STUDIES ON THE LIFE-CYCLE COST ANALYSIS OF EXISTING PRESTRESSED CONCRETE BRIDGES

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Key words: capital benefit, failure probability, inspection, maintenance, quality assurance.

ABSTRACT

The principal purpose of this paper was to study the life-cycle cost analysis (LCCA) of existing prestressed concrete (PC) bridges. A reasonable analytical model was established and provided for evaluating existing PC bridges. This model consists of design, production, quality assurance, capital benefit and other costs. To verify this analytical model, two existing PC bridges in Taiwan were used as illustrative examples. The results of present study show that the analytical model is very reasonable, reliable, and serviceable. The results represented in this study may be used as an engineering decision-making tool for the repair, strengthening or demolition rankings for existing PC bridges.

INTRODUCTION

The management of public construction has widely been referred as an important research topic all over the world. There are a great deal of researches that concentrate on the set up of maintenance management system and durability design. Bridge is a significant public transportation installation. Nevertheless, cost analysis with respect to bridge is free of a common sense or a general method. Recently, the concept of life-cycle cost analysis (LCCA) [18] is widely used in the field of public construction. However, it is just a few applications in the researches of bridge structures. This is actually a kind of short-coming. For compensating this deficiency, the concept of LCCA is herein used in the bridge structures. Each related factor is detailly introduced and unified. The life-cycle cost (LCC) of bridge is found by the value of failure probability. The total cost included design, production, quality assurance, capital benefit and other costs is estimated and controlled.

The LCCA is fully applied in many research fields. In opposite position, the bridge engineering is not of numerous researches using the concept of LCCA. In a large amount, reliability analysis is used to find the structural safety criteria. Recently, the reliability is broad used to seek the optimal design of reinforced concrete (RC) structures [7, 17, 19, 24]. Both the failure probability and failure cost are combined to predict the optimal reliability of structure [4, 10, 11]. Frangopol et al. [3] developed a lifetime optimization method for planning the inspection and repair of a highway bridge with RC T-girders that deteriorate over time. This method is based on minimizing the expected total life-cycle cost and improved efficiency. Kong and Frangopol [13] used the reliability as a basis for seeking the optimal cost. Frangopol et al. [2] applied the reliability as a basis for finding the accumulative cost in the years past for evaluation. Sexsmith and Reid [22] provided the effect of failure cost to overall bridge structure cost. They pointed out that both increasing allowable strength and reducing burden pressure are possibly error concept. Finding the overall structural safety coefficient is the major keypoint.

This paper proposes a method to find a predicted value of an overall structural cost needed based on the accumulation following lifetime. This approach is optimized the lifetime inspection/repair strategy of corrosion-critical prestressed concrete (PC) bridges based on the cost-effectiveness and/or failure probability. This methodology is applied to illustrate two existing PC bridges in Taiwan. The method is applicable for any type of structural damage whose evolution can be modeled over time. The investigated results in this paper may be offered as an engineering decision-making reference for the repair, strengthening or demolition rating for existing PC or RC bridges.
THEORECTICAL BACKGROUND

Only a small fraction of the bridge LCCA paper published deal with minimization of the overall cost. Most of the papers published on cost optimization of concrete structure are concerned beams or girders. Sarma and Adeli [21] expressed the general cost function for reinforced, fibers, or PC beams as

\[ C_m = C_{cb} + C_{sb} + C_{pb} + C_{fb} + C_{sbv} + C_{fib} \]  \hspace{1cm} (1)

where \( C_m \) is the total material cost, \( C_{cb} \) is the cost of concrete in the beam, \( C_{sb} \) is the cost of reinforcing steel, \( C_{pb} \) is the cost of prestressing steel, \( C_{fb} \) is the formwork cost, \( C_{sbv} \) is the cost of shear steel, and \( C_{fib} \) is the cost of fiber in the concrete.

