Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 73/1/73/2 (1995)

Artikel: New approach in the ultimate life calculation for cracked concrete

Autor: Bjegovic, Dubravka / Krstic, Vedrana / Mikulic, Dunja

DOI: https://doi.org/10.5169/seals-55343

New Approach in the Ultimate Life Calculation for Cracked Concrete

Nouvelle méthode d'évaluation de la durée de service de structures en béton armé

Eine neue Methode zur Bemessung von Stahlbetonkonstruktionen im gerissenen Zustand

Dubravka BJEGOVIC
Dr. Eng.
University of Zagreb
Zagreb, Croatia

Vedrana KRSTIC
Civil Engineer
Rutgers University
Piscataway, NJ, USA

Dunja MIKULIC
Dr. Eng.
University of Zagreb
Zagreb, Croatia

Jure RADIC
Prof. Dr.
University of Zagreb
Zagreb, Croatia

Vinko CANDRLIC
Dr. Eng.
University of Zagreb
Zagreb, Croatia

SUMMARY

The paper describes a new proposal for the design of reinforced concrete structures in an aggressive environment. The procedure takes into account the real condition of concrete section cracking under dead and live loads and special durable loads. In this way the least possible probability of structural damage resulting from the effect of special durable loads, can be provided for already in the design phase.

RÉSUMÉ

L'article propose une nouvelle méthode pour le projet de constructions en béton armé dans un environnement agressif. La procédure prend en compte l'état réel de la fissuration du béton sous charges permanentes et variables et sous charges spéciales durables. Cette méthode permet de prévoir, déjà lors de l'établissement du projet, les dommages structuraux les moins probables qui proviennent de l'effet de charges spéciales durables.

ZUSAMMENFASSUNG

Eine neue Methode zur Bemessung von Stahlbetonkonstruktionen in aggressiver Umgebung wird beschrieben. Das Verfahren zieht in Betracht reelle Verhältnisse von Stahlbetonquerschnitten im gerissenen Zustand unter ständigen Verkehrslasten und speziellen Dauerlasten (Umgebungseinflüssen). Die kleinstmögliche Wahrscheinlichkeit von strukturellen Schäden kann so schon in der Projektphase gesichert werden.

1. INTRODUCTION

The fulfillment of the crack limitation criteria frequently results in considerable increase of reinforcement necessary for ultimate limit state design, as well as other criteria of serviceability limit state. However, the manifestation of cracks greater than obtained by the calculations and prescribed, cannot be completely eliminated. Therefore, this paper proposes to introduce the new criterion of the serviceability limit state instead of the cracking limit state. In this way, other numerous factors of reinforced structure durability could be considered.

Such additional durability factors are proposed to be called "special durable loads" [1]. As special durable loads increase material degradation, especially reinforcement corrosion, the new criterion is proposed to be called "the criterion of corrosion limit state" [1].

According to the corrosion limit state it is necessary to prove that the calculated service life t_c is higher or at least equal to the designed life t_p:

$$t_o + t_1 = t_c > t_p \qquad /1/$$

where:
t_o is period of initiation of reinforcement corrosion in concrete,
t_1 is period of propagation of reinforcement corrosion in concrete [2].

2. PERIOD OF INITIATION AND PERIOD OF PROPAGATION REINFORCEMENT CORROSION PROCESS IN CONCRETE

The period of initiation of reinforcement corrosion in concrete stimulated by chlorides (structures in marine environment or structures on roads where the surfaces are strewed with salt for defrosting in the conditions of continental winters), can be determined by diffusion analysis of chlor ions in reinforced concrete cross-sections. The time necessary for the concentration of chlor ions to reach the critical value C_{cr} on the level of reinforcement should be calculated as follows:

$$C(c, t_o) = C_{cr} = 0.4\% \ [3] . \qquad /2/$$

The continuous diffusion process of chlor ions for time-varying diffusion coefficients and the initial concentration of chlor ions is most appropriately expressed by the following experimental formula [1]:

