AKADÉMIAI KIADÓ

# Analysis of composite bridge deck considering the effects of concrete cracking

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## ABSTRACT

Cracking in composite steel-concrete bridge decks is a common problem in civil engineering. Before, or shortly after, the bridge is subjected to live loads; various levels of cracking can appear, mostly due to plastic shrinkage and temperature effects.

This paper presents an investigation of the behavior of cracked concrete in a composite deck slab of a railway bridge supported by steel girders using the finite element method. Eurocode 4-2 proposes a few simplified methods for calculating shrinkage and cracking effects in concrete. Through the proposed methods of analysis, an analytical simulation of a continuous composite steel-concrete bridge deck is performed and some practical recommendations for analyzing beam girders of this type are given.

KEYWORDS

cracking of concrete, composite bridge deck, elastic analysis, railway bridge

## 1. INTRODUCTION

Composite steel-concrete girders are common structural systems used for bridges and buildings [1]. The generation of shrinkage and temperature cracks is a well-known problem that reduces its durability and service life [2–4].

In various bridge configurations, significant cracking can form, in both concrete and steel superstructures. Cracks may appear in the early stages of a bridge's life, even before it is subjected to traffic [5]. At the early stage of curing, concrete strength is increasing but may be low, and shrinkage stresses may cause cracking in the concrete due to the low strength.

The design types, continuous or simple span, have a significant influence on the cracking of concrete bridge decks. Hence, bridges with continuous spans are more likely to crack than simple span bridges. This is due to negative moments above the internal supports that produce more tensile fiber stress in continuous span bridge decks, resulting in deck cracking. These fiber stresses in the deck over the support are worsened by tension due to shrinkage and temperature effects [6].

Schindler et al. [7] noticed that the longitudinal restraint produced by steel girders may cause cracking since most of the cracking on the bridge deck is perpendicular to the steel girder direction. While cracks affect the durability of the bridge, Baah [8] noted that damage to concrete structures can also reduce their moment and shear capacity.

To maintain the safety of the railway bridges it is necessary to evaluate the capacity of the deck slab section for the applied loads without accelerated deterioration, and therefore that

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the bridge remains serviceable [9]. The cracking of concrete in composite bridge decks is a problem that is being constantly investigated; the first finite element analysis that evaluated this kind of damage was presented by Ngo and Scordelis [10]. In his model, to model the formation of a crack during loading, a discrete crack element is introduced into the concrete. The surrounding concrete is separated after the discrete crack element is inserted by cutting the concrete elements at the crack. However, the crack sites must be pre-determined for discrete crack elements to be added at the start of the analysis. For this reason, the discrete crack elements must be inserted based on the actual stress field obtained during the analysis [11–13].

This paper presents an elastic global Finite Element Analysis (FEA) that considers cracking in composite steel-concrete bridge deck on the girder beams as suggested by Eurocode 4-2 [14]. Two approaches for dealing with concrete cracking in composite bridges will be investigated, the first practical method, called “uncracked”, where the participation of the slab concrete to the mechanical characteristics of the modeled girder beam is considered in all the cross-sections of the deck. And the second is called “cracked”, where the participation of the concrete slab in the cracked zones is reduced. With these simplified procedures, the two conditions are compared to determine the contributions of the slab (cracked or not cracked) to bridge performance.

Furthermore, many study cases have been performed to analyze the cracking effect on resistance (moments) and rigidity. However, this study is discussing only resistance since the railway bridge is a high-speed line and has enough rigidity reserve. The cracks phenomena in the beam sections will not have a significant impact on deflections.

## 2. ANALYSIS OF COMPOSITE STEEL-CONCRETE BRIDGE DECK

Continuous composite beam girders are a popular choice for bridges because of their ability to carry heavy loads and their rigidity [1].

This type of girder is subjected to negative bending moments close to the region of intermediate supports. Therefore, since the concrete in these regions is in tension, it is prone to cracking. This is an unfavorable design situation and leads to stiffness reduction. According to part 5.4, EN 1994-2 [14]. The treatment of this effect in bridge design can be evaluated using elastic global analysis, even if the beam section behavior is plastic or non-linear.

### 2.1. Cracking of concrete in composite slab deck

Three methods for the determination of internal forces and bending moments based on elastic theory are suggested by the Eurocode 4-2 [14], which is shown in Fig. 1.

