Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 999 (1997)

Artikel: Cracking and durability of concrete slabs of composite bridges
Autor: Ernens, Michel / Cremer, Jean-Marie / Dotreppe, Jean-Claude
DOI: https://doi.org/10.5169/seals-966

Cracking and Durability of Concrete Slabs of Composite Bridges

Michel ERNENS
Civil Eng.
University of Liège
Liège, Belgium

Jean-Claude DOTREPPE
Dr. Eng.
University of Liège
Liège, Belgium

Jean-Marie CREMER
Civil Eng.
Greisch Consulting
Liège, Belgium

Alain LOTHAIRE
Civil Eng.
Greisch Consulting
Liège, Belgium

Summary

The performance of composite steel-concrete bridges during their full service life is essentially conditioned by the durability of the concrete slab. This article presents a brief survey of the causes of the degradation processes, the influence of crack opening and the various actions leading to cracking of the slab. In case there is some doubt about the water - tightness of the membrane a satisfactory performance during a sufficiently long period can only be ensured by prestressing of the slab, but several parameters have to be assessed carefully and some questions still remain open.

1. Introduction

Composite steel-concrete constructions are presently widely used, particularly in the field of continuous bridges where they appear quite competitive. Solutions have been brought to many structural problems, but less attention has been paid to the performance of these bridges during their full service life[1], conditioned by the durability of the concrete slab.

The paper presents first a brief survey of the causes of deterioration of the concrete deck. The influence of the crack opening on the corrosion of reinforcing steels is then analysed. Crack openings ranging from 0 to 0.3 or 0.4 mm are now considered as acceptable for a satisfactory performance, but during a period of time which is presently unknown[2].

The first essential protection consists in using a waterproof membrane of good quality placed on a concrete with very low permeability.

If there is some doubt about the quality of the membrane, a satisfactory performance during a sufficiently long period of time can only be ensured by prestressing of the slab. In order to determine the amount of prestressing to be introduced, the various actions leading to cracking are examined and the results of a practical example presented. Several quantities such as the tensile stresses and the loss of prestress during the service life have to be assessed carefully. The question whether crack openings under some variable loads can be accepted has not received sufficient attention.

2. Causes of degradation processes in the concrete slab

To build a durable construction implies that this construction does not necessitate important rehabilitation and renovation works, which become necessary in order to avoid that safety can be reduced substantially with respect to ultimate limit states or that serviceability limit states are no longer fulfilled.

The service life of constructions, and more particularly here of bridges, must also be defined. It is presently agreed that this period of time is situated between 50 and 100 years. A duration of 50 years appears to be non economical, while a duration of 100 years seems too long due to the evolution of the traffic needs. Therefore 80 years is presently considered as an optimum service life for most bridges.

In order to determine the durability of a concrete element, and more particularly of the concrete deck of a composite bridge, it is necessary to define the possible deterioration processes and their governing factor. The slab contains concrete and reinforcing steel and both materials must be durable, as the deterioration of one of them leads to the deterioration of the other and to insufficient serviceability or resistance.

In nearly all chemical and physical processes influencing the durability of concrete structures, two dominant factors are involved : transport within the pores and cracks, and water. More particularly, in the case of the concrete deck of a bridge the following factors have to be considered : freezing and thawing cycles, effects of deicing salts, penetration of chemically aggressive agents, alkali-silica reaction[3].

The mechanisms of corrosion must also be examined carefully. This is the most critical degradation process, as it can lead to collapse of the element. Corrosion is mainly due to carbonation of concrete in relation with penetration of CO_2, and to penetration of chloride ions originating from deicing salts.

Considering all the degradation processes of a concrete deck, it appears that appropriate durability cannot be ensured easily, as the concrete slab is submitted to severe environmental conditions. The major factors in connection with durability are the water-tightness of the membrane and the quality of concrete. In relation with this characteristic the following parameters must be examined carefully : W/C ratio, type of aggregate, cement type, cement content, admixtures, handling and placing, curing.