Few papers have been published on the minimizing cost of concrete columns. Sarma and Adeli [21] represented the general cost function for a concrete column in terms of

\[ C_m = C_{cc} + C_{sc} + C_{pc} + C_{fc} + C_{ic} \]  \hspace{1cm} (2)

where \( C_{cc}, C_{sc}, C_{pc}, C_{fc}, \) and \( C_{ic} \) are the costs of concrete, reinforcing steel, prestressed steel, form work, and lateral ties in columns, respectively. The total cost of a concrete structure (\( C_T \)) can be written as

\[ C_T = C_m + C_{FB} + C_{TR} + C_s + C_{CD} + C_E \]  \hspace{1cm} (3)

where \( C_{FB}, C_{TR}, C_s, C_{CD}, \) and \( C_E \) are the costs of fabrication (or placement), transportation, substructure (or foundation), cladding, and erection, respectively.

The reliability factor in the cost optimization is considered either directly or indirectly. In the direct method, the reliability factor is included directly in the objection function. Moses [20] presents the total cost (\( C_T \)) in the following form

\[ C_T = C_I + P_F C_F \]  \hspace{1cm} (4)

where \( C_I \) is the initial cost, \( C_F \) is the expected failure cost, and \( P_F \) is the failure probability.

Koskisto and Ellingwood [14] used the reliability theory to present the minimum LCC optimization of prefabricated concrete structures. They defined the total LCC (\( C_L \)) as

\[ C_L = C_D + C_P + C_C + C_Q + C_M + P_F C_F \]  \hspace{1cm} (5)

where \( C_D \) is the planning and design cost, \( C_P \) is the production cost, \( C_C \) is the construction cost, \( C_Q \) is the quality-assurance and quality control cost, and \( C_M \) is the preventive and corrective maintenance costs.

Frangopol et al. [3] provided that the expected total cost (\( C_{ET} \)) can be expressed as

\[ C_{ET} = C_{TC} + C_{PM} + C_{INS} + C_{REP} + C_F \]  \hspace{1cm} (6)

where \( C_{TC} \) is the initial cost of the structure, \( C_{PM} \) is the expected cost of routine maintenance, \( C_{INS} \) is the expected cost of inspection and repair maintenance, \( C_{REP} \) is the cost of repair, and \( C_F \) is the expected failure cost.

Wen and Kang [27] considered the limit-state cost function which consists of damage cost, loss of contents, relocation cost, economic loss, cost of injury, and cost of human fatality. It can be formulated as in the following:

\[ C_j = C_j^{dam} + C_j^{con} + C_j^{rel} + C_j^{eco} + C_j^{inj} + C_j^{fat} \]  \hspace{1cm} (7)

where \( C_j \) is the cost due to the jth limit state, \( C_j^{dam} \) is the damage/repair cost function, \( C_j^{con} \) is the loss of contents, \( C_j^{rel} \) is the relocation cost, \( C_j^{eco} \) is the economic loss caused by a structural damage, \( C_j^{inj} \) is the cost of injuries, and \( C_j^{fat} \) is the cost of human fatality.

BRIDGE LIFE-CYCLE COST ANALYSIS

The usage of concept of LCCA can be based on the requirement of the user. Taking into account the alternatives employed different construction methods and materials, we may obtain the cost optimization after comparing the optimum and pessimum. When a bridge engineering is determined to be constructed, the overall cost should be included from design cost to the costs of repair, strengthening and failure. The design goal of a bridge engineering is to minimize the total expected cost to manufacture. Koskisyo and Ellingwood [14] suggested a cost formula as follows:

\[ C_T = C_D + C_P + C_C + P_{f_j} C_{f_j} + P_{f_u} C_{f_u} \]  \hspace{1cm} (8)

where \( C_T \) is the total cost of project, \( C_D \) is the planning and design costs, \( C_P \) is the production cost, \( C_C \) is the construction cost, \( C_{f_j} \) and \( C_{f_u} \) are the costs associated with slab reaching unserviceability and ultimate limit states, respectively, and \( P_{f_j} \) and \( P_{f_u} \) are the probabilities of occurrence of serviceability and ultimate limit states, respectively.

