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Practical Application of Life-Cycle Cost Effective Design and Rehabilitation of Bridges

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Recently, the demand on the practical application of life-cycle cost effective design and rehabilitation of bridges is rapidly growing in civil engineering practice. However, in spite of impressive progress in the researches on the Life-Cycle Cost (LCC), the most researches have only focused on the theoretical point but did not fully incorporate the critical issues for the practical implementation. Thus, this paper is intended to suggest a systemic integrated approach to the practical application of various LCC methodologies for the design and rehabilitation of bridges. For that purpose, hierarchical definitions of LCC models are presented to categorize the approach of LCC assessment applicable for the practical implementation. And then, an integrated LCC system model is introduced with an emphasis on data uncertainty assessment and user-friendly knowledge-based database for its successful implementation. Finally, in order to demonstrate the LCC effectiveness for design and rehabilitation of real bridge structures, illustrative examples are discussed.

Keywords : *life-cycle cost, design, rehabilitation, bridges, LCC system model*

1. Introduction

Though the concept of Life-Cycle Cost (LCC) itself is not new, its effectiveness for planning, design, rehabilitation and maintenance/management of bridges is becoming increasingly recognized, recently in practice. However, the Life-Cycle Cost Analysis (LCCA) for bridges becomes extremely complex simply because time-variant degrading resistance and stochastic extreme load effects can incur various failures related with strength, serviceability, durability, deterioration, and damage throughout the whole life span of a bridge, which, in turn, bring forth highly complicated cost and uncertainty assessment that often involves the lack of cost data associated with various direct and indirect losses, and the absence of uncertainty data available for the assessment as well.

During the last two decades, there are impressive progress in the researches on the LCC, a number of researchers proposed methodologies for LCCA and LCC assessment of design, maintenance and rehabilitation of civil structures. However, it has been found that the most researches have only focused on the theoretical point but did not fully incorporate the critical issues for the practical implementation. Thus, the objective of this paper is to suggest a systemic integrated approach to the practical application for the design and rehabilitation of bridges. First, hierarchical definitions of LCC models are presented to categorize the approach of LCC assessment applicable for the practical implementation of the LCC-effective design and rehabilitation of bridges. And then, an integrated LCC system model is introduced with an emphasis on data/uncertainty assessment and user-friendly knowledge-based database for its successful implementation. Finally, in order to demonstrate the LCC effectiveness for design and rehabilitation of real bridge structures in practice, illustrative examples are presented.

2. Life-cycle cost approaches

LCC may be simply defined as an economic evaluation of a structure over a desired service life, taking into consideration of all the expected costs incurred. Feasible improvements in each alternative decision on design or rehabilitation can be evaluated or compared, using the equivalent values. Equivalent values are computed by converting the stream of all the time-related costs to a single equivalent value such as the present worth, annual worth, or future worth. Based on the investigation of various kinds of LCC models available so far for the LCC assessment of design and rehabilitation as well as maintenance and management of structure, the following four approaches of LCC models may be defined depending upon the characteristics of applied problems for LCC assessment of bridges.

2.1 Deterministic or probabilistic LCCA approach

A simple LCCA without reliability and uncertainty assessment may be effectively used in the conceptual design of a new bridge, so that the economical efficiency of the structure over the life span can be achieved by the optimal selection of construction type, durable construction materials, and construction method. And also, it can be applied to the maintenance and rehabilitation problems of existing bridges, so that the optimal decision on the maintenance or repair method, economical efficiency and maintenance strategy can be made in terms of LCC effectiveness during the remaining or extended service life of the bridge. Theoretically, these LCCA problems could be very complex or stochastic mainly due to the loading history and operational environment, etc. However, usually practical approaches to LCCA are based on the most simplified form of LCC model. In general, this simple LCCA can be divided into Deterministic LCCA (DLCCA) and Probabilistic LCCA (PLCCA).

DLCCA is the simplest method that only uses simple expected cost assessment without considering uncertainties of input variables in a LCC analysis and produces only one deterministic result. But the problem with this approach is that the uncertainty is often ignored in a DLCCA, which can be reduced by incorporating a sensitivity analysis or probabilistic approach into decision-making process as in the following way. PLCCA may be defined as the LCCA method that utilizes MCS in the treatment of uncertain input variables to generate probabilistic results. Therefore, it is recommended in FHWA[11] that this PLCCA approach is more reasonable and scientific than the DLCCA. Similar to the inputs, the results of PLCCA are visually presented in the form of a probability distribution. Thus, more information such as distribution of LCC, and the chance (probability) for becoming optimal alternative, etc. can be acquired.