3. Concrete cracking

3.1 Corrosion process

Steel in concrete is protected against corrosion by passivation due to the alkalinity of concrete. In such an environment the corrosion rate is insignificantly low. The passivity of steel may be destroyed by the carbonation of concrete surrounding the reinforcement and by the penetration of chlorides through the pores. For passive or active reinforcement situated near the top or the centre of the concrete slab of a composite bridge the penetration of the chloride ions is the prevailing action.

On the basis of theoretical and experimental studies a model[4] has been proposed which allows one to better understand the corrosion process in a reinforced concrete element and therefore the influence of the propagation of the chloride ions. Two stages can be distinguished (Fig.1) :

- the initiation period, during which the metal, having been embedded in concrete remains passive whilst, within the concrete, environmental changes are taking place that ultimately lead to depassivation ;
- the corrosion period, which begins at the moment of depassivation and involves the propagation of corrosion at a significant rate until a final state is reached, when the structure is no longer considered acceptable regarding structural integrity, serviceability or appearance.

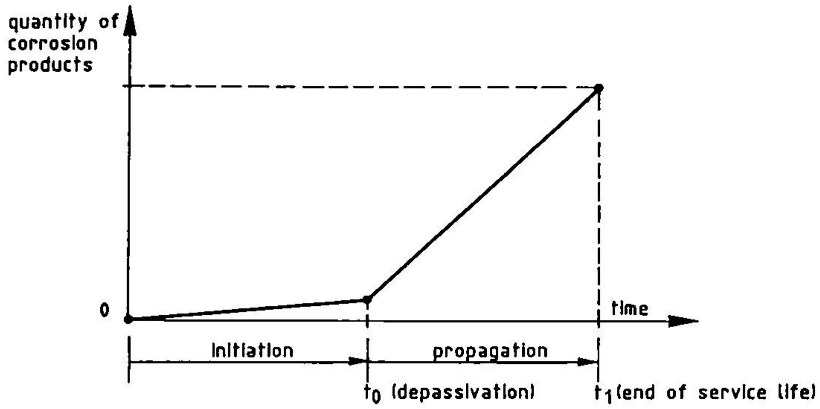

Fig. 1 : Schematic representation of corrosion process

The corrosion process may result in a reduction of cross-section of the reinforcement : the load-bearing capacity of the steel decreases, but ductility and fatigue strength are reduced more substantially. Splitting of the concrete cover may also occur. Rust has a substantially higher volume than steel, which causes cracking and spalling. This may lead to sudden failure, if longitudinal cracking along the bar occurs in the region of the bar anchorages. These unacceptable damages usually correspond to the service life of the element (time t_1 in Fig.1).

For the design engineer two possibilities can be envisaged :
- t_o > expected service life : this solution is quite safe, since any depassivation of steel is avoided ;
- t_1 > expected service life : the safety level is not known precisely, as it is difficult to assess the propagation period due to the number of parameters involved.

3.2 Influence of cracks on the corrosion development

There has been a considerable evolution regarding the problem of the influence of the crack width on the durability of concrete. Twenty years before it was admitted that this parameter had a significant effect on the corrosion process. The observation of existing constructions and laboratory tests have shown that there is no direct relation between the crack widths and the degree of corrosion provided they remain smaller than 0.4 mm.

However the existence of cracks, even with a small width (0.1 mm), does influence significantly the corrosion process. It has been shown that the diffusion of chloride ions is ten times more rapid in a cracked than in an uncracked concrete[5]. This means that the initiation period will be approximately ten times longer in an uncracked material compared with a cracked one, provided that in both cases the permeability of the material is low and concrete cover is sufficient. Therefore in an uncracked concrete, t_o will be large enough to prevent the steel from reaching the propagation stage during the service life. If concrete is cracked, t_o is small with respect to the service life, and t_1 becomes the critical parameter with much more uncertainty regarding structural safety.

3.3 Development of cracking in the concrete deck

Cracks can be classified in various ways. We shall consider here the time of appearance. Cracks due to chemical effects such as corrosion and alkali reaction will not be considered ; only cracks due to thermal, physical and structural effects are envisaged.