$$C(x,t) = \left[C_o + k(t-1)\right]\left(1 - \operatorname{erf}\frac{x}{2\sqrt{\tau}}\right) + \\ + k\left[\left(1 + \frac{x^2}{2\tau_1}\right)\left(1 - \operatorname{erf}\frac{x}{2\sqrt{\tau_1}}\right) - \frac{x}{\sqrt{\pi \cdot \tau_1}} e^{-\frac{x^2}{4\tau_1}}\right], \quad 0 \le C_o \le C_{max}, \qquad /3/$$

while after reaching the maximum starting concentration $C_o = C_{max}$ the following expression is valid:

$$C(x,t) = C_o\left(1 - \operatorname{erf}\frac{x}{2\sqrt{\tau}}\right), \quad C_o = C_{max} \qquad /4/$$

where:
C_o is initial concentration of chlor ions,
C_{max} is maximum concentration of chlor ions [1, 4],
k is the coefficient of linear increase of initial concentration [1, 5],
τ is the substitution by which variation of D_{Cl} with time [4] is being taken into account,
$\tau_1 = \tau(t = 1)$.

The period of propagation of reinforcement corrosion in concrete (t_1) can be defined from the expression for the corrosion rate [6], which is modified by the introduction of the coefficient of corrosion current density (p) and of the safety coefficient (γ) [1]. The coefficient of increase of corrosion current density takes into account the influence of sulphates, carbonation and real cracking of concrete section under the live and dead load, on the rate of reduction of the reinforcement area.

The safety coefficient takes into account the contribution of qualitative probability factors of failure probability of the bearing capacity of cross-section where the corrosion process has already started. By introducing these coefficients the formula for corrosion rate [6] takes the following form[1]:

$$\phi(t)=\phi_i - \gamma(0.023 \cdot p \cdot i_{corr} \cdot t) \qquad /5/$$

where:

$\phi(t)$ is the reinforcement diameter in time t (mm),
ϕ_i is the initial reinforcement diameter in time t = 0 (mm),
0.023 is transformation constant ($\mu A/cm^2$) in (mm/year),
i_{corr} is corrosion rate density ($\mu A/cm^2$),
p is coefficient of corrosion rate density increase,
γ is safety coefficient calculated on the basis of fuzzy sets theory [1].

From the condition of equalization of reinforcement diameter in the period of corrosion process propagation (t_1), with the limiting value $\phi_u = 0.9 \cdot \phi_i$ [1, 7], the final period of corrosion process development is determined by the formula:

$$\phi(t_1) = \phi_i - \gamma(0.023 \cdot p \cdot i_{corr} \cdot t_1) = \phi_u = 0.9 \cdot \phi_i \Rightarrow t_1 = \frac{0.1 \cdot \phi_i}{\gamma(0.023 \cdot p \cdot i_{corr})} . \qquad /6/$$

3. THE EXAMPLE OF CALCULATION ACCORDING TO THE CORROSION LIMIT STATE CRITERION

The complete calculation procedure, according to the corrosion limit state criterion, will be shown on the example of the flange of box-type concrete arch of new Maslenica bridge (Fig. 1).