In general, either deterministic or probabilistic LCC model can be formulated as follow:

$$E[C_T(x,T)] = C_I(X) + \sum_{t=1}^{T} \frac{1}{(1+q)^t} \left[E[C_D(x,t)] + E[C_{ID}(x,t)] \right] \quad (1\text{-a})$$

$$E[C_D(x,t)] = E[C_M(x,t)] + E[C_R(x,t)] + \sum_{K=1}^{K} O_k(d_k(x,t)) \cdot r_k(d_k(x,t)) \cdot C_I(x) \quad (1\text{-b})$$

$$E[C_{ID}(x,t)] = \begin{bmatrix} C_H \cdot \left\{ t_M(x) \cdot r_M(x) + t_R(x) \cdot r_R(x) + \sum_{k=1}^{K} O_k(d_k(x,t)) \cdot \left[t_{d_k}(x) \cdot r_{d_k}(x) \right] \right\} + \\ C_U \cdot \left\{ t_M(x) + t_R(x) + \sum_{k=1}^{K} O_k(d_k(x,t)) \cdot \left[t_{d_k}(x) \right] \right\} + \\ C_E \cdot \left\{ t_M(x) \cdot + t_R(x) \cdot + \sum_{k=1}^{K} O_k(d_k(x,t)) \cdot \left[t_{d_k}(x) \right] \right\} \end{bmatrix} \quad (1\text{-c})$$

where C_I = initial cost; C_D, C_{ID} = direct rehabilitation cost and indirect losses, respectively, espectively which are functions of time t and design variable x; q = discount rate; C_M, C_R = ordinary maintenance costs and repair/replacement costs, respectively; C_H, C_U, C_E = loss of contents or fatality and injury losses, user cost, and socio-economic losses, respectively; O_k = occurance probability of damage state d_k ; t_M, t_R, t_{d_k} = period of ordinary maintenance, repair/replacement, and restoration for damage state d_k, respectively ; r_M, r_R, r_{d_k} = accident rate during ordinary maintenance, repair/replacement, and restoration for damage d_k, respectively; d_k = system damage state (k=1, ..., K); and r_k = percent of initial cost for damage state k

2.2 Structural reliability based approaches

Optimal LCC-effective structural design of a new structure or optimal rehabilitation design of an existing structure involves the assessment of all the expected failure probability and associated costs. Therefore, obviously, neither DLCCA nor PLCCA can be used for these cases. These LCC design problems could be effectively solved rationally using Time-Invariant Structural Reliability based Approach (TISRA) or Time-Variant Structural Reliability based Approach (TVSRA).

In the LCC optimization of structural design, TISRA could be used practically but approximately except for the cases where time-variant loading like that of earthquake or other natural hazards should be considered. In the design phase, it may be very difficult to precisely estimate expected maintenance and repair costs. Wen and Kang (1997)[13] did not consider the maintenance cost on the ground that its dependence on the design variables would be generally weak. So the TISRA could be applied practically to new structural design or a rehabilitation problem of the bridges if the expected maintenance costs and repair/replacement costs are not considered in the problem formulation. In this case, the discount rate should not be applied, since only expected failure costs for critical limit states are considered in the model. Therefore, the general TISRA model can be formulated as follows:

$$E[C_T(X,T)] = C_I(X) + \sum_{k=1}^{K} E\left[C_{FS_k}(X,T)\right] \tag{2-a}$$

$$E\left[C_{FS_k}(X,T)\right] = P_{FS_k}(X,T) \cdot \left[C_{r_k}(X) + C_H \cdot r_{r_k}(X) + C_U(t_{r_k}(X)) + C_E(t_{r_k}(X))\right] \tag{2-b}$$

where $E\left[C_{FS_k}\right]$ = expected failure cost for considered limite state k; T = specified time such as design life or service life; C_r = direct rehabilitation cost; P_{FS_k} = probability of failure for considered limite state k; t_{r_k} = period of rehabilitation activities; and r_{r_k} = accident rate during rehabilitation activities

