Linearly Unbiased Estimation Combined with JC Method for the Carbonation Contamination of Some Concrete Bridges in Taipei

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LINEARLY UNBIASED ESTIMATION COMBINED WITH JC METHOD FOR THE CARBONATION CONTAMINATION OF SOME CONCRETE BRIDGES IN TAIPEI

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ABSTRACT

The main purpose of this investigation was to study the durability evaluations of existing concrete bridges due to carbonation contamination. The linearly unbiased estimation method associated with the JC method developed by the Joint Committee on Structural Safety was adopted to predict the mean value and standard deviation of the normal distribution for the carbonation depths and cover thickness of concrete bridges. The reliability index (β) and failure probability (P_f) of concrete bridges were also evaluated. Since the linearly unbiased estimation method is very suitable for analyzing a small number of specimens obtained from practical engineering problems, the unknown parameters can be conveniently and actually determined. In order to verify this proposed method, ten concrete bridges in Taipei were used to predict the mean value, standard deviation, reliability index and failure probability. In this paper, the results of this investigation indicate that both the Beei-men viaduct (β = 0.23) and the Jzyh-chyang bridge (β = 0.39) require extensive repair. Both the Ay-gwo west road viaduct (β = 0.92) and the Shi-yuan bridge (β = 0.88) require relatively light repairs. The other bridges (β = 1~2.0) are safe and serviceable. The linearly unbiased estimation combined with JC method is useful to evaluate the durability of existing concrete bridges with carbonation contamination.

INTRODUCTION

The reinforced steel bars embedded in concrete are protected from corrosion by a thin oxide film that forms on their surface due to the highly alkaline, with pH

values above 12.5, environment of the surrounding concrete. This alkalinity occurs calcium hydroxide ($Ca(OH)_2$)) produced during the reaction between water and the constituents of cement which occurs the hardening and development of strength of cement and concrete. Carbon dioxide (CO_2) in air penetrates into concrete and reduces the pH value less than 9, that can result in the corrosion of embedded reinforcing steel bars which cause concrete to spall or split. This process is called carbonation that is principally a diffusion phenomenon and the rate of penetration of CO_2 depends mainly on concrete quality and exposure conditions.

The existing concrete bridges in Taipei were evaluated for corrosion contamination in order to select the most effective repair methods. A detailed investigation was required to determine the extent and cause of deterioration. Corrosion in steel reinforcement is a major cause of concrete deterioration in Taipei. It has been observed that significant corrosion-induced deterioration in Taipei occurs with 10 to 15 years of construction. Corrosion of the existing concrete bridges is at first caused by the presence of carbonation. The aggressive environment in Taipei is characterized high temperature and humidity cycles, and high levels of carbon dioxide.

As the various factors which influence concrete carbonation are uncertain, the actual carbonation depths of concrete structures are also uncertain. The carbonation processes of concrete structures are very complex. At present there is little statistical data on the factors which influence concrete carbonation. Thus, it is still difficult to use the existing calculation formulas to determine the statistical rules for concrete carbonation. However, in practical engineering problems, it is sometimes urgent to perform a probability estimation for concrete carbonation. A simple and practical method is to directly carry out statistical analysis for the concrete carbonation. The traditionally statistical methods re-

quire numerous specimens. However, in actual practice, few specimens obtained from field tests are used to determine the extent of carbonation.

Freudenthal [1] used the principle of constant reliability over the domain of load influence coefficients to study the structural reliability. Cornell [2], Lind [3] and Ravindra *et al.* [4] developed the theory of codified structural design to serve as an efficient way to encode experience. Ang and Amin [5] proposed an approach which explicitly separates the elements of risk (variables with known probability measure) from the elements of uncertainty (variables with unknown probability measure). This format can be completely reconciled with the partial safety factor format derived by appropriate identification of terms. Lind [6] demonstrated how partial safety factors in a design code can be selected to balance safety and economy. Paloheimo and Hannus [7] derived a deterministic design equation in which all random variables are substituted by appropriate design values. A design value is a function of the mean value and standard deviation of the corresponding random variable; the reliability factor, which is determined by the acquired level of safety; and the sensitivity factor, which expresses the sensitivity of the structure to the individual random variable. Stewart and Rosowsky [8, 9] developed a structural deterioration reliability model to calculate probabilities of structural failure for a typical reinforced concrete continuous slab bridge. Until now, however, no studies have attempted to predict the durability of existing RC bridges without employing linearly unbiased estimation combined with the JC method. This is a notable shortcoming, because the use of reliability analysis in previous studies may be needed a lot of specimens.

This paper is focused on the durability evaluation of concrete bridges due to carbonation contamination. In order to investigate this subject, the research significance must first be pointed out. Second, the linearly unbiased estimation of parameter method is described. Third, the JC method [7] is introduced. Fourth, a testing technique for specimens which were extracted from ten different concrete bridges in Taipei is described. Fifth, the results and discussion are provided. Finally, concluding remarks are drawn.

RESEARCH SIGNIFICANCE

The reliability index or the failure probability can be used to predict the state of contamination in structures. The carbonation contamination of ten concrete bridges in Taipei were evaluated using the reliability index. The decision as to whether a given bridge requires repair can be made based on the estimated reliability index.

LINEARLY UNBIASED ESTIMATION OF PARAMETER

The unknown parameters of a small number of specimens with a small account of engineering problem data can be conveniently and actually predicted using linearly unbiased estimation method. Suppose that there exists a set of specimen sequence $(x_1, x_2, ..., x_n)$. Consider an estimated value of linear function

$$x_p = \lambda + \alpha y_p \qquad (1)$$

where λ is position parameter and α is scale parameter.

The linear function with specimen sequence $(x_1, x_2, ..., x_n)$ is defined as

$$L = \sum_{i=1}^{n} w_i x_i \qquad (2)$$

where w_i is the weighting value and is expressed as

$$w_i = a_i + b_i y_p \qquad (3)$$

where a_i and b_i are coefficient functions.

The limit property of w_i is $\sum_{i=1}^{n} w_i = 1$.