***2.1.1. Method I: uncracked analysis.*** For the analysis, Eurocode 4-2 [14] suggests that for serviceability, a typical load case is considered, which includes long-term effects. A first study of the continuous composite beam must be carried out to determine the length over which cracking develops, designated as “uncracked analysis”. For this analysis, the participation of concrete in the tension of the girder is considered over its entire length. Then, in locations where concrete’s tensile resistance is attained or exceeded. A reduced section in the region can be defined by ignoring the existence of the concrete designated as “cracked analysis”.

***2.1.2. Method II: simplified cracked analysis (the 15% method).*** A simplified method is used for continuous bridge beams by considering the reduction in bending moment at the intermediate supports, as it is illustrated in Fig. 1. Over-length of 15% (0.15 $L_1$) on both sides of the intermediate support, where a negative moment occurs, cracking behavior is modeled by ignoring the concrete component of the composite sections, and the rest of the span assumes a full composite section.

***2.1.3. Method III: rigorous cracked method (the 2 $f_{ctm}$ method).*** According to the produced bending moment distribution, the locations where the theoretical stress in the extreme concrete fiber ($\sigma_{bsup}$) exceeds almost double the average axial tensile strength of concrete 2.0 $f_{ctm}$ should be considered to have a cracked zone by ignoring the concrete in these zones ($L_{cr1}$ and $L_{cr2}$), as it is illustrated in Fig. 1. Over the rest of the span, the full composite section is assumed.

## 3. CASE STUDY

In order to compare the results generated from the different Eurocode 4-2 [14] methods mentioned above, a composite viaduct deck was numerically tested by linear elastic analysis using SAP2000 software. Following is a brief description of the model.

### 3.1. Bridge description

The bridge is a viaduct designed for railway traffic. The railway bridge is principally composed of four isostatic spans of 80 m, separated by an expansion joint, each of them is supported at mid-span (40 m) by an additional pier as it is shown in Fig. 2.

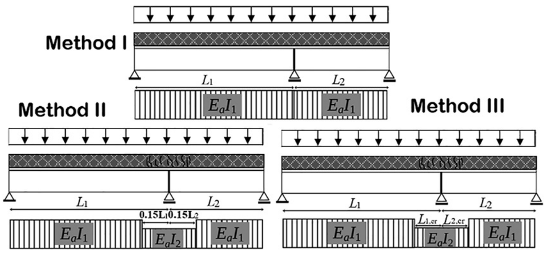

*Fig. 1.* Three methods of crack evaluation on composite girders based on elastic theory

*Fig. 2.* General view of the composite steel-concrete viaduct

In the transverse direction, the deck is formed by a 12.90 m wide Reinforced Concrete (RC) slab with a double-track spaced 4.20 m between centerlines. The thickness of the RC slab varies from 450 mm in the middle to 350 mm at the sides, see Fig. 3, the slab is supported by four 'I' type beam girders with a total height of 2.30 m. The top flange thickness of the steel girder beam is 25 mm ~ 40 mm, and the bottom width varies from 25 to 65 mm. There is a variable section, as it is shown in Fig. 4. The bridge components must be designed in accordance with the Eurocode 3 [15].

### 3.2. Material proprieties

The structure analyzed in the present study is composite. The steel used in the construction of the double-track railway bridge conformed to the EN 1993-1-1 [15] standard and the concrete slab conformed to the EN 1992-1-1 [16] standard. Further properties are listed in Table 1.

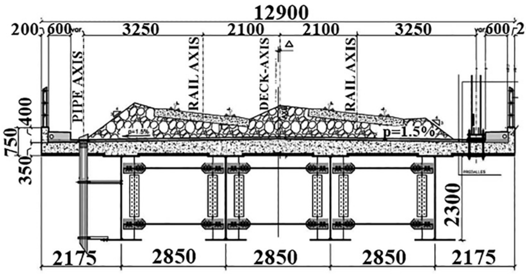

*Fig. 3.* Cross-section of the railway bridge

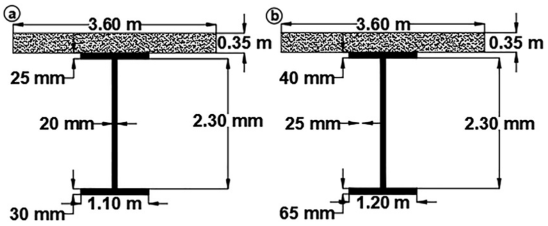

*Fig. 4.* Dimensions and cross-section of composite beams a) in spans, b) in supports