And thus the formulation for the cost effective optimum design or rehabilitation problem using TISRA can be represented as follows:

$$\text{Minimize} \quad E[C_T(X,T)] \tag{3-a}$$

$$\text{For} \quad X^L \le X \le X^U \tag{3-b}$$

$$\text{Subject to} \quad G_j(X) \le 0, \; j = 1,2,\ldots,N_s \quad P_{FS}(X,T) \le P_{FS_{allow}} \tag{3-c}$$

where $E[C_T(X,T)]$ = total expected LCC specified in Eq. 2 for a specified life time T; X = the vector of design variables such as thickness or length; $G_j(X)$ = j-th constraint; N_s = the number of constraints; X^L, X^U = the lower and upper bounds, respectively; and $P_{FS_{target}}$ = allowable probability of failure

In reality, the performance of a structure is a time-variant property which depends on the history of applied loads and the operational environmental deterioration. For the LCC assessment of optimal design or upgrading criteria under natural hazards such as seismic or wind loads, TVSRA should be inevitably applied. In this case the quantification of the structural damages under all possible natural hazards, and the evaluation of the total expected LCC through the establishment of quantitative relations between the computed structural damage and life cycle damage costs are required. A general LCC model for optimal design or upgrading criteria under multiple hazards can be found in reference.[12]

So far, many analytical performance prediction models for the critical damage have been developed by many researchers. However, the model which describes the real phenomenon in detail is rare. A general LCC model for optimal maintenance or management strategies considering performance prediction models for the critical damage can be found in the references.[6),10)] The detailed description of seismic models and frameworks for LCC assessment is also given in the references.[3),9)]

3. Indirect cost model

As aforementioned, each LCC model involves the assessment of direct and indirect costs. For an individual structure like a building structure, it can be argued that only the owner's cost may be relevant and thus it might have a minor influence on public user cost or socio-economic losses. But for the bridges, the indirect costs accruing to the public user of these structural systems should also be accounted for because those structures are primary public investments. In the paper, improved indirect cost models of road user cost and indirect socio-economic losses cost model are presented in particular for rational assessment of indirect cost of bridges.

In general, road user costs consist of 5 major cost items – namely, vehicle operating costs, time delay costs, safety and accident costs, comfort and convenience costs, and environmental costs. Among the items, time delay costs and vehicle operating costs have been generally considered as major cost items of the road user cost.[3),4)] To evaluate the rational road user costs, the essential factors such as traffic network, location of bridge, and the information on rehabilitations (i.e., work zone condition, detour rate, the change of traffic capacity of traffic network, etc.) must be considered. Based on the previous research,[3)] in this study, a new road user cost model is introduced as follows:

$$C_U = C_{TDC} + C_{VOC} \tag{4-a}$$

$$C_{TDC} = \left\{\sum_{j=1}^{J} n_{P_{0j}} \cdot T_{0j} \cdot u_{1_{0j}}\right\} \cdot \left(1 - \sum_{i=1}^{I} r_i\right) \cdot \Delta t_{d0} + \sum_{i=1}^{I}\left\{\sum_{j=1}^{J} r_i \cdot n_{P_{ij}} \cdot T_{0j} \cdot u_{1_{0j}} + n_{P_{ij}} \cdot T_{ij} \cdot u_{1_{ij}}\right\} \cdot \Delta t_{di} \tag{4-b}$$

$$C_{VOC} = \left[\begin{array}{l} \left\{\sum_{j=1}^{J}(T_{0j} \cdot u_{2j})\right\} \cdot \left(1 - \sum_{i=1}^{I} r_i\right) \cdot \Delta t_{d_0} + \sum_{i=1}^{I}\left\{r_i \cdot \sum_{j=1}^{J}(T_{0j} \cdot u_{2j}) + T_{ij} \cdot u_{2j}\right\} \cdot \Delta t_{d_i} + \\ \sum_{i=1}^{I}\left\{r_i \cdot \sum_{j=1}^{J}\left[T_{0j} \cdot (u_{3_{ij}} l_{d_i} - u_{4_{ij}} l_{d0}) + T_{ij} \cdot u_{2j}\right]\right\} \cdot \Delta t_{d_i} + \end{array}\right] \tag{4-c}$$

$$\Delta t_{d_i} = \frac{l_{d_i}}{v_{d_{ai}}} - \frac{l_{d_i}}{v_{d_{ni}}}, \quad \Delta t_{d_0} = \frac{l_o}{v_{o_a}} - \frac{l_0}{v_{d_n}} \tag{4-d}$$