If all attributes and consequences of a decision concerning a bridge structure can be represented in monetary terms, then an optimal decision will be the one that minimizes the LCC of the bridge structure. Generally speaking, if the benefits of each alternative are the same, then the expected LCC up to time \( T \) may be written as [26]
\[ C_T(T) = C_D + C_P + C_{QA} + C_{IN}(T) + C_M(T) + \sum_{t=1}^{N} P_{ft}(T_t)C_{SFt} \]  \hspace{1cm} (9) \\

where \( C_{QA} \) is the expected cost of quality assurance/control, \( C_M(T) \) is the expected cost of maintenance, \( C_{IN}(T) \) is the cost of inspections, \( N \) is the number of independent failure limit states (e.g., flexure, shear, spalling), \( P_{ft}(T) \) is the cumulative probability of failure for each limit state (i.e., probability that failure will occur anytime up to time \( T \)), and \( C_{SFt} \) is the failure cost (i.e., damages, cost of life, injury, user delay, etc) associated with the occurrence of each limit state.

The failure cost \( (C_{SFt}) \) in Eq. (9), Ang and Leon [1] suggested as

\[ C_{SFt} = C_r + C_c + C_e + C_{in} + C_f \]  \hspace{1cm} (10) \\

where \( C_r \) is the cost of repair or replacement, \( C_c \) is the loss of contents, \( C_e \) is the economic loss due to business interruption, \( C_{in} \) is the cost of injury, and \( C_f \) is the cost of fatality.

Huang and Lien [5] developed a performance-based bridge LCCA. The determination of the future time and cost scenario for a bridge alternative is divided into those of bridge components such as deck, pier, foundation, expansion joints, and so on [15]. For each component, the time and cost scenario are determined according to the past performance of similar components with similar engineering and environmental conditions. The total LC of a bridge can then be determined by summing up those of components.

Based on the theory of LCCA aforementioned, we may unify the relative factor of bridge LCC in a formula in terms of

\[ C_T(T) = C_D + C_C + C_P + C_{QA} + C_{M}(T) + \sum_{t=1}^{N} P_{ft}(T_t)C_{SFt} \]  \hspace{1cm} (11) \\

where \( C_R(T) \) is the cost of repair or replacement periodically.

Eq. (11) considers not only the current cost but also the most factors during life-cycle (LC). Since the occurrence factor during LC is the effect of economic cost, the capital benefit is to be considered. Thus, Eq. (11) may be rewritten as [12, 23, 25]

\[ C_T(T) = C_D + C_C + C_P + C_{QA} + \sum_{t=1}^{T_N} \frac{C_R(T_t) + C_{IN}(T_t) + C_M(T_t) + \sum P_{ft}(T_t)C_{SFt}}{(1 + r^t)} \]  \hspace{1cm} (12) \\

where \( T_N \) is the considering time (year) of LCC, and \( r \) is the capital benefit rate per year. The value of \( r \) for a RC or PC structure will not exceed 0.20. Note that a high value of \( r \) favours a short service life while a low value of \( r \) encourages longer service lives [26]. The value of \( 1 + r^t \) appeared in the denominator of Eq. (12) is taken the approximation of \((1 + r)^t\) which can be expanded by the general binomial expansion for a positive integer \( t \).

Although Eq. (12) consists of many factors, each factor may not be found the exact value. There are mutually related among factors. We now described them as follows:

1. Generally, the design cost, \( C_D \), is approached 2.5% of the production cost, \( C_P \) [14].
2. The production cost can be expressed as \( C_P = C_m + C_w \), where \( C_m \) is the material cost included the costs of concrete and steel, and \( C_w \) is the wages. Speaking generally, the ratio of \( C_m/C_w \) is 70/30 in those manufacturing plants surveyed [14].
3. The impact of the manufacturing process rate on \( C_w \) is stated by multiplying \( C_w \) by the factor \((55/fc')^2\), where \( fc' \) is the compressive strength of concrete. 55 MPa concrete needs 8 hours, which is one work shift, to achieve the release strength of 30 MPa in the concrete. Higher concrete strengths necessitate less time and thus reduce labor costs. As if reversed, lower strengths demand more time and increase labor costs [14].
4. The net area, \( A_n \), of the cross sections varies between 0.38 and 0.46 of the total area. An average fraction, 0.42, is applied by the formulation of the cost function [14].
5. The construction cost, \( C_C \), is equal to 0.01 times the span length (L) in m and thickness (h) in mm of the slab [14].
6. An optimum probability of failure is varied in the range 0.000001 to 0.01 [21].
7. In the safe range, the production cost, \( C_P' \), is obtained by the relationship between cover thickness and concrete strength. The ratio of \( C_P'/C_{QA} \) is listed in Table 1 [26].
8. To examine the effect of \( C_{SFt} \) on the LCC and, afterwards, on the optimal durability design specification, this parameter can be expressed in a formula as [26].