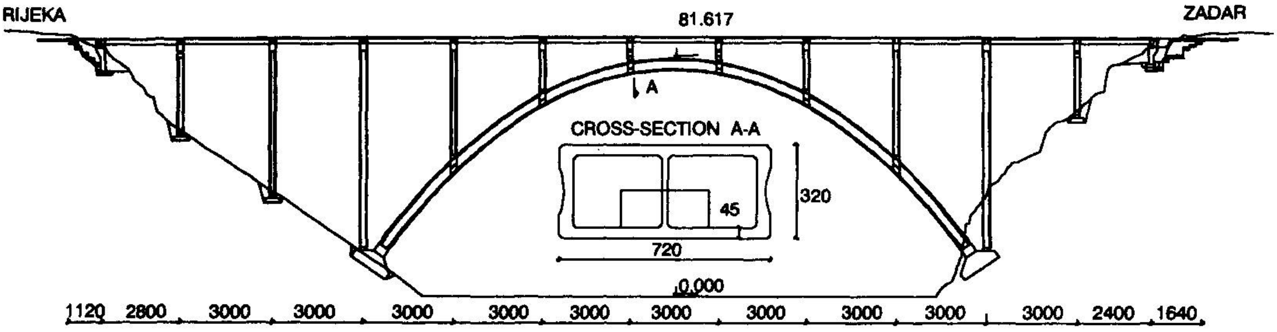


Fig. 1 Arch cross-section and longitudinal layout of new Maslenica bridge

By the dimensioning the flange in the transverse direction, according to the limit state design, the necessary reinforcement has been determined as:
$A_s = 7.3$ cm²/m', and calculated crack width under the dead and live loads $w_k = 0.26$ mm [1].

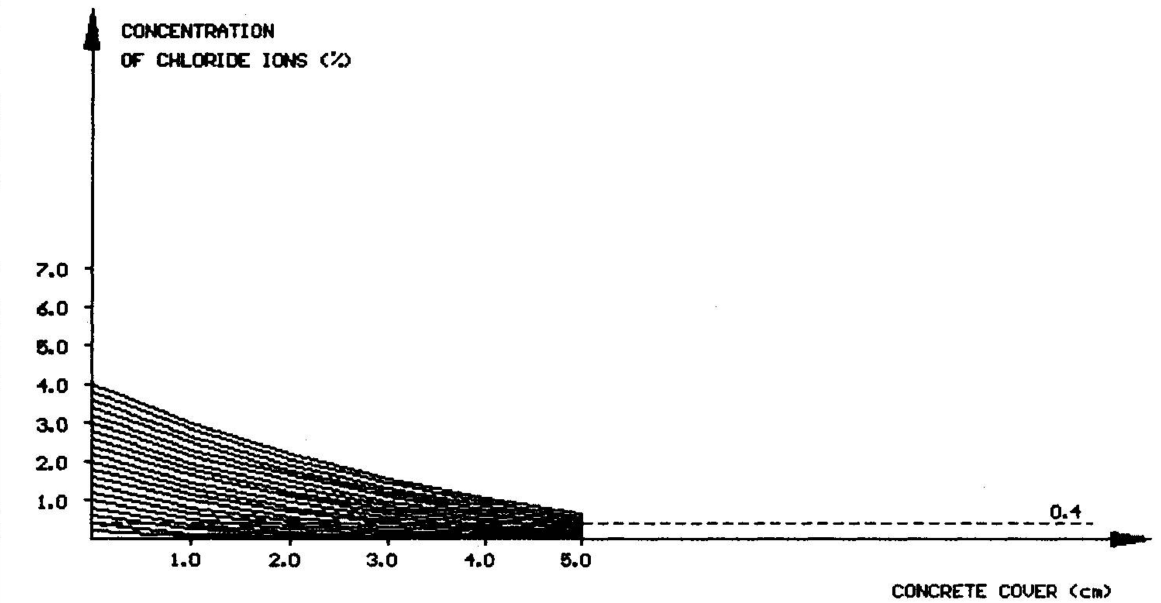
As the structure is located in the aggressive marine environment and as the owner prescribed the life of 100 years, the crack width in concrete is limited to 0.1 mm. The calculations, taking into consideration the criteria of limit cracking condition, resulted in almost 100% increase of reinforcement quantity, compared to the required one from the ultimate limit state design: A_s ($w \leq 0.1$ mm) = 14.0 cm²/m'.

In order to avoid such an increase, the cross-section will be designed according to the corrosion limit state criterion, which permits the real concrete cracking under the dead and live loads only. Due to marine environment, chlorides can be taken as special durable loads so that the period of corrosion initiation is calculated by the analysis of chlor ions diffusion process (formula /3/ and /4/) and under the following assumptions:

- $w/c = 0.45$,
- $c = 5.0$ cm,
- $C_o\ (t=0) = 0$,
- $k = 0.2$ for structures at 50 - 250 m from the sea [1],
- $C_{max} = 7.64\%$ [4],
- cement with slag addition, $D_{01} = 0.3$ [1],
- crack width $w = 0.26$ mm, $D_{02} = 1.08$ [1], $D_o = D_{01} \cdot D_{02} = 0.324$ [1],

and $t_o = 17$ years (Fig. 2).