where i = an index for route in network; j = an index of types of vehicles which should be classified into those for business or non-business such as owner car for business, owner car for non-business, taxi, bus for business, bus for non-business, small truck, and large truck etc.; o = an index for original route in network; $n_{P_{ij}}$ = number of passengers in vehicle; $n_{P_{ij}}$ = number of passengers in vehicle; T_{ij} = Average Daily Traffic Volume (ADTV); $u_{1_{ij}}$ = average unit value of time per the user ; u_{2j} = average operator wages for each type of vehicle ; $u_{3_{ij}}$ = average unit fuel cost per unit length on the each detour route; $u_{4_{ij}}$ = the average unit fuel cost per unit length on the original route; r_i = detour rate form original route to i-th route ; Δt_{d0} = the additional time delay on the original route; l_o, l_{d_i} = the route length of bridge route (the route including bridge) and detour route; V_{o_n}, V_{o_w} = the average traffic speed on the original route during normal condition and rehabilitation activity; and $V_{d_{ei}}$, $V_{d_{wi}}$ = the average traffic speed on detour route during normal condition and rehabilitation activity, respectively.

Indirect socio-economic losses are result of multiplier or ripple effect in economy caused by functional failure of a structure. In case of a bridge, these indirect losses are influenced by not only the road user of a functionally failed bridge but also all the road users and the regional industrial sectors within the traffic networks where the bridge is located. Recently, based on the previous research,[9] an improved cost model is proposed, which can be reasonably applied to a bridge for the assessment of the indirect socio-economic losses incorporating the effect of traffic network.[2]

However, because for the assessment of road user cost and indirect socio-economic losses using the proposed indirect cost models, highly complicated site-specific data are required, it is extremely difficult or even impossible to apply these models to each bridge. Therefore, currently, an extensive study on the approximate but reasonable approach is underway, that utilizes site-categorizing data for each major parameter of these cost models for the practical implementation of the indirect cost.

4. LCC system model for practical application

4.1 LCC system model

Though a number of LCC systems have been developed, there are only few systems practically applicable to the real problems. Moreover, nowadays engineers in practice are always concerned about the availability of integrated system applicable for LCC-effective decisions on design and rehabilitation of various kinds of structures. For instance, in conceptual design phase, engineers need some powerful LCC assessment tools for the selection of construction type, durable construction materials, and construction methods. For these problems, the DLCCA and PLCCA model may be applied effectively. In case of the structural design of the superstructure of a bridge, or in case of repair/retrofit/strengthening design or upgrading of a deteriorated and/or damaged bridge, design live loads will dominate the optimum LCC design in most cases, where the TISRA model could be applied effectively. But, whenever the risk of earthquake or other natural hazards must be considered in the design of civil infrastructure like substructures of a bridge, it should be carried out by TVSRA seismic LCC model. The more detailed schematic integrated LCC system model is presented in the reference.[2]

4.2 The uncertainty assessment and development of user-friendly knowledge-based data base

In the development of the LCC software system, first of all, the construction of the knowledge-based DB is the most important part. The main function of the knowledge-based DB is to store and assess all the cost and uncertainty data as well as all the information, such as essential information on rehabilitations (i.e., rehabilitation cost, work-zone condition, etc.), site-specific information on site characteristics and traffic network, etc., and various information associated with indirect cost assessment. As shown in Fig. 1, the information can be acquired by historical data, expert's opinion, engineering practice and analytical damage prediction model which comprise of key components of the DB. However, it should be emphasised that, because the acquired data and the models for the LCC assessment have uncertainties, the effort to reduce these uncertainties must be done in the uncertainty assessment and, moreover, the system should be constructed with user-friendly pre-and post-processor.[2]