The expectation of linear function L can be expressed in terms of

$$E(L) = \sum_{i=1}^{n} w_i E(x_i) = x_p \qquad (4)$$

The linearly unbiased estimation method means that the sought variance of L is the minimum weight w_i. If the value of specimen x_i coincides with expectation $E(x_i)$, then the variance vanishes. However, if the value of specimen x_i does not coincide with expectation $E(x_i)$, then we must determine w_i such that

$$x_p = E(L) \approx \sum_{i=1}^{n} w_i x_i = L \qquad (5)$$

The variance of L is

$$\sigma_L^2 = E[L - E(L)]^2 = E(L^2) - [E(L)]^2 \qquad (6)$$

Because

$$\sum_{i=1}^{n} w_i = 1 \qquad (7)$$

$$\sum_{i=1}^{n} w_i E(y_i) = y_p \qquad (8)$$

$$L = \sum_{i=1}^{n} w_i x_i = \sum_{i=1}^{n} w_i (\lambda + \alpha y_i) \qquad (9)$$

The substitution of Eqs. (7), (8) and (9) into Eq. (6) yields

$$\sigma_L{}^2 = \alpha^2 \sum_{i=1}^{n} \sum_{j=1}^{n} [E(y_i y_j) - E(y_i) E(y_j)]\, w_i w_j \qquad (10)$$

Introducing the Lagrangian coefficients λ_1 and λ_2 which are to be determined, and using the constrain conditions, i.e. Eqs. (8) and (9), we can construct the function

$$I = \sum_{i=1}^{n} \sum_{j=1}^{n} [E(y_i y_j) - E(y_i) E(y_j)]\, w_i w_j$$
$$+ \lambda_1 \left(\sum_{i=1}^{n} w_i - 1 \right) + \lambda_2 \left[\sum_{i=1}^{n} w_i E(y_i) - y_p \right] \qquad (11)$$

In order to find the w_i such that the variance, $\sigma_L{}^2$, is minimum, it is required that

$$\frac{\partial I}{\partial w_i} = 0 \; ; \quad (i = 1, 2, ..., n) \qquad (12)$$

When w_i is determined using the above method, we can obtain a system of linear equations. After rearrangement of Eq. (5)

$$x_p = \lambda + \alpha y_p = \sum_{i=1}^{n} (a_i + b_i y_p) x_i$$
$$= \sum_{i=1}^{n} a_i x_i + \left(\sum_{i=1}^{n} b_i x_i \right) y_p \qquad (13)$$

we get

$$\lambda = \sum_{i=1}^{n} a_i x_i \qquad (14)$$
$$\alpha = \sum_{i=1}^{n} b_i x_i \qquad (15)$$

where a_i and b_i are the functions of $E(y_i)$, $E(y_i^2)$ and $E(y_i y_j)$ in the system of linear equations mentioned above. For calculating the values of $E(y_i)$, $E(y_i^2)$ and $E(y_i y_j)$, we adopted the following method (see Fig. 1). If the value of y_i is the statistical value according to the right i-th orders, then the 1st to $(i-1)$-th data locates the A region, as shown in Fig. 1 and the $(i+1)$-th to n-th data set in B region. Thus, the probability density function of the -th value of y_i is
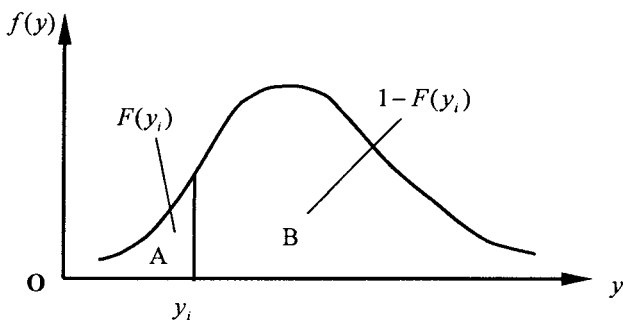
$$P_i(y) = \frac{n!}{(i-1)!(n-1)!} [F(y)]^{i-1} [1 - F(y)]^{n-i} f(y) \qquad (16)$$

The corresponding expected values of y_i and y_i^2 are, respectively, expressed as

$$E(y_i) = \int_{-\infty}^{+\infty} y P_i(y)\, dy \qquad (17)$$
$$E(y_i^2) = \int_{-\infty}^{+\infty} y^2 P_i(y)\, dy \qquad (18)$$

Assume that the values of the i-th and j-th variables of y_i and y_j are u and v, respectively. In a similar manner, using Fig. 2, the probability density function of the expected value of $y_i y_j$ can be calculated. The 1st to $(i-1)$-th, $(i+1)$-th to $(j-1)$-th, and $(j+1)$-th to n-th data locate A, B and C regions, as illustrated in Fig. 2, respectively. Therefore, the probability density function of u and v is

$$P_{ij}(u, v) = \frac{n!}{(i-1)!(j-i-1)!(n-j)!} [F(u)]^{i-1}$$
$$[F(v) - F(u)]^{j-i-1} [1 - F(v)]^{n-j} f(u) f(v) \qquad (19)$$

The corresponding expected value of u and v is

$$E(y_i y_i) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} uv P_{ij}(u, v)\, dudv; \; (u < v) \qquad (20)$$

When both $f(\bullet)$ and $F(\bullet)$ are given, the representative equations $E(y_i)$, $E(y_i^2)$ and $E(y_i y_j)$ can be calculated from Eqs. (17), (18) and (20), respectively.

Zhao (1996) pointed out that the concrete carbonation corrosion usually obeys the standard normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{(x-\mu)^2}{2\sigma^2} \right] \qquad (21)$$

$$F(x) = \Phi(x) = \int_{-\infty}^{x} f(t)\, dt \qquad (22)$$

where $f(x)$ and $F(x)$ are the probability density function

Fig. 1. Schematic diagram for finding $E(y_i)$.