*Table 1.* Material properties

| | | |
|---|---|---|
| Concrete | | |
| Class of concrete | C35/45 | - |
| Concrete compressive strength $f_{ck}$ | 35 | [MPa] |
| Concrete tensile strength $f_{ctm}$ | 3.24 | [MPa] |
| Modulus of elasticity | $3.6 \times 10^4$ | [MPa] |
| Specific mass density | $2.5 \times 10^3$ | [kg m$^{-3}$] |
| Poisson's ratio | 0.2 | - |
| Steel | | |
| Class of steel | S355 | - |
| Steel yield stress $f_y$ | 355 | [MPa] |
| Steel tensile stress $f_u$ $t \leq 40$ mm | 510 | [MPa] |
| Steel tensile stress $f_u$ $t > 40$ mm | 470 | [MPa] |
| Young's modulus | $210 \cdot 10^3$ | [MPa] |
| Poisson's ratio | 0.3 | - |

## 4. FINITE ELEMENT EVALUATION

It is possible to consider plastic cross-section resistance in spans where the moments are positive, whereas the resistance of the cross-section should be considered elastic above the intermediate supports, where the concrete under tension is cracked, or reduced elastic. In this part, the impact of cracked concrete on continuous composite beam tension and the reaction of these beams to actions are discussed.

### 4.1. Composite bridge deck model

In this first model, the deck is modeled with grid lines. Steel-concrete composite beam elements are defined using a section designer, and steel diaphragms are defined using steel frames. The non-structural elements (ballast and rails) are not modeled but are instead applied as an equivalent constant dead load. The middle support is defined to be fixed so that it cannot translate. The model is shown in Fig. 5.

### 4.2. Loads

To determine the maximum stresses on the deck, there must be considered the combination of loads that yield the most unfavorable conditions. For this reason, several combinations and loading models were used for each variation of the beam geometry and all trial runs were linear elastic.

The model of the slab is subjected to a load combination consisting of the self-weight, equivalent constant load of the un-modeled elements considered as superstructure load, and the live load combination Load Model 1 from EN 1991-2: 2003 [17] (Load Model LM 71, SW0, SW2), temperature gradient and shrinkage.

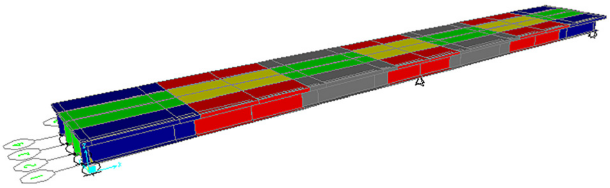

*Fig. 5.* Three-dimensional deck section of the viaduct

The stresses were summed and combined for each load case as given by Eq. (1):

$$\sum G_{k,j} + Q_{k,1} + \sum \Psi_{0,i} Q_{k,i}, \tag{1}$$

where $\sum G_{k,j}$ is the sum of self-weight, superstructure, and concrete shrinkage loads; $Q_{k,1}$ is the live load; $Q_{k,i}$ is the temperature gradient; $\Psi_{0,i} = 0.6$.

On elastic global analysis, the normal stresses are assumed to be uniform on the steel part of the element, unlike the concrete slab, this part changed in a linear way. Thus, a constant effective width of the concrete slab ($b_{eff}$) will be introduced over the whole of each span, as proposed by Eurocode 4-2 [14], this value may be taken as the value $b_{eff} = 3.60$ m at edge beams and $b_{eff} = 2.85$ m in intermediate beams.

Since there is a difference in steel and concrete material's behavior and the values of these materials' properties change over time due to deterioration [18], the modular ratio has a significant impact on the load shared by these materials. In elastic theory, the composite span sections may be conveniently analyzed using the method described in Section 2, and the various materials are, thus transformed into an equivalent one common material.

The modular ratios change according to the type of loading. For shrinkage and superstructure effects, the modular is given by Eq. (2):

$$n_L = n_0(1 + \psi_L \varphi_t), \tag{2}$$

where $n_0$ is the short-term loading modular ratio ($E_a/E_{cm}$); $\varphi_t$ is the creep coefficient, EN 1992-1-1 [16]. $\psi_L$ is the creep multiplier depending on the charge: 1.1 for superstructure loads and 0.55 for shrinkage effects, EN 1994-2-1 [14]. In addition, for the temperature variation, the action is considered as an instantaneous solicitation EN 1991 [16]. The calculation results are shown in Table 2.

