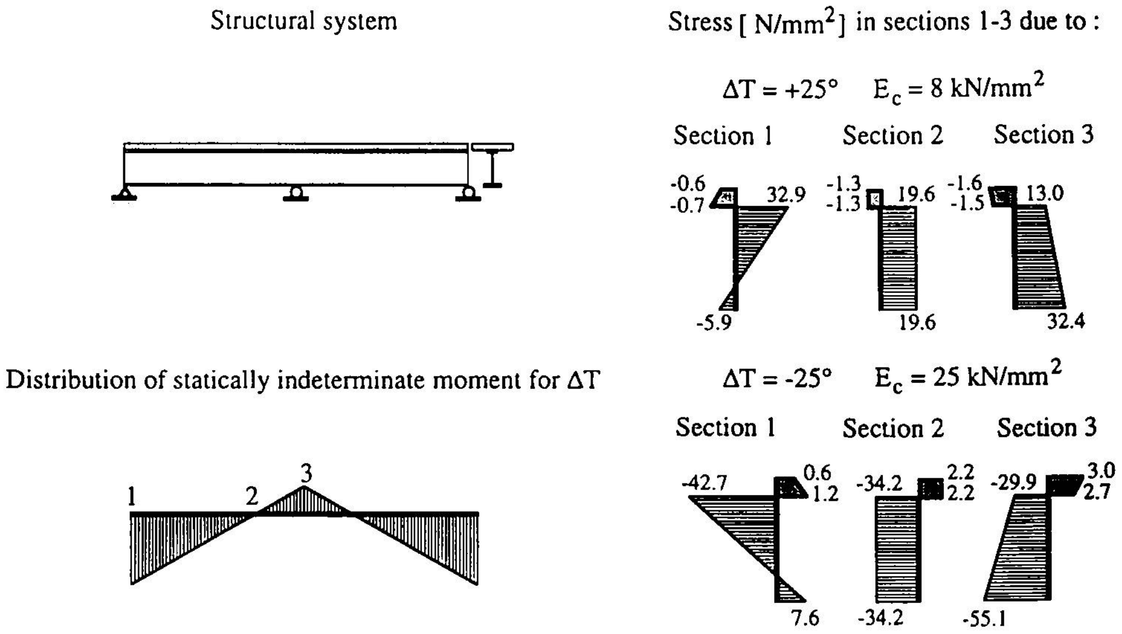

Figure 1 : Stresses in a composite section during concrete hydration : (a) heating period, (b) cooling period

3. Measurement results and numerical simulations

3.1 Site measurements

Site measurements have been made during the construction of a number of continuous composite bridges (typical span around 50 m) in Switzerland, two of which are illustrated in Figure 2 [6]. These measurements have demonstrated the following :

- The evolution of the temperature of standard types of concrete used for bridge construction in Switzerland is as expected (temperature increase between 15-25 °C) in both summer (Figure 3a) and winter (Figure 3b) conditions, with delayed hydration during winter.

- The stresses measured in steel beams are different before and after concrete hydration, indicating the presence of resultant stresses in both the beams and the concrete slab (Figures 4 a and b).
- The use of optical fibre sensors (OF) and vibrating wire strain gauges has enabled the expansion and contraction of the concrete to be measured qualitatively and quantitatively (Figures 5 a and b).