Early cracks (before hardening) are due to plastic settlement and plastic shrinkage. These two phenomenons may induce important cracking but preventive measures can be adopted in order to avoid them.

After hardening there exists at least five causes of cracking under service conditions : external loads, creep, drying shrinkage, external temperature variation (daily and seasonal) and thermal shrinkage (appearing very early after concreting of the slab).

In order to evaluate the tensile stresses and cracking state that may occur in the slab, the example of a classical composite continuous bridge with two spans has been analysed. The stress distribution has been calculated precisely using the computer code SAFIR developed at the University of Liège[6]. For the assessment of the thermal stresses due to external temperature variation, the recommendations presented in reference[7] have been adopted.

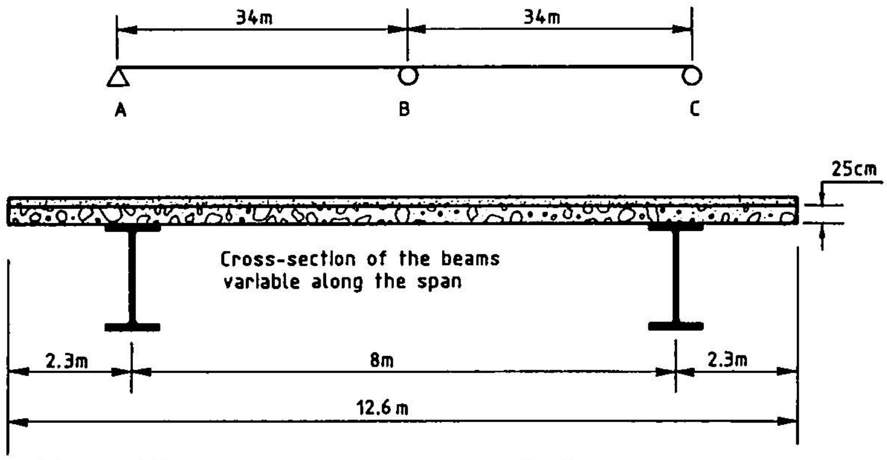

Fig. 2 : Classical composite continuous bridge with two spans

Tensile stresses (MPa)	Upper fiber		Lower fiber	
	perm.	perm. + var	perm.	perm. + var
Mid-span	(1) 1.2	(2) 2.5	(1) 1.7	(2) 2.2
Support	(1) 5.1	(3) 7.8	(1) 4.1	(3) 5.3

(1) : permanent loads + thermal shrinkage + drying shrinkage
(2) : (1) + external temperature variation
(3) : (1) + variable loads + external temperature variation

Table 1 : Tensile stresses in the concrete slab under service conditions

Table 1 shows the maximum tensile stresses under permanent and permanent+variable conditions. It can be seen that tensile stresses are present in the slab during the whole life even at mid-span. Cracking may occur both near supports and at mid-span. These considerations are in agreement with the calculations presented in reference[8].

4. Reinforcement and prestressing of the slab

The classical solution consists in designing the slab with passive reinforcement. In this case cracks will open and it is impossible to limit their width to values < 0.1 mm. Usually suitable detailing regarding the diameter of the bars and their placing in the slab is adopted in order to limit the crack width to 0.15 or 0.2 mm. As it is now acknowledged that crack widths up to 0.4 mm can develop in the slab, would this mean that such a careful detailing for the reinforcement is no longer necessary ? We think it would not be wise to do so. Nowadays many bridges are subjected to very heavy traffic loads. Though very few studies have been devoted to this problem, crack widths may tend to increase, due to progressive deterioration of bond at the boundaries of the crack.

As already mentioned other detailing characteristics such as waterproof membranes and joints are essential, but they are not discussed here.

Despite all precautions taken deicing salts will cause chloride ions to penetrate in concrete. As the slab is cracked the rate of penetration is very high and depassivation will occur quickly. According to the model of Fig.1 the durability is controlled by the corrosion development. In these circumstances, as soon as water - tightness is no longer ensured, it does not seem possible to expect a service life of 80 years. Values situated between 20 and 40 years are sometimes mentioned, but this has to be confirmed by additional research studies.