Fig. 2. Schematic diagram for finding $E(y_i y_j)$.

and distribution function, respectively. $\Phi(x)$ is the standard normal distribution function. The mean value μ_x and standard deviation σ_x of the concrete carbonation depth can be, respectively, estimated in terms of

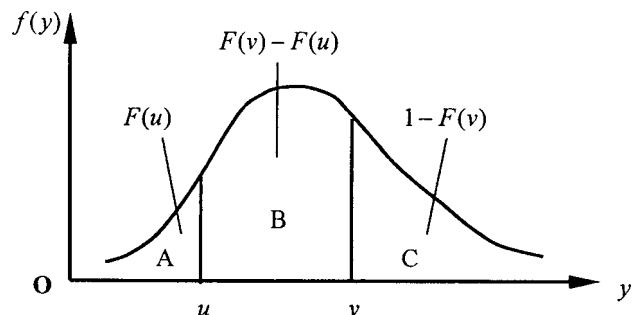$$\mu_x = \sum_{i=1}^{n} a_i x_i = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad (23)$$

$$\sigma_x = \sum_{i=1}^{n} b_i x_i \qquad (24)$$

where the coefficient b_i can be determined from Table 1, and the permutation order of specimen is $x_1 \geq x_2 \geq ... \geq x_n$.

JC METHOD

Paloheimo and Hannus [7] proposed a method of checking computations. The feature of this method is considered an abnormal random variable. Under the computational data conditions, increased by only a few, the reliability index, β, could actually perform the approximate calculation and determine the design value by checking which computation point satisfies the limit state equation. It is very convenient to calculate each item coefficient of the standard value given by the specification. It is also easy to produce the expressed design formula with the usual multiple coefficient for the designer.

In this study, the linearly limit state equation, with two normal random variables, was considered to eluci-

date the reliability index, β, and the concept of checking designed the computation point.

The limit state equation with two random variables can be expressed as

$$Z = g(R, S) = R - S = 0 \qquad (25)$$

where R is the structural resistance, S is the loading effect of the structural surface, and $Z = g(R, S)$ is a function. It is pointed out that R and S are mutually independent and are obeyed the standard normal distribution. Fig. 3 indicates the limit state equation and designed computation check point for two normal random variables. In the case of the *OSR* coordinate, the limit state equation is a straight line which have an inclined angle 45° with a horizontal axis. Let R and S be divided by the standard deviations σ_R and σ_S, respectively. The coordinates $S' = \frac{S}{\sigma_S}$ and $R' = \frac{R}{\sigma_R}$ are formed as shown in Fig. 3. When $\sigma_S \neq \sigma_R$, the inclined angle of the straight line $R' = (\sigma_R/\sigma_S)S'$ of the limit state equation in the coordinate $O'S'R'$ is not 45° while $\tan^{-1}(\sigma_R/\sigma_S)$. If the coordinate $O'S'R'$ is translated from origin $O'(0, 0)$ to $\overline{O}\,(\frac{\mu_S}{\sigma_S}, \frac{\mu_R}{\sigma_R})$ as depicted in Fig. 3, then the new coordinate $\overline{O}\,\overline{S}\,\overline{R}$ is obtained and is expressed by

$$\overline{S} = \frac{S}{\sigma_S} - \frac{\mu_S}{\sigma_S} = \frac{S - \mu_S}{\sigma_S}$$

$$\overline{R} = \frac{R - \mu_R}{\sigma_R} \qquad (26)$$

Table 1. Coefficient b_i of linearly unbiased estimation in standard normal distribution

n	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}	b_{12}	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}	b_{19}	b_{20}
2	-0.886	0.88																		
3	-0.591	0.000	0.591																	
4	-4.454	-0.110	0.110	4.454																
5	-0.372	-0.135	0.000	0.135	0.372															
6	-0.318	-0.139	-0.043	0.043	0.139	0.318														
7	-0.278	-0.135	-0.062	0.000	0.062	0.135	0.278													
8	-0.248	-0.129	-0.071	-0.023	0.023	0.071	0.129	0.248												
9	-0.224	-0.123	-0.075	-0.036	0.000	0.036	0.075	0.123	0.224											
10	-0.204	-0.117	-0.076	-0.044	-0.014	0.014	0.044	0.076	0.117	0.204										
11	-0.188	-0.111	-0.076	-0.048	-0.024	0.000	0.024	0.048	0.076	0.111	0.188									
12	-0.175	-0.106	-0.075	-0.051	-0.029	-0.010	0.010	0.029	0.051	0.075	0.106	0.175								
13	-0.163	-0.101	-0.074	-0.052	-0.033	-0.017	0.000	0.017	0.033	0.052	0.074	0.101	0.163							
14	-0.153	-0.097	-0.072	-0.052	-0.036	-0.022	-0.006	0.006	0.022	0.036	0.052	0.072	0.097	0.153						
15	-0.144	-0.093	-0.070	-0.053	-0.037	-0.026	-0.011	0.000	0.011	0.026	0.037	0.053	0.070	0.093	0.144					
16	-0.137	-0.089	-0.068	-0.053	-0.038	-0.028	-0.016	-0.005	0.005	0.016	0.028	0.038	0.053	0.068	0.089	0.137				
17	-0.130	-0.086	-0.066	-0.052	-0.040	-0.029	-0.019	-0.009	0.000	0.009	0.019	0.029	0.040	-0.052	0.066	0.086	0.130			
18	-0.124	-0.082	-0.065	-0.050	-0.041	-0.030	-0.020	-0.014	-0.004	0.004	0.014	0.020	0.030	0.041	0.050	0.065	0.082	0.124-		
19	-0.118	-0.079	-0.063	-0.051	-0.039	-0.032	-0.024	-0.014	-0.008	0.000	0.008	0.014	0.024	0.032	0.039	0.051	0.063	0.079	0.118	
20	-0.113	-0.076	-0.061	-0.049	-0.041	-0.032	-0.025	-0.017	-0.010	-0.003	0.003	0.010	0.017	0.025	0.032	0.041	0.049	0.061	0.076	0.113