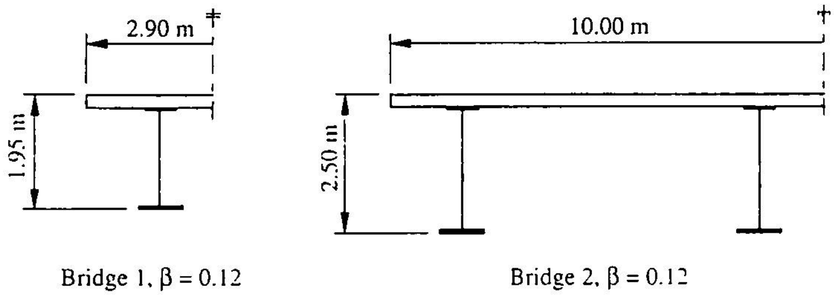

Figure 2 : Typical bridge cross sections

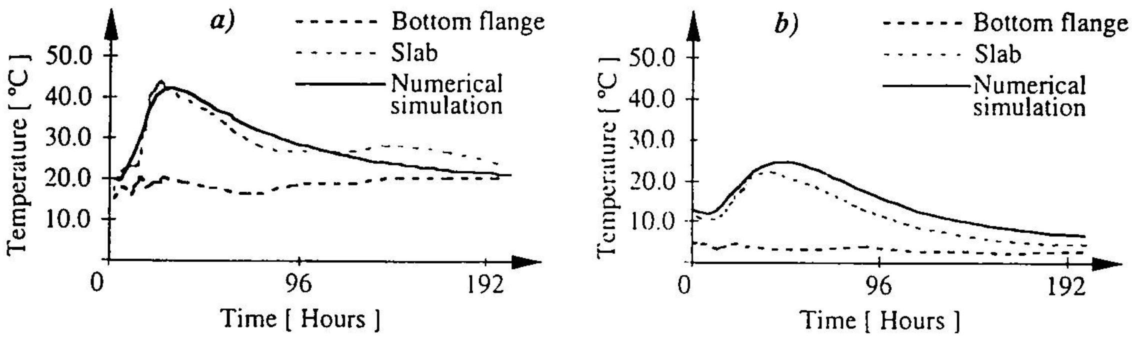

Figure 3 : Temperature evolution : a) Bridge 1, b) Bridge 2

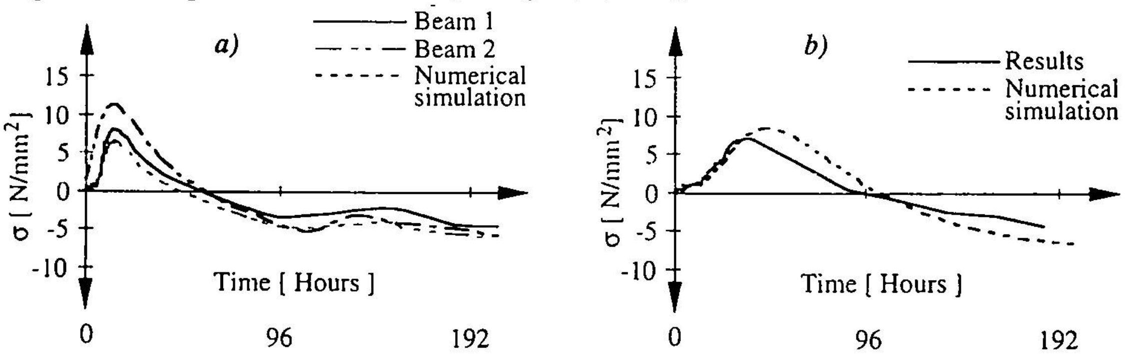

Figure 4 : Stresses in steel beam bottom flanges : a) Bridge 1, b) Bridge 2

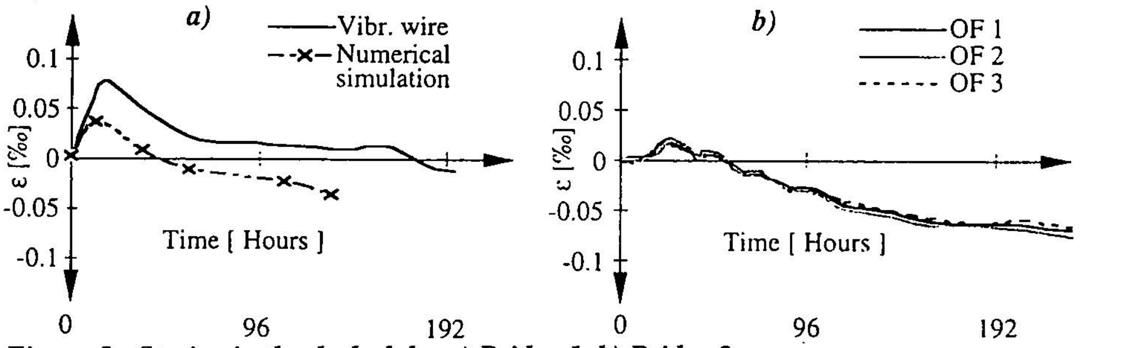

Figure 5 : Strains in the deck slab : a) Bridge 1, b) Bridge 2

The β values for the two bridges shown in Figure 2 are relatively high and in both cases cracks between 0.1 and 0.15 mm wide were visible within ten days after concrete placement. This indicates that the residual tensile stresses due to concrete hydration were very close to the tensile strength of the concrete.

3.2 Simulation procedure

The results of numerical simulations illustrated in Figures 4 (a) and 5 (a) were calculated using the computer programme DIANA (TNO). The results shown in other figures were calculated using INTRON (Dr. P. Roelfstra). The evolution of temperature is relatively simple to model, but the stresses in the steel beams and in the deck slab are strongly dependent on the mechanical behaviour of young concrete and in particular its creep. In order to interpret the site measurements correctly, the following approach was adopted :

- Definition of the relevant physical laws and simulation of the temperature evolution.
- Verification of the simulated stresses in the steel beams with respect to measured values.
- Model validation by comparing simulated strains in the deck slab to strain measurements.
- Calculation of stresses in the deck slab.

