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Comparison study of durability design for concrete bridges: Chinese-code and Eurocode

Tong Teng Liu Zhao

(Key Laboratory of RC & PC Structures of Ministry of Education, Southeast University, Nanjing 210096, China)

Abstract: Differences and similarities of durability design for concrete bridges in Chinese-code and Eurocode are identified and discussed. Exposure environment classes and regulations of the minimum concrete cover and strength of the two codes are compared and analyzed. Numerical calculations for predicting the durable life of bridges related to carbonization and chlorides corrosion (marine and de-icing) are conducted. The results show that provisions in the two codes can satisfy the durability requirements under carbonization whereas they cannot guarantee the durability for bridges in spray and splash zones. Enhancing the waterproof capacity and reducing the frequent use of de-icing agents are vital to improving the bridge durability. Some recommendations for upgrading the durability are also included.

Key words: bridge; durability; carbonization; chloride corrosion; concrete cover

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The durability of concrete bridges has received increasing attention because of the importance of bridge structures and their comparative severe exposure environments. Nowadays, durability requirements are codified more or less in the majority of concrete bridge design and construction specifications around the world.

In China, the code for the durability design of concrete structures [1] (referred as Chinese-code hereafter) enacted in 2008 serves as a national direction for bridge durability design. Correspondingly, the European code[2] (referred as Eurocode hereafter), enacted between the years 2002 and 2010 by the European Standardization Committee, is mandatory for designing European public works, including the durability design of bridges.

However, there are discrepancies between the Chinese-code and the Eurocode which may lead to different durability performances on actual bridges. Comparisons of the requirements for minimum concrete cover and strength specified in the two codes are conducted in this paper, concerning their impacts on bridge durability. Tentative suggestions for improving the durability of concrete bridges are offered.

1 Comparison of Exposure Classes and Structural Classification

1.1 Exposure classes

Exposure classes under various environmental conditions, as a basis for durability design, are divided into A to F in the Chinese-code and 1 to 4 in the Eurocode. Parallel classifications can be found in both codes, except those involved in a marine environment, as shown in Tab. 1.

Tab. 1 Parallelism of exposure classes

Chinese-code		Eurocode	
General environment	Ⅰ-A	Corrosion induced by carbonation	XC1
	Ⅰ-B		XC2
			XC3
	Ⅰ-C		XC4
Freeze/thaw attack	Ⅱ-C	Freeze/thaw attack	XF1
	Ⅱ-D		XF2
			XF3
	Ⅱ-E		XF4
Marine environment	Ⅲ-C	Chlorides from sea water	XS2
	Ⅲ-D		XS1
	Ⅲ-E		
	Ⅲ-F		XS3
De-icing agent	Ⅳ-C	Chlorides	XD1
	Ⅳ-D		XD2
	Ⅳ-E		XD3
Chemical attack	Ⅴ-C	Chemical attack	XA1
	Ⅴ-D		XA2
	Ⅴ-E		XA3
		No risk of corrosion or attack	X0

The Chinese-code and the Eurocode hold different standpoints on the exposure classes of concrete structures permanently submerged in sea water. In the Chinese-code, a lower class is set in consideration of less corrosion due to the absence of oxygen. Conversely, a higher class is given in the Eurocode since the piers are inaccessible components.

1.2 Structural classification

Structural components are divided in the Eurocode into different structural classes, ranging from S1 to S6. The recommended structural class of civil works with 50 years' design working life is S4, and the recommended modifications are presented in Tab. 2 (C30/37 means the cylinder concrete strength is 30 MPa or the cube concrete strength is 37 MPa).

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Biographies: Tong Teng (1988—), male, graduate; Liu Zhao (corresponding author), male, doctor, professor, mr.liuzhao@seu.edu.cn.

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Tab. 2 Recommended structural classification (Eurocode)

Criterion	Exposure class						
	X0	XC1	XC2/XC3	XC4	XD1	XD2/XS1	XD3/XS2/XS3
Design working life of 100 years	Increase class by 2	Increase class by 2	Increase class by 2	Increase class by 2	Increase class by 2	Increase class by 2	Increase class by 2
Strength class	⩾C30/37 Reduce class by 1	⩾C30/37 Reduce class by 1	⩾C30/45 Reduce class by 1	⩾C40/50 Reduce class by 1	⩾C40/50 Reduce class by 1	⩾C40/50 Reduce class by 1	⩾C45/55 Reduce class by 1
Position of reinforcement not affected by construction process	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1
Special quality control of the concrete production ensured	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1	Reduce class by 1

Since concrete bridges are mostly prestressed and their working lives are generally set as 100 years, the structural class of the main components of the bridges should be S6 (see Tab. 3).