The only way of improving noticeably the durability of the slab is then to apply prestressing. The beneficial effect of transversal prestressing is well-known [1,8], but in this article we will consider more particularly the problem of longitudinal prestressing.

Several factors have to be examined carefully. The first one is the economy of the project as, regarding the structural behaviour no prestressing. is necessary ; it is introduced only for durability purposes.

The second one is the difficulty of calculating the stresses induced by prestressing in the slab. The efficiency of prestressing is reduced by the composite interaction and by the classical time-dependent losses due to creep, shrinkage and relaxation.

The type of prestressing must also be examined carefully. Several procedures are used[8] : prestressing by jacking supports, prestressing the slab and steel section by a longitudinal cable situated in the slab, prestressing the slab only before composite action, use of external cables. These various methods will not be discussed here. Each of them has its advantages and drawbacks.

We shall focuse here a little bit more on the problem of the amount of prestress to be introduced in the slab in order to ensure sufficient durability for a service life of approximately 80 years. This question is a difficult one and so far it has not received enough attention.

The minimum value should be such that under actions existing at any time, i.e. permanent loads including creep, drying shrinkage and thermal shrinkage no crack would occur. In this situation cracks will open under variable actions such as traffic loads and variation of external temperature.

In our opinion this type of design can be unsafe, as cracks may be present during rather long periods. In this case heavy traffic loads can cause fatigue effects leading to a progressive increase of the crack width. After a certain time some cracks may remain permanently open.

Design with full prestressing (no crack at any time) seems more appropriate, though it may be difficult to introduce such a high level of prestress for technical and economical reasons. For the example described in Fig.2, it has been calculated that a compressive stress of approximately 5.5 N/mm^2 should be introduced in the slab in order to fulfil this condition.

5. Conclusions

The following conclusions can be drawn from this research study.

1. In order to obtain adequate durability of the concrete slab of a composite bridge, the first requirement is to place a waterproof membrane of good quality, to use a concrete with good mechanical characteristics and very low permeability, and to provide sufficient concrete cover.

2. The use of passive reinforcement is the classical solution. Despite the recent studies on the influence of crack widths, adequate detailing regarding the diameter and the placing of the bars should still be recommended, as the crack width may tend to increase due to heavy traffic loads inducing fatigue effects.
   According to the model described here for the corrosion process, depassivation will arrive rather quickly and durability will be controlled by the corrosion development. This leads to uncertainty regarding service life. Additional research studies and observations on existing bridges should be performed.

3. Prestressing can be used to improve the durability of the slab. The amount of longitudinal prestress to be introduced has been discussed in this paper. Full prestressing is not economical but on the other hand, to allow crack development for all variable loads may be unsafe due to fatigue effects. Again additional research on this matter should be performed.

References

1. JOHNSON R.P. and BUCKBY R.J. *Composite structures of steel and concrete - Volume 2 : Bridges.* Second Edition, Collins Professional and Technical Books, London, 1986.

2. ERNENS, M. *La précontrainte dans les structures mixtes - Fissuration et durabilité d'une dalle de pont mixte.* Travail de fin d'études, Université de Liège, 1996.

3. CEB. Durable concrete structures. *Bulletin d'Information n°183,* Comité Euro-International du Béton, Lausanne, 1992.

4. SCHIESSL P. *Corrosion of steel in concrete.* Rilem Report, Chapman and Hall, London, 1988.

5. BARON J. et OLLIVIER J-P. *La durabilité des bétons.* Presses de l'ENPC, Paris, 1992.

6. FRANSSEN J-M. *The computer code SAFIR.* Service des Ponts et Charpentes, Université de Liège, 1995.

7. COPE R.J. *Concrete Bridge Engineering : Performance and Advances.* Elsevier Applied Science, London, 1987.

8. LEBET J-P. *Composite bridges.* Proceedings of an IABSE Short Course on Composite Steel-Concrete, Brussels, 1990, pp. 147-164.