This approach treats the steel beams as load cells and has enabled the INTRON numerical model to be verified as well as qualitative and quantitative evaluations of the residual stresses in the concrete deck slab.

3.3 Laboratory tests

Laboratory tests have been carried out in the second half of 1996 in order to investigate the predominant influence of the ratio β on the residual tensile stresses resulting from concrete hydration. Tests were carried on three 8.6m long composite beams (Figure 6) which had different steel sections (β =0.05, 0.08 et 0.11) but were otherwise identical (constant slab geometry, concrete grade/mix and reinforcement).

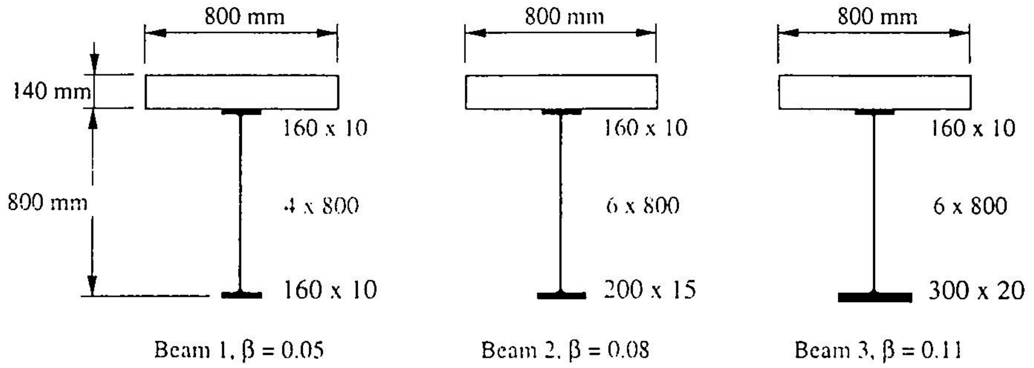

Figure 6 : Geometry of tested beams

Deck slabs were insulated in order to reproduce the temperature evolution measured on site and to ensure that test results were representative of typical bridge construction. Measurements were made continually from the moment that concrete was placed.

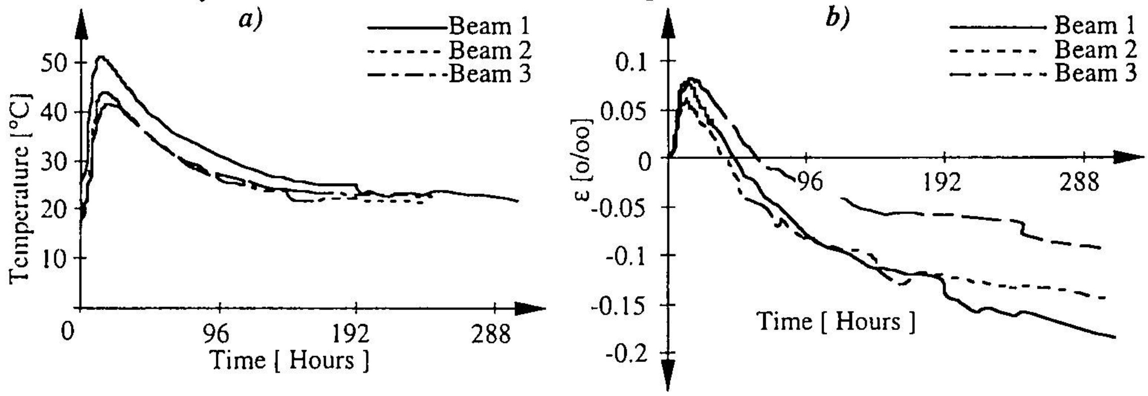

Figure 7 : Laboratory test results : a) Temperature evolution b) Strains in the deck slab.

Figure 7 (a) shows the measured temperature evolution, which was similar to that observed on site. The evolution of strains shown in Figure 7 (b) highlights the importance of the ratio β with respect to the effects of hydration. The strain measurements demonstrate that the restraint provided by the steel beam increases with its rigidity represented by the ratio β.

Service load tests at 28 days allowed the residual tensile strength of the concrete slab to be estimated. The three tests have shown that the residual tensile stress in the concrete slab after hydration is :

- 0.5-0.8 N/mm^2 for a section with a β value of 0.05,
- 1.0-1.4 N/mm^2 for a section with a β value of 0.08,
- 1.4-1.8 N/mm^2 for a section with a β value of 0.11.