\[ C_{SFt} = 2C_P + C_{QA} \]  \hspace{1cm} (13) \\

9. The maintenance cost \( C_M(T_t) \) is 3 times per year. The value of each area with 1m\(^2\) is about 25 dollars.
10. The inspection cost \( C_{IN}(T_t) \) is 2 times per year. The value of each inspection point is about 200 dollars.
11. The cost of periodic repair or replacement is about
0.6 times the cost of repair or replacement [5].

Based on the condition formula mentioned above, Eq. (12) may be used to predict the expected LCC, \( C_T \), to different construction models. It is worthy to point out that we may increase or decrease the factor in Eq. (12) based on the suitable situation. Moreover, the values of terms 9 to 11 above is the current predicted value.

**ILLUSTRATIVE EXAMPLES**

**Example 1**

The Ching-shoei bridge in I-land, Taiwan, is located at Tai-7-bing 6K + 360. This bridge belongs to a straight one and has total length 490 m. The width of the bridge is 14 m. This bridge has a standard cross-sectional PCI Type VI of AASHTO as shown in Figure 1. This PCI-Type VI has the value of 20,000 dollars per m\(^2\). Six PC Type I beam with height 185 cm are beared by capping beam. The substructure is employed by the two column piers above pile cap. The length and width of road base are 750 m and 15 m, respectively. Assume that the rate of capital benefit per year is 15\%. Find the needed cost after 50 years. If use a single PC box-type beam with two hides on a pier wall as shown in Figure 2. There are three bearing between box-type beam and pier wall. The PC box-type beam has the value of 24,000 dollars per m\(^2\). The beam is of varied height between 190 to 230 cm. Find the needed cost after 50 years.

1. **Use PC I-type beam**

First, we calculate the material cost \( C_m \). Assume that the engineering cost of road base is of 3503 dollars per m\(^2\). The engineering cost of the total area 11250 m\(^2\) of road base is about 3940 \times 10^4 dollars while the engineering cost of the total area 7154 m\(^2\) of PCI-type VI is 14308 \times 10^4 dollars. Thus, the material cost is \( C_m = (3940 + 14308) \times 10^4 = 18248 \times 10^4 \) dollars. Because \( C_m/C_w = 70/30 \), we obtain \( C_w = 7820.6 \times 10^4 \) dollars. The production cost is \( C_p = C_m + C_w = (18248 + 7820.6) \times 10^4 \) dollars. Assume that both the compressive strength and cover thickness of concrete are 50 MPa and 50 mm, respectively. Using Table 1, the quality assurance cost is \( C_{QA} = 0.022 C_p = 573.5 \times 10^4 \) dollars. Employing Eq. (13), \( C_{SFt} = 2C_p + C_{QA} = 2.022 C_p = 52710.7 \times 10^4 \) dollars. As to failure probability, we know 0.000001 < \( P_f(T_f) < 0.01 \). Owing to it has not real calculation, we assume that the safe value is 0.0001. If further consider the relationship between time and failure probability, then the failure probability may be increased correspondingly passed long time. Suppose that the increasing value is 0.0001 per t years. Therefore, we obtain \( P_f(T_f) = 0.0001it \). The maintenance cost is \( C_m(T_f) = 25 \) (dollars/m\(^2\)) \times (11250 + 7154)(m\(^2\)) = 46 \times 10^4 dollars. Since the maintenance cost \( C_m(T_f) \) is 3 times per year, we have \( C_m(T_f) = 3 \times 46 \times 10^4 = 138 \times 10^4 \) dollars. The inspection cost \( C_{IN}(T_f) \) is referred as one point per 10 m\(^2\). We calculate out 1840 points from all area. The inspection cost of one times is 200 (dollars/point) \times 1840 point.
Table 1. Additional(+) or reduced(–) cost of expected cost of quality assurance (CQA) estimated by production cost (Cp) [26]

<table>
<thead>
<tr>
<th>Cover thickness (mm)</th>
<th>Compressive strength f’c (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>50</td>
<td>–0.072 Cp</td>
</tr>
<tr>
<td>70</td>
<td>0.026 Cp</td>
</tr>
</tbody>
</table>

Thus, we have

\[ C_\text{T}(T) = [651.7 + 740 + 26068.6 + 573.5 + 0.00005 \times (52710.7) \times 10^4] \times 10^4 \]

\[ = 48291.6 \times 10^4 \text{ dollars} \]

According to Eq. (12), we obtain that the total LCC of Ching-shoei bridge needs 48291.6 \times 10^4 dollars after using 50 years.