Tab. 3 Minimum cover for prestressed structures concerning levels from S4 to S6 mm

Structural class	Exposure class						
	X0	XC1	XC2/XC3	XC4	XD1	XD2/XS1	XD3/XS2/XS3
S4	10	25	35	40	45	50	55
S5	15	30	40	45	50	55	60
S6	20	35	45	50	55	60	65

2 Comparison of Durability Design between Chinese-Code and Eurocode

In order to obtain a general realization of the durable life of concrete bridges in accordance with the Chinese-code and the Eurocode, numerical calculations are necessary. Some environmental parameters are stipulated allowing for most common circumstances as below: the annual average temperature ranges from −20 to 35 ℃, the relative humidity varies from 50% to 90%, and the rebar diameter changes between 10 and 35 mm. In addition, *w/c* ratio in the following discussion is selected from 0.3 to 0.35. The threshold chloride equals 1.4 kg/m^3 if the *w/c* ratio is below 0.4[3].

2.1 Structural durable life under carbonation

The carbonation of concrete is apt to trigger off the dissolution of the protective layer around the rebar, which results in expansion of the rust, and eventually leads to longitudinal cracks or even spall of the concrete cover. The deterioration deriving from carbonation can be divided into two periods: the onset of corrosion and the propagation period.

The classifications of carbonation performed on concrete bridges are rated as "Ⅰ-B" and "Ⅰ-C" within Chinese-code and "XC2" and "XC4" within the Eurocode (XC3 denotes general building structures). The durable life can be predicted[3] as shown in Figs. 1 (a) and (b), which represents general and severe corrosive environments, respectively.

Setting 100 years as a threshold for the life expectancy of concrete bridges, from data presented in Tab. 4, the requirements specified in both codes can resist carbonation under a normal environment for around 100 years, the least one being Ⅰ-B. Furthermore, the minimum cover provided in the Eurocode is generally 10 to 15 mm thicker than that in Chinese-code, which results in a longer durable life.

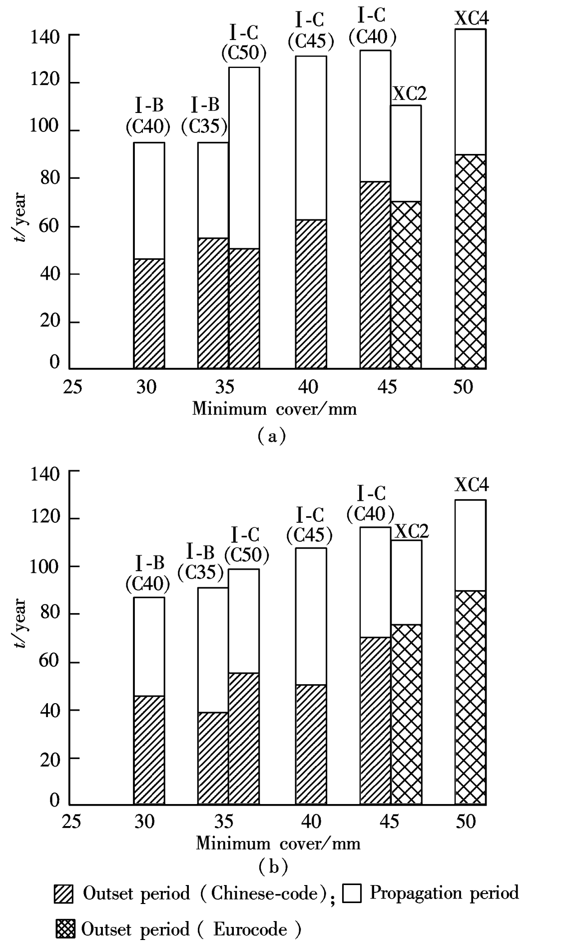

Fig. 1 Durable life predicted under different carbonization conditions. (a) $T=15$ ℃, RH = 0.8, $d=25$ mm; (b) $T=35$ ℃, RH = 0.9, $d=35$ mm

2.2 Structural durable life related to chloride corrosion

As to chloride corrosion, both the Chinese-code and the Eurocode concern two typical environments: marine and deicing environments. The minimum requirements provided for the environments are presented in Tab. 5. The deterioration due to chloride corrosion can be subdivided into two periods: the onset of corrosion and the propagation period. The corresponding predicted durable life is calculated and shown in Tab. 5.