## 4.3. Analyses description

The following analyses were performed by taking into consideration the primary cracking of the concrete, temperature and shrinkage, superstructure and load effects:

- *Analysis 1:* The resistant section corresponds to steel elements only; the effects of shrinkage are neglected, and the bridge analysis leads to the determination of longitudinal stresses of the composite beams;
- *Analysis 2:* Several analyses for long-term loadings are performed using the superstructure modular ratio, also shrinkage is added by introducing the modular ratio ($n_L$), and the effective width ($b_{eff}$) is defined over each span. The variations of the analysis's method related to concrete cracking for Eurocode 4 [14] serviceability limit states are: "uncracked" analysis; "15% cracked" analysis; "2 $f_{ctm}$ cracked" analysis;
- *Analysis 3:* Introducing the railway loading systems (LM71, SW/0, SW/2) with their modular ratio, the thermal action is calculated in addition to the shrinkage effect. The same analysis of concrete cracking as explained above is conducted with a) b) and c);

*Table 2.* The modular ratio for a different type of loading

| Action | Modular ratio $n$ |
|---|---|
| Superstructure | 17.58 |
| Shrinkage | 13.69 |
| Temperature effect | 6.16 |

#### *4.3.1. Methods of application.*

- *Uncracked analysis:* Flexural rigidity can vary greatly over the length of a composite deck beam with a regular cross-section, producing uncertainty in the distribution of bending moments and, consequently the extent of cracking to be predicted in the intermediate support of the bridge, as this location is critical, the tension cracks of concrete in these regions should be considered in the next analyzes;
- *Cracked analysis:* Analysis by the 15% cracked method: the intermediate beams have their cracked lengths ($L = 0.15\, l_1$ and $0.15\, l_2$) (Fig. 6) where the concrete slab is supposed to be cracked and that flexural rigidity is reduced.
- *Analysis by the 2 $f_{ctm}$ cracked method:* Also, the intermediate beams have their cracked lengths, where the concrete slab is supposed to be cracked. The cracked lengths can be calculated from the condition described above (Section 2.1) where $f_{ctm} = 3.24$ N mm$^{-2}$ for grade C35/45, as illustrated in Fig. 7, and the cracked zone is presented in Fig. 8.

## 5. RESULTS AND DISCUSSION

### 5.1. Relative cracking length

Table 3 and Fig. 9 show that the extent of the cracked area of the concrete for the rigorous method (cracked 2 $f_{ctm}$) is greater. It is equivalent to 22% on the exterior span section and 20.4% on the interior section. This is higher than 15% for the fixed method.

The same results were found by Elgazzar and Ansnaes [19] during the experimental testing of the Ångermanälven Bridge on the final inspection, where large cracks were found in the exterior beam sections.

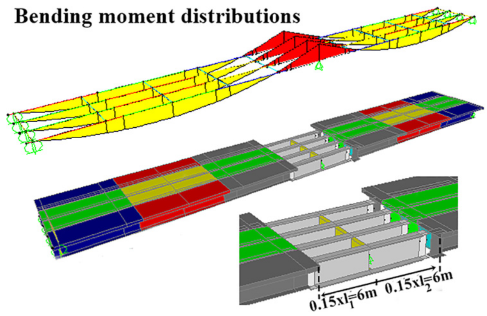

*Fig. 6.* Zone of cracks on deck section for the simplified method

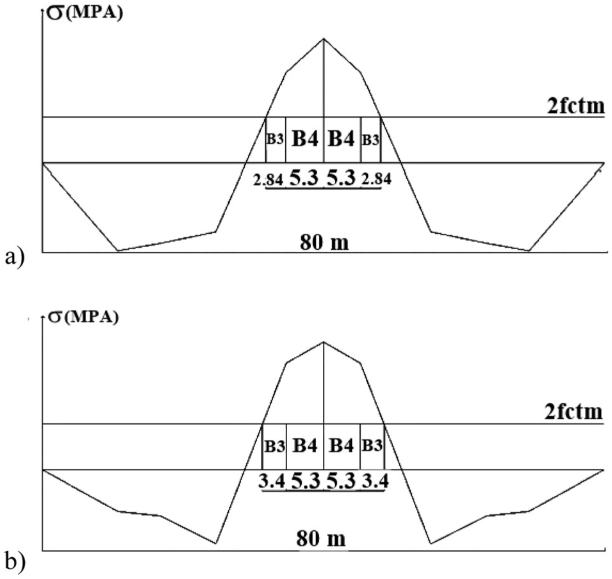

*Fig. 7.* Lengths of the cracked concrete zone a) at interior sections; and b) at exterior sections