$$R' = \frac{R}{\sigma_R} \qquad \overline{R} = \frac{R - \mu_R}{\sigma_R}$$

$$\overline{R}\sigma_R + \mu_R - (\overline{S}\sigma_S + \mu_S) = 0$$

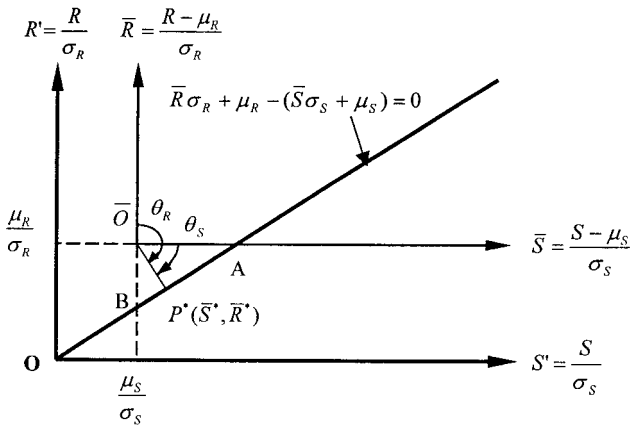$$\overline{S} = \frac{S - \mu_S}{\sigma_S}$$

$$S' = \frac{S}{\sigma_S}$$

Fig. 3. Limit state equation and designed checking computation point of two normal random variables.

The coordinate transform stated above is in fact the normal distribution $N(\mu_i, \sigma_i)$ standardized as $N(0, 1)$.

The relationship between the original coordinate OSR and the new coordinate $\overline{O}\,\overline{S}\,\overline{R}$ is

$$S = \overline{S}\,\sigma_S + \mu_S$$

$$R = \overline{R}\,\sigma_R + \mu_R \qquad (27)$$

Substituting Eq. (27) into Eq. (25), we get

$$\overline{R}\,\sigma_R - \overline{S}\,\sigma_S + \mu_R - \mu_S = 0 \qquad (28)$$

Equation (28) divided by $-\sqrt{\sigma_R{}^2 + \sigma_S{}^2}$ and compared with the straight line of the standard type normal expression in analytic geometry

$$\overline{S}\cos\theta_R + \overline{R}\cos\theta_R - \beta = 0 \qquad (29)$$

we obtain

$$\cos\theta_S = \frac{\sigma_S}{\sqrt{\sigma_R{}^2 + \sigma_S{}^2}} \qquad (30)$$

$$\cos\theta_R = \frac{-\sigma_R}{\sqrt{\sigma_R{}^2 + \sigma_S{}^2}} \qquad (31)$$

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R{}^2 + \sigma_S{}^2}} \qquad (32)$$

where β is the distance $\overline{OP^*}$, in which P^* is perpendicular toe, from the original point $\overline{O}$ in coordinate $\overline{O}\,\overline{S}\,\overline{R}$ to the straight line of limit state equation, $\cos\theta_S$ and $\cos\theta_R$ are the directional cosine of normal line $\overline{OP^*}$ to coordinate. The β in Eq. (32) is a reliability index. Hence, the reliability index, β, is the shortest

distance from the original point $\overline{O}$ of the standard normal coordinate $\overline{O}\,\overline{S}\,\overline{R}$ to the straight line of the limit state equation. This is the geometrical illustration of β. In the method for checking the computation point, the calculation of β is equivalent to finding the length of $\overline{OP^*}$. P^* is the point on the straight line of the limit state equation. It is called the design computation check point. From Fig. 3, the coordinates $\overline{S}^*$ and $\overline{R}^*$ of P^* are, respectively, stated as

$$\overline{S}^* = \overline{OP^*}\cos\theta_S = \beta\cos\theta_S \qquad (33)$$

$$\overline{R}^* = \overline{OP^*}\cos\theta_R = \beta\cos\theta_R \qquad (34)$$

Obviously, the directional cosine of $\overline{OP^*}$ has the following relationship

$$\cos^2\theta_R + \cos^2\theta_S = \frac{\sigma_R{}^2}{\sigma_R{}^2 + \sigma_S{}^2} + \frac{\sigma_S{}^2}{\sigma_R{}^2 + \sigma_S{}^2} = 1 \qquad (35)$$

According to Eq. (27), the designed checking computation point $P^*(\overline{S}^*, \overline{R}^*)$ in the coordinate $\overline{O}\,\overline{S}\,\overline{R}$ is expressed in the coordinate OSR as

$$S^* = \overline{S}^*\sigma_S + \mu_S = \beta\cos\theta_S\sigma_S + \mu_S \qquad (36)$$

$$R^* = \beta\cos\theta_R\sigma_R + \mu_R \qquad (37)$$

The limit state equation $(R - S) = 0$ in the coordinate OSR is described early. Therefore, the coordinate $P^*(S^*, R^*)$ on the straight line of the limit state equation should be satisfied

$$R^* - S^* = 0 \qquad (38)$$

If μ_R, μ_S, σ_R and σ_S are given, then the reliability index β and both R^* and S^* of the value of the design computation check point can be found from Eqs. (32), (36) and (37). Thus, the corresponding failure probability $P_f = \Phi(-\beta)$ is also determined. If both the objective reliability index, β_T, (or the failure probability, P_f) and μ_S, σ_R and σ_S are known, then μ_R can be obtained and carried out through the cross-section area design.

The criteria for comprehensive test about reliability index in this paper is suggested as follows: If $0 < \beta < 0.5$, bridge requires extensive repair. If $0.5 < \beta < 1.0$, bridge requires relatively light repair. If $\beta \geq 1.0$, bridge is safe and serviceable.

TESTING TECHNIQUES

Cores were extracted from ten different bridges in Taipei. For each bridge, numerous cores of 55 mm diameter with 110 mm height were taken. These specimens were tested carbonation depth.

Cores were taken from exposed reinforced concrete members of bridges. The majority of the bridges considered were concrete bridges. Cores were extracted and tested according to ASTM-C-39 [10]. All cores were extracted from the girders, diaphram, capbeam, parapets, decks, piers, abutments, and ramps. The cores were cut using a rotary steel cutting machine with diamond bits.