2. Use single PC box-type beam with two holes

Since the unit cost of PC box-type beam is 24,000 dollars/m², and the total area of the beam is of 7154 m², we need engineering cost 24,000 dollars/m² \times 7154 m² = 17169.6 \times 10^4 dollars. The engineering cost of the total area 11250 m² of road base is of 3940 \times 10^4 dollars. Hence, the material cost is \[ C_m = (17169.6 + 3940) \times 10^4 = 21109.6 \times 10^4 \text{ dollars.} \] The wage \[ C_w = 9047 \times 10^4 \text{ dollars due to} C_w/C_m = 70/30. \] The production cost is \[ C_p = C_m + C_w = (21109.6 + 9047) \times 10^4 = 30156.6 \times 10^4 \text{ dollars.} \] The design cost is \[ C_D = 2.5\% C_p = 0.025 \times 30156.6 \times 10^4 = 753.9 \times 10^4 \text{ dollars.} \] The construction cost is \[ C_c = 0.01H = 0.01 \times 48 m \times 2100 (mm) = 1008 \times 10^4 \text{ dollars.} \] It is needed to point out that the value 2100 mm of thickness is the average of 1900 mm and 2300 mm of varied height. Because both the compressive strength and cover thickness employed are not changed, the quality assurance cost is still the same, i.e. \[ C_{QA} = 573.5 \times 10^4 \text{ dollars.} \] Inserting the values of \[ C_p \text{ and } C_{QA} \text{ into Eq. (13), we got } C_{SP} = 60976.6 \times 10^4 \text{ dollars.} \] Because the degree of durability of single PC box-type beam with two holes is better than that of the PC I-type beam, we set that the failure probability is of 0.0001 and is increasing with 0.00005 per t years. Thus, we have \[ P_f(T_t) = 0.0001 + 0.00005t. \] Since the maintenance, inspection, and periodic repair or replacement costs are still not changed, we know \[ C_m(T_t) = 138 \times 10^4 \text{ dollars,} \] \[ C_{IN}(T_t) = 73.6 \times 10^4 \text{ dollars, and} \] \[ C_R(T_t) = 60 \times 10^4 \text{ dollars.} \] Putting the above calculated values into Eq. (12), we have

\[ C_T(T) = [753.9 + 1008 + 30156.6 + 573.5 + 0.00005 \times (52710.7) \times 10^4] \times 10^4 \]

\[ = 49652 \times 10^4 \text{ dollars} \]

Based on Eq. (12), we know that the total LCC of Ching-shoei bridge necessitates 49652 \times 10^4 dollars after using 50 years.

Example 2

The Keelung Gang-xi viaduct in Taiwan, was built in 1972. This viaduct was the only convenient and fast road connected to external region of the west harbor in Keelung. This viaduct is from the Guang-hwa tunnel of west harbor to jointing the beginning point of Jong-shan highway. The total length of the viaduct is 2.9 km. The viaduct has width 7.5 m with two lane for single traveling. The superstructure is used PC beam. Using the recent testing data [8, 9] and analytical results of failure probabilities [6] of the viaduct, we may predict the LCCA to this viaduct. Assume that the rate of capital benefit r is 14%. It needs how much cost when used till 1996. And it also necessitates how much cost when employed until 2002.