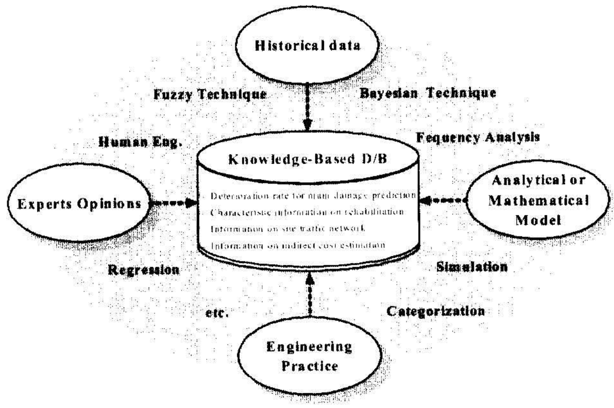

Fig. 1. Conceptual Diagram for Knowledge-Based Data Base

5. Illustrative examples and disscusions

5.1 Determination of LCC-effective optimal bridge type at conceptual design stage

This example demonstrates that the PLCCA model can be effectively applied in practice in order to select the LCC-effective optimal bridge type of an actual bridge at conceptual design stage. For the purpose, two bridge types - namely, Steel Box Girder bridge (alternative-1) and PSC Box Girder bridge (alternative-2) by Full Staging Method (FSM) are considered as the alternatives. The bridge will be constructed as a part of a rural highway which has relatively moderate ADTV. Fig. 2 shows the neighboring highway. In this example, the LCCA is implemented for 75 years, and the traffic volume more than 20 years is assumed not to increase after 20 years. At the conceptual design stage, optimal bridge type should be selected by considering VE aspects incorporating economy (LCC), safety, aesthetic, workability, functionality, maintenance convenience, environmental effect, etc. Thus, for this conceptual design problem, the LCCA is carried out as a part of VE evaluation of the alternative bridge types.

In evaluating the LCC for each alternative, maintenance scenario is assumed to be conducted by the current Korean

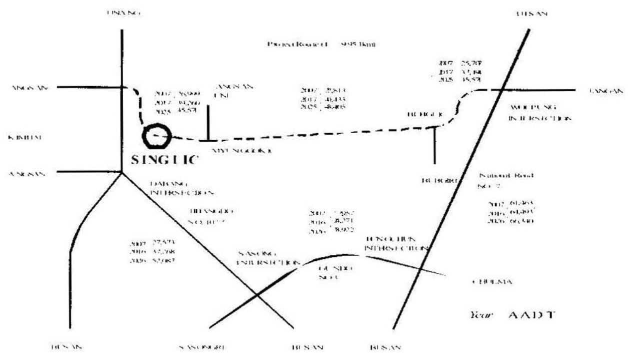

Fig. 2. Traffic Network Neighboring Sample Bridge

Table 1. Amount and Maintenance Period for LCC Analysis (current maintenance)

Item		Alternative-1 (Steel Box Girder bridge)					Alternative-2 (PSC Box Girder bridge)				
		Amount	Period			Cost (×1,000won)	Amount	Period			Cost (×1,000won)
			I	II	III			I	II	III	
Deck	Re	1,150m^2	20	26	34	392.18	-	-	-	-	-
	R	575m^2	-	-	-	372.85	575m^2	12	16	20	372.85
	M	610m^2	10	12	15	111.2	1,410m^2	14	18	22	111.2
Pier	M	136.7m^2	8	12	16	111.2	136.7m^2	8	12	16	111.2
Pavement	M	1,050m^2	8	10	12	66,315	1,050m^2	8	10	12	66,315
Girder	P	1,704m^2	10	13	15	111.9	-	-	-	-	-
	M	-	-	-	-	-	575m^2	1	3	4	95.03
Bearing	M	2.82ea	5.56	6.95	8.34	331.0	2.82ea	5.56	6.95	8.34	331.0
	R	6ea	8	11	15	13,292	6ea	8	11	15	13,292
Expansion Joints	Re	23m	8	10	15	7771.5	23m	8	10	15	13,280
Railing	M	244m	6.4	8.05	9.66	266.3	224m	6.44	8.05	9.66	266.3
	R	400m	11.0	13.8	16.6	416.2	400m	11.0	13.8	16.6	416.2
Initial inspection		-	one time at first year			91,705	-	One time at first year			91,705
Periodic inspection		-	four times per year			4,383	-	four times per year			4,383
Detailed inspection		-	every five years			12,628	-	Every five years			13,088
Detailed diagnosis			every five years after 15 years			91,705	-	every five years after 15 years			83,986
Preventive maintenance		-	Every years			0.15% of C_I		every years			0.15% of C_I

Descriptions
Re : Replacement, R : Repair, M : Management, P : Painting
I : Minimum traffic volume, II : Mean traffic volume, III : Maximum traffic volume