The density and compressive strength are not considered in this paper. The carbonation depth was assessed by splitting the concrete cores and spraying the split specimens uniformly with phenolphthalein pH indicator (a solution of 1% phenolphthalein ($C_{20}H_{14}O_4$) in 70% ethyl alcohol (C_2H_5OH)) (Dhir, *et al.* [11]), Papadakis, *et al.* [12], Loo, *et al.* [13], Al-Khaiat and Haque [14]). The depth of carbonation was measured with a steel ruler to the nearest 1mm. Several measurements were taken on given specimens. The average cover thickness of each member of the ten bridges were also obtained and are shown in Table 2 to 11.

Table 2. Unbiased estimation of concrete carbonation depth for the Huey-tong bridge in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	North deck	30	0	0.17	-0.318	0.00	0.00
2	Arch bridge(south)	30	8	0.17	-0.139	1.36	-1.112
3	S11 deck	30	13	0.17	-0.043	2.21	-0.559
4	D11 diaphram	30	15.1	0.17	0.043	2.57	0.649
5	West abutment	30	19.5	0.17	0.139	3.32	2.711
n = 6	East abutment	30	21	0.17	0.318	3.57	6.678

*: The actual service life of the structural members, $t_0 = 49$ years; the normal distribution of cover thickness, N(30, 0);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.17;$ $\mu_x = \sum_{i=1}^{n} a_i x_i = 13.03;$ $\sigma_x = \sum_{i=1}^{n} b_i x_i = 8.367;$ $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{30 - 13.03}{\sqrt{0^2 + (8.367)^2}} = \frac{16.97}{8.367} = 2.03;$ $P_f = \Phi(-\beta) = \Phi(-2.03) = 0.02118$

Table 3. Unbiased estimation of concrete carbonation depth for the Beei-men viaduct in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	pier (left, back)	25	1.8	0.05	-0.113	0.09	-0.203
2	A10 pier (back)	25	2.0	0.05	-0.076	0.10	-0.015
3	A5 capbeam (back)	20	3.6	0.05	-0.061	0.18	-0.220
4	G4 girder (left) (C5~C6)	20	4.4	0.05	-0.049	0.22	-0.216
5	A15 pier	25	5.1	0.05	-0.041	0.26	-0.209
6	C7 pier (back)	25	5.5	0.05	-0.032	0.28	-0.176
7	A13 pier	25	6.8	0.05	-0.025	0.33	-0.170
8	G5 girder (left) L	20	7.4	0.05	-0.017	0.37	-0.126
9	A1 pier (right, back)	25	7.8	0.05	-0.010	0.39	-0.078
10	A8 capbeam	20	8.4	0.05	-0.003	0.42	-0.001
11	G8 girder (left)	20	10.1	0.05	0.003	0.51	0.030
12	A17 abutment	25	10.3	0.05	0.010	0.52	0.103
13	G3 girder (right) M	20	10.9	0.05	0.017	0.55	0.185
14	G15 girder (right)	20	11.3	0.05	0.025	0.57	0.283
15	G4 girder (left) M	20	13.0	0.05	0.030	0.65	0.390
16	C5 pier (back)	25	22.6	0.05	0.041	1.13	0.927
17	C3 deck	30	52.6	0.05	0.049	2.63	2.577
18	S12 deck	30	59.4	0.05	0.060	2.97	3.564
19	S10 deck	30	63.8	0.05	0.076	3.19	4.849
n = 20	S8 deck	30	79.1	0.05	0.113	3.96	8.938

*: The actual service life of the structural members, $t_0 = 20$ years; the normal distribution of cover thickness, N(24, 3.485);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.05;$ $\mu_x = \sum_{i=1}^{n} a_i x_i = 19.32;$ $\sigma_x = \sum_{i=1}^{n} b_i x_i = 20.432;$ $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{24 - 19.32}{\sqrt{(3.485)^2 + (20.432)^2}} = \frac{4.68}{20.727} = 0.23;$ $P_f = \Phi(-\beta) = \Phi(-0.23) = 0.01287$

Table 4. Unbiased estimation of concrete carbonation depth for the Way-shuang rivulet bridge in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	A2 abutment (middle)	25	0.0	0.17	-0.318	0.00	0.00
2	S2-1 deck	20	0.0	0.17	-0.139	0.00	0.00
3	G-1-4 girder	20	1.5	0.17	-0.043	0.26	-0.065
4	G2-5 girder	20	6.5	0.17	0.043	1.11	0.280
5	A2 abutment (middle)	25	18.0	0.17	0.139	3.06	2.502
n = 6	P15 pier (back)	35	19.3	0.17	0.318	3.28	6.137

*: The actual service life of the structural members, $t_0 = 26$ years; the normal distribution of cover thickness, N(24.17, 5.68);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.17$; $\mu_x = \sum_{i=1}^{n} a_i x_i = 7.71$; $\sigma_x = \sum_{i=1}^{n} b_i x_i = 8.854$; $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{24.17 - 7.71}{\sqrt{(5.68)^2 + (8.854)^2}} = \frac{16.46}{10.519}$

$= 1.56$; $P_f = \Phi(-\beta) = \Phi(-1.56) = 0.05938$

Table 5. Unbiased estimation of concrete carbonation depth for the Her-pyng west road viaduct in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	P5 capbeam (middle)	20	0.0	0.08	-0.175	0.000	0.000
2	P3 capbeam (middle)	20	0.0	0.08	-0.106	0.000	0.000
3	S6-3 deck	20	1.6	0.08	-0.075	0.128	-0.120
4	P6 pier (right, back)	35	10.5	0.08	-0.051	0.840	-0.536
5	G3 girder (left)	20	11	0.08	-0.029	0.880	-0.319
6	G2 girder (right)	20	11.9	0.08	-0.010	0.952	-0.119
7	G7 girder (left)	35	12.9	0.08	0.010	1.032	0.129
8	P2 bridge pier (middle, back)	35	13	0.08	0.029	1.040	0.377
9	P2 capbeam(middle)	20	17.6	0.08	0.051	1.408	0.898
10	G9-3 girder	20	18.3	0.08	0.075	1.464	1.373
11	P5 capbeam(middle)	20	18.4	0.08	0.106	1.472	1.950
n = 12	S-3-2 deck	20	38.3	0.08	0.175	3.064	6.703