C H L O D I F output results



water/cement ratio	0.45	total observation time T (years)	20
concrete cover c (cm)	5.00	time for C(c) = 0.0 % (years)	1
Dcl (t = 1 year)	1.27290212600E-08	time for Ccr(c) = 0.4 % (years)	17
Dcl for C(c) = Ccr	9.58848779935E-09	Cmax (%)	7.64
Dcl (T = 20 years)	9.43391615593E-09	C(c,T) (%)	0.643

Fig. 2. Analysis of chlor ions diffusion process to the period t_o

The period of corrosion progress, propagation time t_1 with parameters [1]:
$i_{corr} = 0.5\ \mu A/cm^2$, $p = 2.37$, $\gamma = 1.2$, according to the formula /6/ is $t = 36.7$ years. Calculated life of the arch element is than $t_c = 17 + 36.7 = 53.7$ years, which is far less than prescribed $t_p = 100$ years.

The problem is solved in such a way that the necessary value of the initial diffusion coefficient $D_{Cl} = 2.34 \cdot 10^{-9}\ cm^2/s$ (prior $D_{Cl} = 1.27 \cdot 10^{-8}\ cm^2/s$, Fig. 2), is read from the nomogram (Fig. 3.) [4, 1], elaborated for the concrete cover thickness $c = 5$ cm and prescribed period $t_o = 64$ years.