First, the material cost \[ C_m \text{ should be considered.} \] Since this bridge engineering was made by many construction companies. The real data is not easy to acquire. Thus, we may assume that the material cost is \[ C_m = 100000 \times 10^4 \text{ dollars.} \] The wages are \[ C_w = 42857 \times 10^4 \text{ dollars due to } C_m/C_w = 70/30. \] The production cost is \[ C_p = C_m + C_w = 142857 \times 10^4 \text{ dollars.} \] The design cost is \[ C_D = 2.5\% C_p = 3571.4 \times 10^4 \text{ dollars.} \] The construction cost
is $C_c = 0.01Lh = 0.01 \times 2900 \text{ (m)} \times 1200 \text{ (mm)} = 34800 \times 10^4$ dollars. Suppose that the compressive strength and cover thickness of concrete are 50 MPa and 70 mm, respectively. Using Table 1, we may find the quality assurance cost is $C_{QA} = -0.075C_p = -10714.3 \times 10^4$ dollars. Applying Eq.(13), we obtain the failure cost $C_{SFt} = 2C_p + C_{QA} = 274999.7 \times 10^4$ dollars. Hung [6] used the linear unbiased evaluation method of normal distribution to predict the failure probabilities of the damage model of Keelung Gang-xi viaduct in 1996 and 2002 as shown in Table 2. It may be predicted that when the failure probability reaches a constant value, the successive increasing failure probability can be of the percentage $t^2$ increase per year. Using this concept and Table 2, we can calculate the following items:

1. Compressive strength
   $$\overline{P}_f = (0.19035 - 0.17234)/\sum_{i=1}^{6} t^2 = 0.000035$$

2. Carbonation
   $$\overline{P}_f = (0.005224 - 0.001462)/\sum_{i=1}^{6} t^2 = 0.0000413$$

3. Chloride ion content
   $$\overline{P}_f = (0.49623 - 0.19435)/\sum_{i=1}^{6} t^2 = 0.00332$$

4. Crack
   $$\overline{P}_f = (0.029494 - 0.00175)/\sum_{i=1}^{6} t^2 = 0.000255$$

Before 1996 (i.e. 1972 - 1996), the predicted increment of failures probability of the viaduct is described as follows:

1. Compressive strength:
   If $\overline{P}_f = \sum_{i=1}^{n} 0.000035(t-1)^2$ then $P_f = 0.00084$.

2. Carbonation:
   If $\overline{P}_f = \sum_{i=1}^{n} 0.00000029(t-1)^2$ then $P_f = 0.000041$.

3. Chloride ion content:
   If $\overline{P}_f = \sum_{i=1}^{n} 0.000000396(t-1)^2$ then $P_f = 0.00031$.

4. Crack:
   If $\overline{P}_f = \sum_{i=1}^{n} 0.00000035(t-1)^2$ then $P_f = 0.000035$.

The maintenance, inspection, and periodic repair or replacement costs are also predicted as $C_{M(T)} = 414 \times 10^4$ dollars, $C_{IN(T)} = 220.8 \times 10^4$ dollars, and $C_{R(T)} = 180 \times 10^4$ dollars, respectively. Substituting these factors mentioned above into Eq. (12), we obtain both the total LCC of Keelung Gang-xi viaduct between 1972 and 1996 and between 1996 and 2002, respectively.

$$C_{T}(T) = \left[ 3571.4 + 34800 + 142857 - 10714.3 + 180 + 220.8 + 414 + \left( 0.001226 + 0.00007524 \sum_{i=1}^{24} t^2 \right) \times 274999.7 \right] \times 10^4 = 299375 \times 10^4 \text{ dollars}$$

and

$$C_{T}(T) = \left[ 3571.4 + 34800 + 142857 - 10714.3 + 180 + 220.8 + 414 + \left( 0.3699 + 0.0576(t-24)^2 \right) \times 274999.7 \right] \times 10^4 = 2356040 \times 10^4 \text{ dollars}$$

**DISCUSSION**

Eq. (12) includes many factors and applies in the real PC bridges. At present, the concept of LCC is seldom used in bridge structures. Some factors are still not of unified constant cost. It is inevitable that we need some experience cumulations for finding the expected costs. For instance, among the maintenance, inspection, and periodic repair or replacement costs are all necessary the experience cumulation for seeking their relations. With regard to employing different materials, they have different merits and defects. Certainly, they need different costs. It is needed the applied material for analysis. As to failure cost, it is also simplified and is just predicted by both the $C_p$ and $C_{QA}$ (see Eq. (13)). Obviously, the choice of material and bridge type will directly influence the other factors and costs.