*: The actual service life of the structural members, $t_0 = 18$ years; the normal distribution of cover thickness, N(23.75, 5.34);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.05$; $\mu_x = \sum_{i=1}^{n} a_i x_i = 12.28$; $\sigma_x = \sum_{i=1}^{n} b_i x_i = 10.336$; $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} \frac{23.75 - 12.28}{\sqrt{(5.34)^2 + (10.336)^2}} = \frac{11.47}{11.634}$

$= 0.99$; $P_f = \Phi(-\beta) = \Phi(-0.99) = 0.1611$

Table 6. Unbiased estimation of concrete carbonation depth for the Jzyh-chyang bridge in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	A4 abutment	20	5.4	0.13	-0.248	0.702	-1.339
2	S4 deck	25	5.9	0.13	-0.129	0.767	-0.761
3	S2 deck	25	6.5	0.13	-0.071	0.845	-0.462
4	P2 pier (left)	35	6.6	0.13	-0.023	0.858	-0.152
5	A2 abutment	20	14.0	0.13	0.023	1.820	0.322
6	P1 pier (left)	35	16.9	0.13	0.071	2.197	1.200
7	S4 diaphram	30	46.6	0.13	0.129	6.058	6.011
n = 8	S2 diaphram-1	30	52.6	0.13	0.248	6.838	13.045

*: The actual service life of the structural members, $t_0 = 26$ years; the normal distribution of cover thickness, N(27.5, 6.125);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.13$; $\mu_x = \sum_{i=1}^{n} a_i x_i = 20.09$; $\sigma_x = \sum_{i=1}^{n} b_i x_i = 17.864$; $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{27.5 - 20.09}{\sqrt{(6.125)^2 + (17.864)^2}} = \frac{7.41}{18.885}$

$= 0.39$; $P_f = \Phi(-\beta) = \Phi(-0.39) = 0.3483$

Table 7. Unbiased estimation of concrete carbonation depth for the Ay-gwo west road viaduct in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	a_ix_i	b_ix_i
1	deck 1	25	0.0	0.06	-0.124	0.000	0.000
2	deck 2	25	0.0	0.06	-0.082	0.000	0.000
3	deck 3	25	0.0	0.06	-0.065	0.000	0.000
4	deck 4	25	0.0	0.06	-0.050	0.000	0.000
5	S9A girder	20	3.0	0.06	-0.041	0.180	-0.123
6	S1-3 girder	20	11.3	0.06	-0.030	0.678	-0.339
7	ramp B	30	11.5	0.06	-0.020	0.690	-0.230
8	S12 girder	20	11.8	0.06	-0.014	0.708	-0.165
9	S3-3 girder	20	12.9	0.06	-0.004	0.774	-0.052
10	P3 pier(right)	20	13.0	0.06	0.004	0.780	0.052
11	P7 pier(right)	30	15.9	0.06	0.014	0.954	0.223
12	P2 capbeam	20	18.6	0.06	0.020	1.116	0.372
13	P11 pier	30	18.9	0.06	0.030	1.134	0.567
14	S5-3 girder	20	21.3	0.06	0.041	1.278	0.873
15	guide passage A(South)	30	22.4	0.06	0.050	1.344	1.120
16	Abutment A	25	23.6	0.06	0.065	1.416	1.534
17	Abutment C	25	26.6	0.06	0.082	1.596	2.181
n = 18	P7 pier(middle)	30	32.4	0.06	0.124	1.994	4.018

*: The actual service life of the structural members, $t_0 = 15$ years; the normal distribution of cover thickness, N(24.44, 3.87);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.06;$ $\mu_x = \sum_{i=1}^{n} a_ix_i = 14.492;$ $\sigma_x = \sum_{i=1}^{n} b_ix_i = 10.031;$ $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{24.43 - 14.492}{\sqrt{(3.87)^2 + (10.031)^2}} = \frac{9.94}{10.75}$

$= 0.92; P_f = \Phi(-\beta) = \Phi(-0.92) = 0.1814$

Table 8. Unbiased estimation of concrete carbonation depth for the Hwan-nan viaductin Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	a_ix_i	b_ix_i
1	P80 pier	30	0.0	0.05	-0.113	0.000	0.000
2	R1 papapet	30	0.0	0.05	-0.076	0.000	0.000
3	P58 capbeam	30	0.0	0.05	-0.061	0.000	0.000
4	R9 ramp (east)	30	0.0	0.05	-0.049	0.000	0.000
5	S50A deck	30	0.0	0.05	-0.041	0.000	0.000
6	S80 deck	30	0.0	0.05	-0.032	0.000	0.000
7	S1 girder	20	4.5	0.05	-0.025	0.225	-0.113
8	P44 capbeam	20	6.3	0.05	-0.017	0.315	-0.107
9	P35 capbeam	20	7.5	0.05	-0.010	0.375	-0.075
10	S67 capbeam	20	8.5	0.05	-0.003	0.425	-0.026
11	S50A girder (left)	20	8.5	0.05	0.003	0.425	0.026
12	S45B parapet	20	13.5	0.05	0.010	0.675	0.135
13	P45B pier	30	14.0	0.05	0.017	0.700	0.238
14	P58 pier	30	14.3	0.05	0.025	0.715	0.358
15	P44 capbeam	20	14.5	0.05	0.030	0.725	0.435
16	P1 capbeam	20	15.5	0.05	0.041	0.755	0.636
17	P32 capbeam	30	20.0	0.05	0.049	1.000	0.980
18	S53B parapet	30	22.8	0.05	0.060	1.140	1.368
19	P69 capbeam	30	25.1	0.05	0.076	1.255	1.908
n = 20	P80 capbeam	30	32.3	0.05	0.113	1.615	3.650