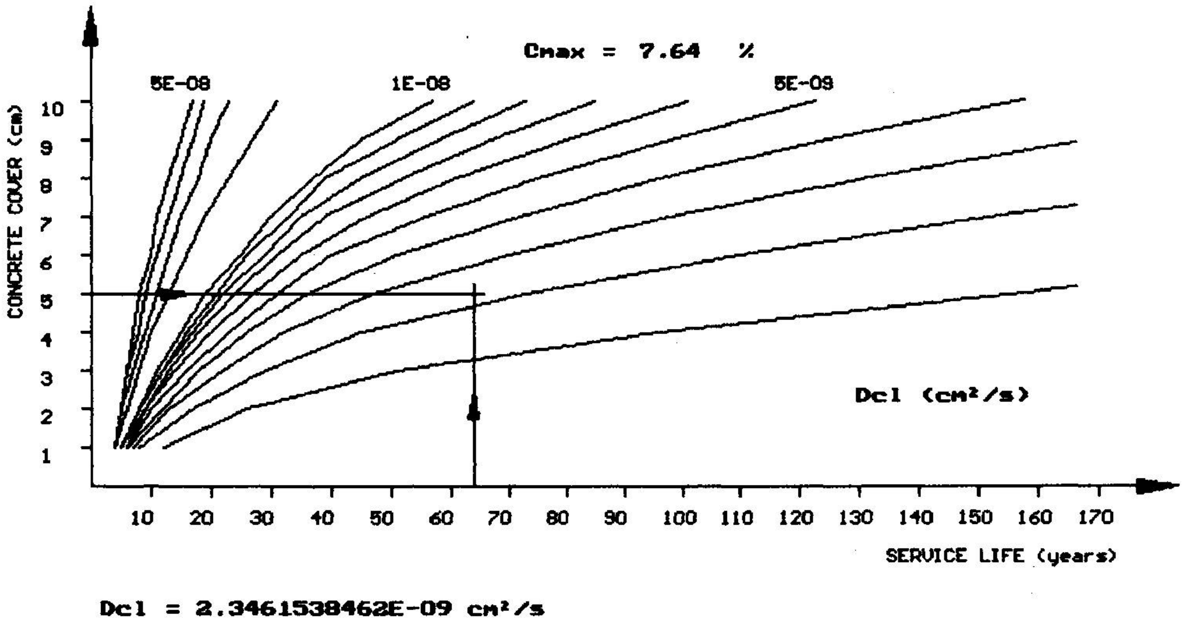


Fig. 3. C-D-c-t nomogram

As it is impossible to fulfill the criteria of the service life of 100 years [8] by above mentioned procedures (the only one remained possibility [8] of water-cement ratio reduction at w/c = 0.4 decreases value of the diffusion coefficient to $D_{Cl} = 8.08 \cdot 10^{-9}$ [1]), it is proposed to apply the mobile corrosion inhibitors [9, 10] in the form of admixtures during concreting or in the form of surface coats, which will in their activation time stop the corrosion process (Table 1, [1]).

t (years)	ACTIVITY
0	Finishing of construction (structural element)
21	Applying of mobile corrosion inhibitors in the form of surface coats
37	Activation of corrosion inhibitors
39	Reaching of critical chlorine ion concentration on reinforcement
64	Stopping of corrosion inhibitors activity, starting of corrosion process
100	Fulfillment of the criterion of corrosion limit state

Table 1 Time schedule of structure maintenance

4. CONCLUSION

The proposed new method is based on supplementing the existing design procedure according cracking limit state design with corrosion limit state design under the conditions of simultaneous action of dead and live loads and special durable loads.

Dimensioning to the corrosion limit state design yields initiation and propagation time for reinforcement corrosion process. This procedure, applied in design phase, frequently results in less reinforcement steel than obtained from standard cracking limit state calculation.

Acknowledgment

The authors wish to acknowledge Mr Zlatko Šavor for useful advices during the preparation of this paper.

REFERENCES:

1. V. Krstić: Numerical Model of Durability Calculation for Reinforced Concrete Structures, Magisterium, Faculty of Civil Engineering University of Zagreb, Zagreb 1994. (in Croatian);
2. K. Tuutti: Service Life of Structures with Regard to Corrosion of Embeded Steel, ACI SP 65-13, International Conference on Performance of Comcrete in Marine Environment, Canada, August 1980, pp 223-236;
3. Croatian Code on Concrete and Reinforced Concrete, 1987;
4. D.Bjegović, V. Krstić, D.Mikulić, V. Ukrainczyk: C-D-c-t Diagrams for Practical Design of Concrete Durability Parameters, Cement and Concrete Research, vol. 25. No. 1. 1995. pp. 187-196;
5. K. Takewaka, S. Mastumoto: Quality and Cover Thickness of Concrete Based on the Estimation of Chloride Penetration in Marine Environments, ACI SP 109-117, Concrete in Marine Environment, Detroit (USA), 1988. pp. 381-400;
6. C. Andrade, C. Alonso, J.A. Gonzales, J. Rodriguez: Remaining Service Life of Corroding Structures, IABSE Symposium on Durability of Structures, Lisabon (Portugal) pp. 359-364;
7. C. Andrade, C. Alonso, J.A. Gonzales: An Initial Effort to Use the Corrosion Rate Measurements for Estimating Rebar Durability, ASTM Symposium on Corrosion Rate of Reinforcements in Concrete, Baltimore (USA), June 1988 pp. 29-37;
8. V. Ukrainczyk, D. Bjegović, D. Mikulić, Z. Rak, V. Krstić; Special Tender Condition for Maslenica Concrete Arch Bridge, Croatian Roads Authority, Zagreb 1993;
9. D. Bjegović, L. Sipos, V. Ukrainczyk, B. Mikšić; Diffusion of the MCI 2020 and MCI 2000 Corrosion Inhibitors into Concrete, International Conference on Corrosion and Corrosion Protection of Steel in Concrete, Sheffield, UK, 1994. Vol 2. pp. 865-878;
10. SHRP-S-666: Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques (Corrosion Inhibitors and Polymers), National Research Council, Washington DC, 1993. 248 pp.