In example 1, we use two kinds of beam. The
difference between the PC I-type and box-type beams for each m², total $C_M(T_t)$ and $C_p$ are $4000 \times 10^4$ and $4088 \times 10^4$ dollars, respectively. If additional the other costs, then they have difference $12648 \times 10^4$ dollars. If additional other costs, then they have difference $12648 \times 10^4$ dollars. The total $C_T$ of both them has difference $1361 \times 10^4$ dollars after using 50 years. It is noteworthy to point out that the failure probability is an important factor. The corresponding occurrence failure probability is relative low when we use the bridge type with higher price. This is not only influenced the bearing capacity but also influenced the total LCC of bridge.

As in the case of example 2, based on the failure probabilities obtained by Hung [6], we have LCC with $2056665 \times 10^4$ dollars between 1996 and 2002. Therein, the failure probability plays an important role in deed. According to the studied results [6], the increment rate of failure probability will enlarge as time increase. From this, we may know that when the failure probability reaches a certain value the bridge should be done repair or strengthening for reducing the value of failure probability. Assume that the Keelung Garg-xi viaduct was done a repair and strengthening in 1996. The failure probabilities of compressive strength, carbonation, chloride ion content, and crack are reduced as $0.13221$, $0.0006$, $0.06$, and $0.0005$, respectively. We may also assume that the increment rate is the same as that before 1996. Till 2002, the total LCC is

$$C_T(T) = [3571.4 + 34800 + 142857 + 10714.3 + \sum_{i=1}^{24} (180 + 220.8 + 414 + (0.001226 + 0.00007524 i^2) \times 274999.7) \times 1 + 0.14^t]$$

$$+ \sum_{i=25}^{30} (180 + 220.8 + 414 + (0.19331 + 0.00007524 (i - 24)^2) \times 274999.7) \times 1 + 0.14^t]$$

$$\times 10^4 = 625108 \times 10^4$$

It is very obvious to save $1730932 \times 10^4$ dollars. Therefore, the failure probability of bridge structure needs evaluation periodically. The bridge structure should be repaired or strengthen when it occurs the damage state. For cutting down expenses, the failure probability should be avoided expansion. As a result of the demand cost very large, the Keelung Gang-xi viaduct is not worthy to repair or strengthening. The major reason is that both the failure probabilities of compressive strength of concrete and chloride ion content are too large. According to the used and environmental conditions of the subjective and objective points of view, Liang et al. [16] provided the failure probability grade of existing reinforced concrete structures as shown in Table 3. Based on the evaluation of failure probabilities in 1996 and 2002, both the failure probabilities of chloride ion content have been jumped over grade D. Hence, the Keelung Gang-xi viaduct was determined to demolish by the Keelung Harbor Bureau in 2003.

**CONCLUSIONS**

Based on the results of LCCA of existing PC bridges, some important conclusions are drawn as follows:

1. In this paper, the expected total cost of existing PC bridge consists of the cost of design, content loss, production, quality assurance, periodic repair or replacement, inspection, maintenance, failure and capital benefit.
2. The capital benefit cost of every year increasing was considered in the LCCA of existing PC bridges and was very reasonable and serviceable. This concept is better than that of a single cumulation.
3. Using the existing PC bridge as illustrative examples, the expected total cost after servicing some years can be estimated for avoiding the unsuitable repair or uncertain expense. The routine work needed to be done every year can be truly performed such as the costs of maintenance, periodic repair or replacement, and inspection.
4. The expected total cost of existing PC bridge is influenced by the failure probability. In relation to the finding of failure probability, it is really worthy to study in-depth.

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| Table 3. Failure probability grade evaluation of exist reinforced concrete structures [16] |
|------------------------------------|---------------------------------|-----------------|-----------------|
| **Grade A**                       | **Grade B**                     | **Grade C**     | **Grade D**     |
| $P_f < 10\%$                      | $10\% < P_f < 20\%$            | $20\% < P_f < 30\%$ | $30\% < P_f$   |
| The structure can be used continuously. | The structure need perform a local repair in a small region. | The structure should carry out a large repair. | The structure should be executed the whole repair or reconstruction after demolition. |
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