*: The actual service life of the structural members, $t_0 = 24$ years; the normal distribution of cover thickness, N(26, 4.05);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.05;$ $\mu_x = \sum_{i=1}^{n} a_ix_i = 10.345;$ $\sigma_x = \sum_{i=1}^{n} b_ix_i = 9.413;$ $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{26 - 10.345}{\sqrt{(4.05)^2 + (9.413)^2}} = \frac{15.655}{10.274}$

$= 1.53; P_f = \Phi(-\beta) = \Phi(-1.53) = 0.06426$

Table 9. Unbiased estimation of concrete carbonation depth for the Daw-nan bridge in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	G1-1 girder	20	0.0	0.1	-0.204	0.000	0.000
2	S2-2 deck	20	1.3	0.1	-0.117	0.130	-0.152
3	G3-7 girder	20	2.3	0.1	-0.076	0.230	-0.175
4	P2 pier (back)	35	4.8	0.1	-0.044	0.480	-0.211
5	P2 capbeam(back)	20	5.0	0.1	-0.014	0.500	-0.070
6	A1 abutment	25	6.0	0.1	0.014	0.600	0.084
7	G3-2 girder	20	13.6	0.1	0.044	1.360	0.598
8	G1-6 girder	20	14.1	0.1	0.076	1.410	1.072
9	P1 pier	35	25.8	0.1	0.117	2.580	3.019
n = 10	A2 abutment	25	34.1	0.1	0.204	3.410	6.956

*: The actual service life of the structural members, $t_0 = 14$ years; the normal distribution of cover thickness, N(24, 5.415);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.1$; $\mu_x = \sum_{i=1}^{n} a_i x_i = 10.70$; $\sigma_x = \sum_{i=1}^{n} b_i x_i = 11.121$; $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{24 - 10.70}{\sqrt{(5.415)^2 + (11.121)^2}} = \frac{13.3}{12.369}$

$= 1.08$; $P_f = \Phi(-\beta) = \Phi(-1.08) = 0.1401$

Table 10. Unbiased estimation of concrete carbonation depth for the Shi-yuan bridge in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	$a_i x_i$	$b_i x_i$
1	G13-1 girder	25	0.0	0.05	-0.113	0.000	0.000
2	S9 deck	25	0.0	0.05	-0.076	0.000	0.000
3	S10 deck	25	0.0	0.05	-0.061	0.000	0.000
4	P3 capbeam	20	4.8	0.05	-0.049	0.240	-0.235
5	P14 capbeam	20	5.3	0.05	-0.041	0.265	-0.217
6	G17-1 girder	25	5.9	0.05	-0.032	0.295	-0.189
7	G7-1 girder	25	9.1	0.05	-0.025	0.455	-0.228
8	G4-1 girder	25	10.3	0.05	-0.017	0.515	-0.179
9	G6-1 girder	25	10.5	0.05	-0.010	0.525	-0.105
10	G10-1 girder	25	11.3	0.05	-0.003	0.565	-0.034
11	P8 capbeam (back)	25	14.5	0.05	0.003	0.725	0.044
12	P17 pier (right)	30	15.9	0.05	0.010	0.795	0.159
13	GR-2 girder	25	16.4	0.05	0.017	0.820	0.279
14	P4 capbeam	20	16.5	0.05	0.025	0.825	0.413
15	A18 abutment	25	20.5	0.05	0.030	1.025	0.615
16	P96 capbeam (back)	25	21.8	0.05	0.041	1.090	0.894
17	P17 capbeam (back)	25	25.4	0.05	0.049	1.270	1.245
18	P13 capbeam	20	34.3	0.05	0.060	1.715	2.058
19	P7 capbeam (back)	25	35.4	0.05	0.076	1.770	2.690
n = 20	DR-4 diaphram	25	37.5	0.05	0.113	1.875	4.238

*: The actual service life of the structural members, $t_0 = 24$ years; the normal distribution of cover thickness, N(24.25,1.985);

$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.05$; $\mu_x = \sum_{i=1}^{n} a_i x_i = 14.775$; $\sigma_x = \sum_{i=1}^{n} b_i x_i = 10.553$; $\beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{24 - 14.775}{\sqrt{(1.985)^2 + (10.553)^2}} = \frac{9.475}{10.738}$

$= 0.88$; $P_f = \Phi(-\beta) = \Phi(-0.88) = 0.1894$

RESULTS AND DISCUSSION

The ten bridges in Taipei were reinforced concrete structures. The linearly unbiased parameter estimation method was used to analyze these bridges. The mean value, μ_x, and standard deviation, σ_x, of the carbonation

Table 11. Unbiased estimation of concrete carbonation depth for the Chung-san bridge in Taipei*

Order i	Member Classification	Cover Thickness d(mm)	Carbonation Depth x_i(mm)	a_i	b_i	a_ix_i	b_ix_i
1	Vaulted rib	30	10.0	0.17	-0.318	1.70	-3.180
2	Drainage system	24	10.0	0.17	-0.139	1.70	-1.390
3	Pier	37	13.0	0.17	-0.043	2.21	-0.559
4	Extended for pavement cantilever beam	20	15.0	0.17	0.043	2.55	0.645
5	Deck	27	22.0	0.17	0.139	3.74	3.058
n = 6	Supported plate	52	23.0	0.17	0.318	3.91	7.314

*: The actual service life of the structural members, $t_0 = 26$ years; the normal distribution of cover thickness, N(31.67, 12.112);

$$a_i = [\frac{1}{n}\sum_{i=1}^{n} x_i]/[\sum_{i=1}^{n} x_i] = 0.17; \quad \mu_x = \sum_{i=1}^{n} a_i x_i = 15.81; \sigma_x = \sum_{i=1}^{n} b_i x_i = 5.888; \beta = \frac{\mu_d - \mu_x}{\sqrt{\sigma_d^2 + \sigma_x^2}} = \frac{31.67 - 15.81}{\sqrt{(12.112)^2 + (5.888)^2}} = \frac{15.86}{13.467}$$