Tab. 4 Durable life under carbonation

Exposure class	Chinese-code					Eurocode	
	Ⅰ-B		Ⅰ-C			XC2	XC4
	C35	≥C40	C40	C45	≥C50	C25/30	C30/37
Minimum cover/mm	35	30	45	40	35	45	50
Durability life/year (Fig. 1(a))	94.8	94.8	132.6	130.1	125.9	109.4	140.5
Durability life/year (Fig. 1(b))	90.4	86.6	115.9	107.2	98.5	110.2	127.4

Tab. 5 Minimum requirements for concrete cover and strength under chloride corrosion

Exposure class	Chinese-code					Eurocode				
	Ⅳ-D/Ⅲ-D		Ⅳ-E/Ⅲ-E		Ⅲ-F	XD1	XD3	XS1	XS2	XS3
	C45	≥C50	C50	≥C55	C55	C30/37	C35/45	C30/37	C35/45	C35/45
Minimum cover/mm	60	55	65	60	70	55	65	55	60	65

2.2.1 Onset of corrosion

The factors affecting the initiation of corrosion are the surface chloride concentration, the concrete cover, and the chloride diffusion coefficient. Chloride concentration at a distance x from the concrete surface at time t can be calculated by Fick's second law[4-5]:

$$C(x, t) = C_s\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{1}$$

where C_s is the surface chloride content; D is the diffuse coefficient (cm^2/s); and erf is the error function.

1) Chloride corrosion under marine environment

The surface chloride concentration needs to be measured after the completion of bridges. The recommended values of the surface chloride concentration in a marine environment provided in DuraCrete are adopted, and the values related to different w/c ratios are listed in Tab. 6.

Tab. 6 Surface chloride content C_s kg/m^3

w/c	Splash and spray zones	Airborne salt but not in direct contact with sea water
0.3	8.16	2.7
0.4	10.85	3.6
0.5	13.60	4.5
0.6	16.30	5.4

The diffusion coefficient is sensitive to materials, the porosity of the concrete, and other factors. A descending trend appears during the first 5 years after the completion of bridges and remains unchanged after that[6].

To a specific concrete structure, the diffusion coefficient of concrete under water zones reaches the maximum value (see Fig. 2). Nevertheless, the corrosion is less likely to be activated due to the lack of oxygen. The diffusion coefficient of ordinary Portland concrete is 0.9×10^{-8} cm^2/s in splash and spray zones, and is 0.7×10^{-8} cm^2/s in airborne salt zones (not directly in contact with sea water), respectively. In Fig. 2, SPRC, OPC, SF and FA represent sulfate concrete, ordinary Portland concrete, silica fume, and fly ash, respectively.

The propagations of chloride ions at the location of the rebar shown in Figs. 3 and 4 can be analyzed by Eq. (1), in the case of ordinary concrete with the w/c ratio being 0.35. The dissolution of the protective passive layer would take 35 to 40 years and 85 to 120 years for splash and spray zones and marine airborne zones, respectively. In addition, the durable life associated with the minimum requirements specified in the Chinese-code would be 5 to 10 years longer than that derived from the provisions in the Eurocode.

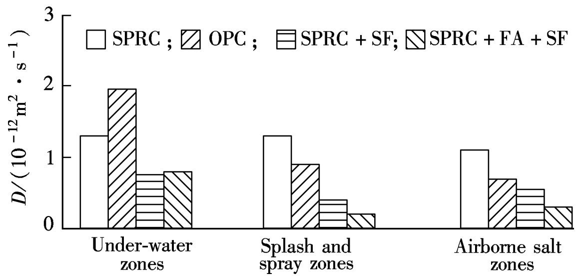

Fig. 2 Diffusion coefficient D measured after five-year exposure experiment ($w/c = 0.4$)