Table 2. Major Parameters used in LCCA

Parameter	Value	Unit	Reference
The traffic accident cost	0.12	billion won	KOTI (http://traffic.metro. seoul.kr)
Traffic accident rate during repair work activity	2.2	million vehicle/kilometers	
Traffic accident rate during normal condition	1.9	million vehicle/kilometers	
The value of fatality	3.5	billion won	Lee and Shim (1997)
The value of injury	21	million won	
The hourly driver cost	21,517	Won/person	KOTI
Discount rate	3.5~5.5	%	KISTEC (2000)

maintenance practice based on the survey of expert's opinion.[8] The total amount for each alternative considered in LCCA, and rehabilitation costs due to maintenance strategy, period of subsequent rehabilitations are shown respectively in Table 1. The data related with the maintenance for each alternative as shown in Table 1 are obtained based on the most commonly used methods in Korea.[7] The more detailed data for each alternative applied in LCCA can be found in the reference.[7] Also, Table 2 shows the major parameters used in the LCCA.[1]

Since indirect cost is one of the most important costs,[2] the following four cases are investigated to demonstrate the effect of applied indirect cost model on the LCC: (1) LCCA considering only direct rehabilitation cost (Case A); (2) LCCA using direct rehabilitation cost and the NIST's simplified road user cost model[5] in which the effect of traffic network is not included in the formulation (Case B); (3) LCCA considering direct rehabilitation cost and elaborate indirect cost model proposed in this study except socio-economic losses (Case C); and (4) LCCA including all aspects of cost model proposed in this study (Case D).

Table 3 show the results of the LCCA based on DLCCA for the alternative-1 and 2, respectively. As shown in the Table, the alternative-2 (PSC-Box Girder bridge) is evaluated as more economical alternative for Case A if only direct rehabilitation cost is considered. However, the alternative-1 (Steel Box Girder bridge) is evaluated as more economical one for Case B~D if direct and indirect effects (road user cost and socio-economic losses) are considered. Also, in the table, it may be seen that the ratio of indirect cost to total LCC are about 82~86% when the NIST's road user cost model is used, about 85~90 % for Case C when the indirect cost model except socio-economic losses, and about 91~94 % for Case D when all aspects of cost model proposed in this study is considered. Consequently, since the indirect rehabilitation costs dominate the total LCC, it may be stated that the indirect costs preferably incorporating elaborate road user cost and socio-economic losses should be included in the assessment of rehabilitation costs for the LCCA.

Table 3. Results of the LCCA based on DLCCA for the Alternative-1 and 2 (billion won)

		Direct rehabili-tation cost	Indirect rehabilitation cost		Total LCC
			Road user cost	Socio-economic losses	
Case A	Alter.-1	5.47 (100%)	-	-	5.47
	Alter.-2	4.87 (100%)	-	-	4.87
Case B	Alter.-1	5.47 (18.4%)	24.31 (81.6%)	-	29.78
	Alter.-2	4.87 (13.6%)	30.95 (86.4%)	-	35.82
Case C	Alter.-1	5.47 (14.6%)	31.88 (85.4%)	-	37.35
	Alter.-2	4.87 (10.4%)	41.93 (89.6%)	-	46.80
Case D	Alter.-1	5.47 (9.2%)	31.89 (53.4%)	22.33 (37.4%)	59.69
	Alter.-2	4.87 (6.4%)	41.93 (55.1%)	29.36 (38.5%)	76.16

As mentioned above, the alternative-1 may be more economical, but for the more reasonable assessment of LCCA results, the optimum alternative should be determined considering the uncertainties unavoidable in the data used in LCCA. Thus, for Case D, the PLCCA that uses a Monte Carlo simulation for evaluating the cumulative distribution of the LCC based on the uncertainties of random parameters is utilized for the probabilistic assessment of LCC. The random variables in the LCCA are assumed to have normal distribution in case the data is available, while triangle distribution in case the data is obtained from expert's judgment as indicated in FHWA.[11]

From the results of the PLCCA, the expected LCC cost for alternative-1 and 2 are obtained as 76.16 and 59.69 billion won, respectively, which means the alternative-1 is more economical by about 27.6%. Fig. 3 shows the cumulative distribution of the LCC for alternative-1 and 2, respectively. As shown in fig., the probability that the LCC of alternative-1 is less than the total expected LCC of alternative-2 is about 91%. While there is the exceedance probability of the LCC of alternative-2 over the total expected LCC of alternative-1 is about 73 %. Though the results of the DLCCA also show that the alternative-1 is more economical, the results from the PLCCA indicate that more reasonable and reliable decision making can be made for the selection of optimal bridge type in most cases.