$= 1.18; {}_f = \Phi(-\beta) = \Phi(-1.18) = 0.119$

Table 12. Reliability index and failure probability of concrete bridges in Taipei

Order i	Bridge name	t_0* (years)	Reliability index β	Failure probability P_f
1	the Huey-tong bridge	49	2.03	2.118×10^{-2}
2	the Beei-men viaduct	20	0.23	1.287×10^{-2}
3	the Way-shuang rivulet bridge	26	1.56	5.938×10^{-2}
4	the Her-pyng west road viaduct	18	0.99	1.611×10^{-1}
5	The Jzyh-chyang bridge	26	0.39	3.483×10^{-1}
6	the Ay-gwo west road viaduct	15	0.92	1.814×10^{-1}
7	the Hwan-nan viaduct	24	1.53	6.426×10^{-2}
8	the Daw-nan bridge	14	1.08	1.401×10^{-1}
9	the Shi-yuan bridge	24	0.88	1.894×10^{-1}
n=10	the Chung-san bridge	63	1.18	1.190×10^{-1}

*: The actual service life of concrete bridge

depth of the concrete can be estimated using Eqs. (23) and (24). The coefficients b_i in Eqs. (24) can be discovered from Table 1. The mean value, μ_d, and standard deviation, σ_d, of the cover thickness of concrete were calculated using the normal distribution method. These results are shown in Table 2 to 11. The JC method was also adopted to predict the reliability index. This means that the substitution of μ_x, σ_x, μ_d, σ_d into Eq. (32) leads to β. The reliability index, β, and corresponding failure probability, P_f, of each bridge in Taipei are listed in Table 12. It was found that both the Beei-men viaduct ($\beta = 0.23$) and the Jzyh-chyang bridge ($\beta = 0.39$) require extensive repairs. Both the Ay-gwo west road viaduct ($\beta = 0.92$) and the Shi-yuan bridge ($\beta = 0.88$) require only limited repairs. The other bridges ($\beta = 1$~2.0) are safe and serviceable. It is worthwhile to point out that the old Chung-san bridge ($\beta = 1.18$) is the oldest, but is very sound. The major factor is that the old Chung-san bridge has enough concrete cover to retard corrosion. It

is also worthwhile to express that the old Chung-san bridge was designed and constructed by Japanese when Taiwan was a Japanese colony.

The model for predicting the required extent of repair and failure probability in this paper is only based on carbonation depth and concrete cover thickness. This appears to be an oversimplified approach to the complex phenomenon of corrosion of steel in concrete. It is in fact that many factors must be considered to effectively assess the extent of corrosion damage, remaining service life, need for repairs and risk of failure for a structure. This paper does not address issues such as the effect of chlorides, concrete cracking, concrete type and mix proportions, cement chemistry, observed corrosion damage (i. e., cracking, spalling, staining), measured corrosion rates, half-cell potentials, the design details and configuration of the bridge, and the exposure conditions for the bridge. All of these factors can actually play a significant role in corrosion

of metals in concrete structure and the need for repairs and failure probability. If this paper considered these issues and dismissed them in the research, this should be explained fully to justify highly simplified approach. If these issues have been overlooked, the validity and usefulness of the method presented in this paper may be questionable. It would be a great disservice to imply that the condition of a bridge and the need for repairs was based solely on the difference between the depth of carbonation and the concrete cover thickness. However, if this paper considered all these issues, this would not be possible. The aim of this paper provides a prediction model of the carbonation contamination of concrete bridge. Although the proposed model considered carbonation depth and cover thickness of concrete, the predicted results are good agreement with actual situation. It is obvious that the propose model in this paper is very useful.

CONCLUSIONS

The linearly unbiased estimation method associated with the JC method to evaluate the carbonation contamination of concrete bridges in the Taipei has been described. The results of this study show that both the Beei-men viaduct ($\beta = 0.23$) and the Jzyh-chyang bridge ($\beta = 0.39$) require extensive repairs. Both the Ay-gwo west road viaduct ($\beta = 0.92$) and the Shi-yuan bridge ($\beta = 0.88$) require limited repairs. The other bridges ($\beta = 1$~2.0) are safe and serviceable. Because the old Chung-san bridge has enough concrete cover, this bridge, even though it is the oldest among ten bridges, it is very sound.

Above all, the concrete cover thickness is the most important factor which determines the service life and durability of a bridge. Insufficient cover thickness is the decisive cause of the early and heavy degradation of reinforced concrete structures.

Measures to improve durability, such as maintaining a low water-cement ratio in the concrete mix, lessening the concentration of carbon dioxide gas are effective only when the cover thickness is sufficient. In order to make reinforced concrete structures durable, it is most important to avoid having an insufficient cover thickness.

Moreover, how many data points needed to use this proposed model effectively is necessary studied in advance. The range of reliability index required extensive repair, relatively light repair, safe and serviceable is also needed recommendations depended on more advanced investigation.

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線性無偏結合JC方法評估台北市混凝土橋樑的碳化損傷

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摘　要

　　本文研究的主要目的是探討具有碳化損傷的既有混凝土橋樑之耐久性評估，採用線性無偏評估法結合由國際結構安全度聯合委員研發的JC法，首先分別預測混凝土橋樑之碳化深度和保護層厚度之常態分佈的平均值和標準偏差，進而計算混凝土橋樑的可靠性指標β及失效機率P。因為線性無偏評估法非常適合分析僅有少數樣本的實際工程問題，且未知參數可以很方便和精確計算，所以本文採用此法。為驗正本文建議方法的實用性，應用台北市十座混凝土橋樑為範例，分別計算各座橋樑之平均值、標準偏差、可靠性指標及失效機率。研究結果表明北門高架橋$\beta = 0.23$及自強橋$\beta = 0.39$需要維修，愛國西路高架橋$\beta = 0.92$和西園橋$\beta = 0.88$需要小維修，其餘橋樑$\beta = 1\~2.0$可安全使用。