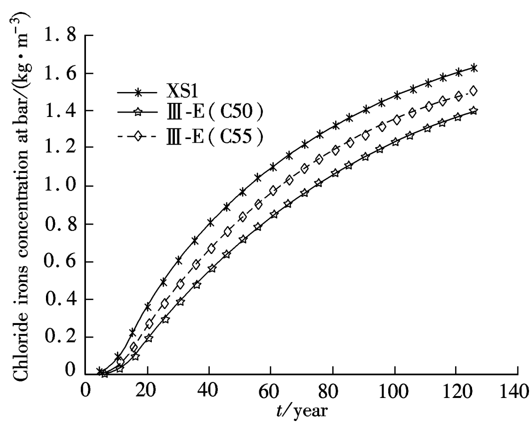

Fig. 3 Trends of chloride concentration (marine airborne zones)

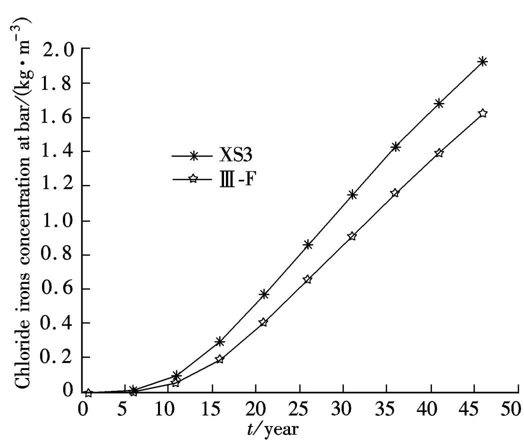

Fig. 4 Trends of chloride concentration (splash and spray zones)

Data obtained from Figs. 3 and 4 show that the minimum requirements need to be enhanced when chloride corrosion in spray and splash zones is taken into account. Nevertheless, general measures (i. e. increasing concrete strength and cover, controlling w/c ratio) will have no substantial improvements. Therefore, extra measures, such as epoxy-coating and cathodic protection of the rebar, need to be considered. For instance, the measures including epoxy-coating reinforcement, stainless steel, cathodic protection, and surface coatings are employed to enhance the durability of the piers in spray and splash zones in the Great Belt Bridge.

Mineral admixtures have positive effects on the resistance capacity to chloride corrosion (see Fig. 2). When concrete is composed of sulphate cement and silica fume admixture, the resistance to chloride corrosion can reach 120 to 180 years under the identical environments. This viewpoint is also verified by the exposure experiments carried out by the Nanjing Hydraulic Research Institute[7].

2) Chloride corrosion under de-icing environment

De-icing chloride corrosion is mainly due to the wide application of de-icing agents or chlorine ions existing in the atmosphere. The resulting corrosive effects on concrete bridges is discrete when compared with the corrosive effects under a marine environment. Even in the same bridge, the diffusion coefficient and the surface chloride content show apparent heterogeneity, which is confirmed by the investigation of bridges exposed to de-icing agent environments [8].

Obviously, the frequency of de-icing salt use, the waterproof capacity of bridges, and environmental factors (i. e. temperature and humidity) are dominating factors accountable for the evolution of deterioration. For instance, the excessive consumption of de-icing agents to Xizhimen overpass in Beijing is responsible for its early demolishment in 1999 after 19 years of operation. Thus, decreasing the frequent use of de-icing agents used in cold zones is critical for the purpose of improving the durability.

Surface chloride concentration is an important factor of chloride corrosion and it should be limited to 1.6 − 1.8 kg/m^3 through enhancing the maintenance and reducing the consumption of de-icing agents. For bridges with a 50 to 60 mm concrete cover, the dissolution period will last approximately 80 years, and the propagation period will last around 10 years. Hence, the overall period is 90 years or so, which will be appropriate for the bridge durability[9].

2.2.2 The propagation period

The propagation period following the dissolution of the protective passive layer can be formulated as

$$t_{\mathrm{cor}} = \frac{W_{\mathrm{crit}}^2}{2k_{\mathrm{p}}} \tag{2}$$

where k_{p} denotes the generation rate of rusts; W_{crit} denotes the rust threshold leading to macro-cracks in the concrete. They can be further expressed as

$$W_{\mathrm{crit}} = \rho_{\mathrm{rust}} \left\{ \pi \left[\frac{cf_{\mathrm{t}}}{E_{\mathrm{ef}}} \left(\frac{b^2 + a^2}{b^2 - a^2} + \nu_{\mathrm{c}} \right) + d_0 \right] d + \frac{W_{\mathrm{st}}}{\rho_{\mathrm{st}}} \right\} \tag{3}$$