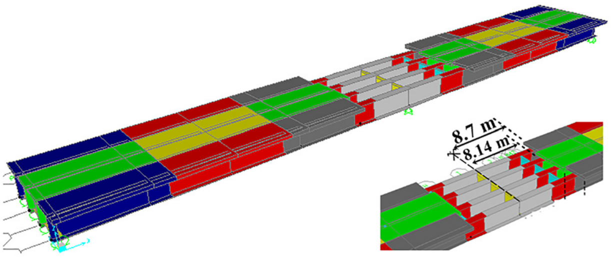

*Fig. 8.* Zone of cracks on deck section for the rigorous method

*Table 3.* Comparison of the relative cracking distances

| | | Simplified Method | Rigorous Method |
|---|---|---|---|
| Cracks (%) | Exterior span section | 15% | 22% |
| | Interior span section | 15% | 20.4% |

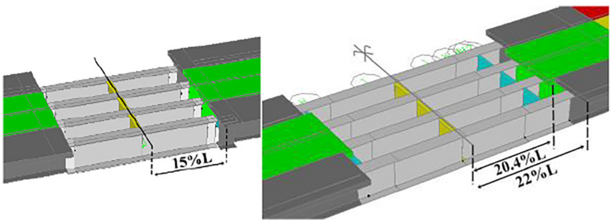

*Fig. 9.* Relative cracking lengths for simplified, and for the rigorous method

## 5.2. Reaction of the composite beam deck section

The sum of bending moment results of analyses 2 and 3 that are appropriate for the Serviceability Limit State (SLS) design under the most disadvantageous load effect combination are graphically shown in Figs 10 and 11.

As it can be seen from these figures, the maximum positive moment is observed in the center span for each analysis, and the maximum negative moment is observed over the supports.

Tables 4 and 5 show that considering the cracking of the concrete, the bending moment of the exterior sections in the supports is reduced by 16.5%, and in the interior section is reduced by 17.1%. This can be explained by the loss of beam stiffness due to the concrete cracking, so it will take a lower bending moment. It should also be noted that the moments of the two cracked models are almost identical.

Also, the results show that in spans, the two cracked models give higher bending moments than the uncracked elastic model, which is 5.4% for the exterior sections and 5.2% for the interior sections. This can be explained by the

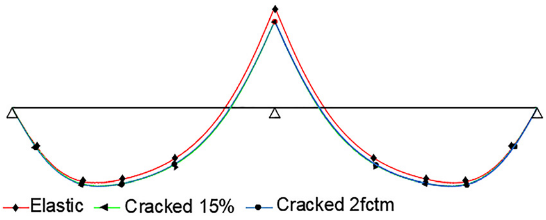

*Fig. 10.* Envelope bending moment diagram of the 3 cases on interior spans

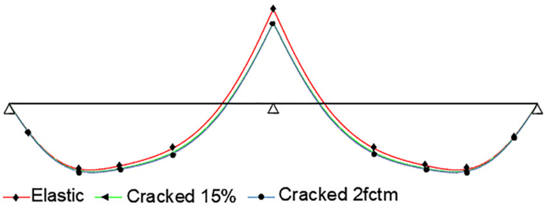

*Fig. 11.* Envelope bending moment diagram of the 3 cases on exterior spans

*Table 4.* Sum of the bending moments in the exterior beam sections

| | | Elastic | Cracked 15% | Cracked $2f_{ctm}$ |
|---|---|---|---|---|
| M (MN.m) | in spans | 21.85612 | 23.11503 | 23.12176 |
| | in supports | 30.74115 | 26.40891 | 26.376691 |

*Table 5.* Sum of the bending moments in the interior beam sections

| | | Elastic | Cracked 15% | Cracked $2f_{ctm}$ |
|---|---|---|---|---|
| M (MN.m) | in spans | 18.86203 | 19.72764 | 19.908823 |
| | in supports | 28.63319 | 24.36875 | 24.433672 |

redistribution of the bending moment after cracking of the concrete at the level of the intermediate supports. This phenomenon is explained by the emigration of the normal stresses from the cracked concrete in supports to the spans.

## 6. CONCLUSION

Eurocode 4-2 provides analysis guidelines for steel-concrete composite bridge based on modified global linear-elastic analysis. In this paper, analyses for the design of a continuous composite railway bridge deck are studied. In addition, the results obtained for both cracked and uncracked models of the deck section by considering a variety of loading conditions are described. Finally, the following are some design recommendations:

- The impact of concrete cracking is a primary indicator for assessing the severity of deterioration in composite bridge girders, its most significant source is assumed to be the low tensile strength in concrete;
- Results from 15% cracked analyses produce less redistribution than assumed; this is dangerous because local yielding in the steel in a hogging moment zone could show up prematurely. Thus, the application of the simplified method is not totally legitimate, and it is advised to apply the rigorous cracking method for concrete evaluation.

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