Discount rate is one of the most doubtful parts in the LCCA. Since the optimal alternative can be sensitively changed in accordance with the discount rate, in this study, a sensitivity analysis is carried out by varying discount rate from 0% to 10% with increment of 1%. The differences of the expected LCC of the two alternatives for 11 different discount rates are shown in Fig. 4. It is interesting to note that the discount rate has significant influence on the LCCA. Moreover, it has been also found that if discount rate is greater than 10%, the alternative-2 will become more economical. Accordingly, as it is widely recognized, the appropriate discount rate may become key critical economic parameter for realistic LCCA especially in developing countries like Korea. However, in case of Korea, more than 10% interest is not desirable and unrealistic. Thus, it may be concluded that the steel box girder bridge (alternative-1) could be selected as the LCC-effective optimal bridge type using the LCCA model proposed in this study with a reasonable discount rate.

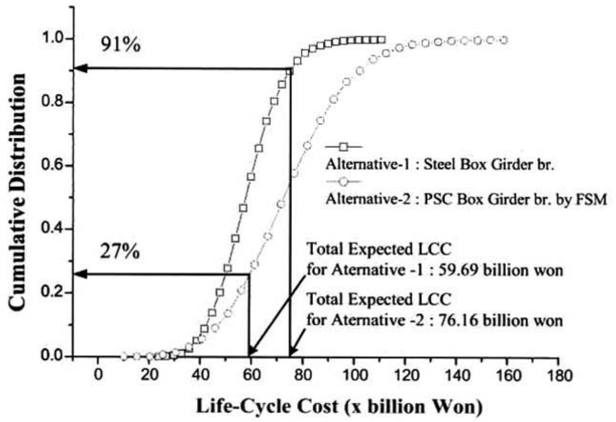

Fig. 3. Cumulative Distributions of LCC of the Two Alternatives

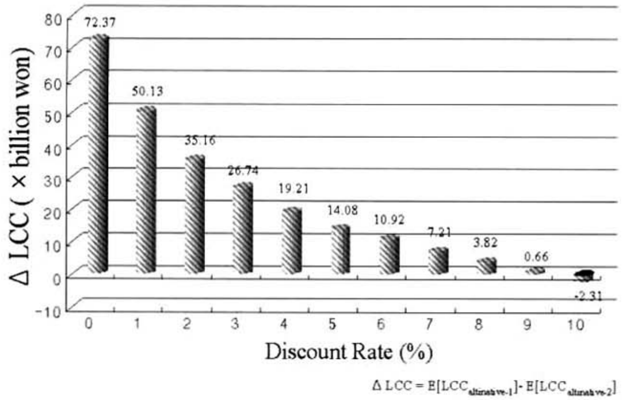

Fig. 4. Differences of Expected LCC of Two Alternatives according to Variation of Discount Rate

5.2 Determination of optimal maintenance strategy for an existing bridge based on visual inspection

This simple example demonstrates that the DLCCA model should be effectively applied in practice in order to make optimal decision on the LCC-effective maintenance strategy of an existing bridge based on visual inspection. The bridge chosen for this example was constructed in 1960 and the type of superstructure is PSC-beam. The bridge agency is planning to retrofit the bridge after about 15years more in service. As shown in Fig. 5, the bridge has 16 span, the roadway of each span is 25m long and 13.2m wide, and has two lanes for each way. The ADTV of the bridge is investigated as 18,130. According to the visual inspection, the decks of all span (1~16) are all in Condition State (CS) B, main girders of 12 spans are in CS B and the others are in CS C, and two piers of substructures are in CS B and the others are in CS C. As shown in Fig. 6, CS deterioration curves of structural components, such as deck, main girders, and substructures,