$$k_{\mathrm{p}} = 0.098 \frac{\pi d i_{\mathrm{cor}}}{a} \tag{4}$$

where $a = (d + 2d_0)/2$, $b = c + (d + 2d_0)/2$; ρ_{rust} is the density of iron oxide; c is the cover depth (cm); f_{t} is the tensile strength of the rebar; E_{ef} is the effective elastic modulus of the concrete, $E_{\mathrm{ef}} = E_{\mathrm{c}}/(1 + \phi_{\mathrm{cr}})$, in which ϕ_{cr} is the coefficient of creep; ν_{c} is Poisson's ratio of the concrete; d_0 is the thickness of the pore band around the concrete/steel interface, and generally it is 12.5 μm; d is the steel bar diameter; W_{st} is the critical weight of corrosion products, $W_{\mathrm{st}} = aW_{\mathrm{crit}}$; a is taken as 0.523 or 0.622 when the corrosion product is $Fe(OH)_2$ or $Fe(OH)_3$, respectively; ρ_{st} is the density of steel; i_{cor} is the corrosion current density per year, $i_{\mathrm{cor}} = 37.8(1 - w/c)^{-1.64}/c$.

The time from the activation of steel corrosion to obvious cracking of the concrete cover related to different w/c ratios is listed in Tab. 7. The duration varying from 4.33 to 6.79 years makes little contribution to the durable life of concrete bridges.

Tab. 7 Cracking time of concrete cover year

w/c	Chinese-code		Eurocode	
	Ⅳ-D	Ⅲ-F	XD3	XS3
0.30	5.58	6.71	5.59	6.79
0.35	4.34	5.21	4.34	5.29

3 Conclusions

There exist some appreciable differences between the Chinese-code and the Eurocode. Such differences due to the various minimum requirements specified in the two codes are summarized as follows:

1) The minimum requirements in the Chinese-code and the Eurocode mostly satisfy the durability design under a carbonization environment, with those provided for Ⅰ-B in the Chinese-code being slightly thinner. Provided that the minimum cover in the Chinese-code is 40 mm(C35) or 35 mm(≥C40) under environment Ⅰ-B, the durable capacity to resist carbonation can be approximately 112 years.

2) As to the de-icing environment, the corrosive effect is discrete. Reducing the frequent use of de-icing salt and enhancing the waterproof capacity of bridges are recommended.

3) When concrete bridges are located in marine airborne zones, the minimum requirements in the two codes can resist chloride corrosion. Comparatively, the thickness of the protective layer according to the Chinese-code will result in 5 to 10 years longer durable life than that determined according to the Eurocode.

4) The minimum requirements provided in the two codes cannot satisfy the durability design of components in splash and spray zones. Application of conventional measures brings limited improvements. Detailed provisions related to special measures need to be adopted.

5) The minimum concrete strength in the Chinese-code is about 5 to 10 MPa higher than that in the Eurocode. Considering the concrete strength would have a negligible impact on the durability[4-5], it is amenable to degrade the minimum strength requirement under a chloride environment in the Chinese-code.

6) Proper proportioning of cement and mineral admixtures

can produce positive effects on the resistant capacity to chloride corrosion. It is predicted that the durable life will be expected to reach 120 to 180 years or so, if sulfate cement and silica fume admixtures are adopted. It would make sense to include relevant provisions in both the Chinese-code and the Eurocode.

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中国和欧洲混凝土桥梁耐久性设计规范比较

仝 腾　　刘 钊

(东南大学混凝土及预应力混凝土结构教育部重点实验室,南京 210096)

摘要:对中国混凝土结构耐久性设计规范(GB/T 50476—2008)和 Eurocode 中有关混凝土桥梁耐久性设计的相关条款进行了对比. 对 2 种规范中关于结构所处环境等级的划分和混凝土最小保护层厚度和最低强度等级等相关规定做了比较和分析. 并用数值计算方法对处于碳化和氯盐侵蚀环境(海洋环境和除冰盐环境)下的桥梁耐久性设计年限进行了预测分析. 分析认为,2 种规范的相关规定都可以满足桥梁在碳化环境下的耐久性要求,但不能满足在海洋浪溅区环境下的桥梁耐久性要求. 增强混凝土桥梁的密水性和减少除冰盐使用频率对改善桥梁耐久性有重要的意义. 最后,探讨了进一步改善混凝土桥梁耐久性的若干设计措施.

关键词:桥梁;耐久性;碳化;氯盐侵蚀;保护层

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