4. Parametric study and simplified approach

A parametric study based on the approach described in Section 3.2 has illustrated the importance of restraint provided by the steel beams with respect to the resultant tensile stress in the concrete deck slab. Using INTRON, numerical simulations of bridges having different cross-sectional dimensions have enabled the influence of β on the evolution of stresses in the deck slab during hydration to be quantified, as illustrated in Figure 8.

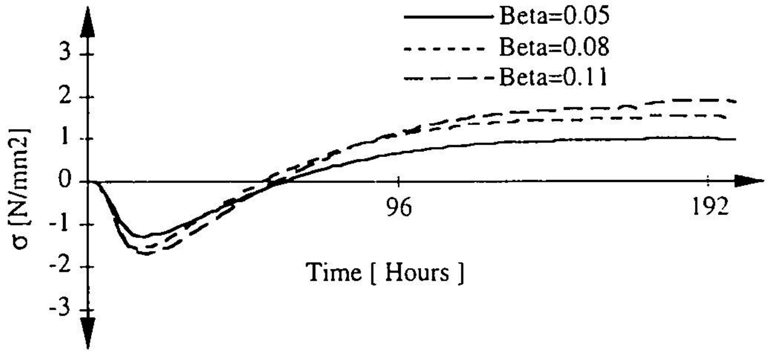

Figure 8 : Evolution of stresses in the deck slab as a function of β

The results shown in Figure 8 illustrate the following points :

- The restraint coefficient β is determinant for the residual stress in the deck slab.
- Typical values of β for the Swiss twin-beam composite bridges (between 0.05 and 0.12) suggest residual stresses of between 0.5 and 1.5 N/mm^2 which corresponds to the results obtained in the laboratory.

In order to avoid the need for complex numerical analyses, a simplified method has been developed. The relationship between residual tensile stress and β can be expressed by Equation (2). This equation is derived from the equilibrium of axial forces within a section and is based on the results of site measurements, laboratory tests and numerical simulations.

$$\sigma_c = \frac{\alpha \cdot \beta^2 \cdot \Delta T \cdot E_s^2 \cdot (E_{c2} - E_{c1})}{(\beta \cdot E_s + E_{c2}) \cdot (\beta \cdot E_s + E_{c1})} \tag{2}$$

σ_c residual tensile stress in the concrete,
α coefficient of thermal expansion of the concrete,
β restraint coefficient defined as the cross-sectional area of the steel beams divided by the cross-sectional area of the concrete slab,
ΔT maximum difference between ambient and concrete temperature during hydration,
E_s elastic modulus of steel,
E_{c1} mean elastic modulus of concrete during the heating period,
E_{c2} mean elastic modulus of concrete during the cooling period.

The following default values for parameters may be used in the absence of other information :

- E_{c1} = 6 kN/mm^2,

- $E_{c2} = 25$ kN/mm^2,
- $\alpha = 1 \cdot 10^{-5}$ K^{-1},
- $\Delta T = 25$ °C.

Based on the results presented above, a qualitative evaluation of the influence of β on the effects of concrete hydration has led to the following observations :

- $\beta \leq 0.05$ limited influence of hydration effects on early cracking,
- $0.05 < \beta \leq 0.08$ hydration effects reduce the tensile strength f_{ctm}, limited risk of early cracking,
- $0.08 < \beta \leq 0.12$ hydration effects reduce the tensile strength, early cracking is probable, actions for reducing residual tensile stresses should be considered,
- $\beta > 0.12$ hydration effects significantly reduce the tensile strength, high risk of early cracking, actions for reducing residual tensile stresses should be adopted.

The residual tensile stress σ_c can be calculated using the Equation (2). The effective tensile strength of concrete $f_{ct,eff}$ should then be adopted in subsequent calculations, in particular when considering the stiffness of the composite section, but excepting the determination of minimum reinforcement for limiting concrete cracking. The value of $f_{ct,eff}$ is given by :

$$f_{ct,eff} = f_{ctm} - \sigma_c$$

The measures mentioned above for limiting the effects of hydration are aimed at reducing the difference between the temperature of the concrete slab and that of the steel beams. This could be achieved for example by using a low-heat cement or by cooling the concrete before or during curing.

5. Conclusions

The effect of concrete hydration in a deck slab which is directly linked to steel beams in a composite bridge has been studied with the aid of site and laboratory tests. A numerical model has been validated using the results of theses tests and has subsequently been used to demonstrate the importance of the restraint coefficient β with respect to the residual tensile stress due to concrete hydration in the deck slab.
Criteria based on the restraint coefficient have been established which define the effects of concrete hydration as a function of the bridge. Furthermore, a simplified method has been developed for evaluating the residual tensile stress due to concrete hydration in the deck slabs.

6. References

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