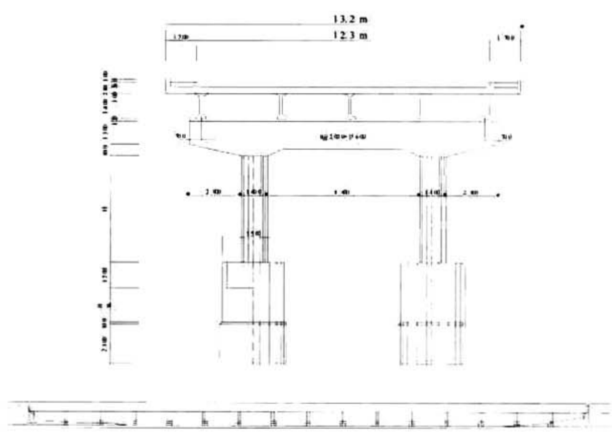

Fig. 5. The General Profile of PSC-Beam Bridge

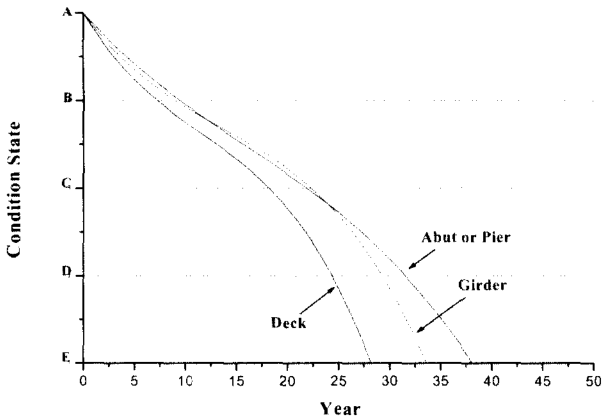

Fig. 6. CS Deterioration Curve for Deck, Main Girder and Substructure

which are developed by the BMS of Korea Road and Transportation Association[7] is used in the LCC assessment for the selection of optimal bridge maintenance strategy.

The following assumptions are considered in the application of the CS deterioration curve. (1) Three alternative decisions on rehabilitation can be chosen depending on the CS as follow: 'repair' for the CS C; 'repair/strengthening' for the CS D; and 'replacement /strengthening/repair' for the CS E. (2) If repair is chosen as countermeasure for a bridge, the CS will be shifted by one state upward, but, for the strengthening, the CS will be shifted by two state upward. (3) After the countermeasure for a performance improvement is set up for a bridge, the CS deterioration rate can be assumed to decline at the same rate as the previous rate before the countermeasure. (4) If 'replacement' of main girder is chosen, this means the replacement of superstructure. Or if 'replacement' of substructure is chosen, this means the replacement of a bridge. (5) If maintenance strategy is made only based on the CS of each individual element, many conflict countermeasures could occur, however, if the CS level of an element is sustained for a while, more realistic and effective countermeasure can be made in accordance with the CS of other elements. Based on these assumptions, possible alternative maintenance strategies can be summarized for the example bridge, as shown in Table 4.

The alternative-3 includes the strategy that the superstructure should be replaced. However, this alternative is excluded from further consideration, because it is not desirable and unrealistic compared with the CS of this bridge. Therefore, the LCCA is conducted only for the alternative-1 and 2. In this example, the other components of the bridge such as expansion joint and shoe, etc. are assumed to be periodically replaced depending on its service life. The service life of those components can be found in the reference.[8] For the repair and strengthening of the bridge, the most commonly used methods in Korea are applied. For instance, the resin injection and fiber adhesion methods are applied to the repair and strengthening of main girder, respectively.

The repair and strengthening cost are taken as 0.109 (million won/surface area) and 0.272 (million won/surface area), respectively, based on the reference.[7] Fig. 7 shows the result of the LCCA for the alternative-1 and 2. As shown in Fig. 7, the alternative-2 will be the most economical alternative. Thus, the repair of main girder can be the best cost-effective countermeasure. Otherwise, a more

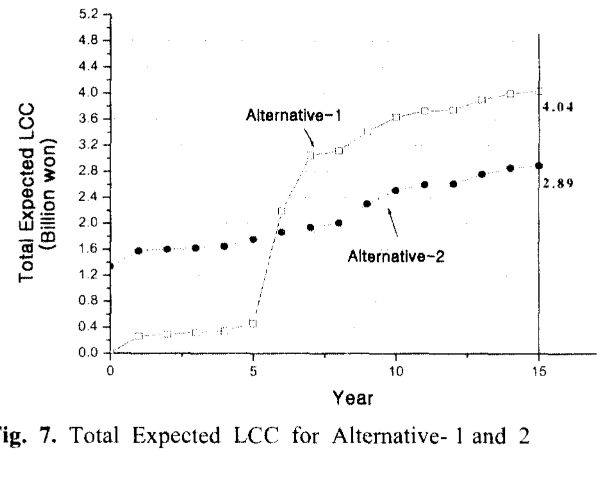

Fig. 7. Total Expected LCC for Alternative- 1 and 2

Table 4. Available Maintenance Strategy for the Example Bridge

	Current countermeasure			Future countermeasure (after x years)			
	Deck	Main girder	Sub-structure	Main girder	Deck	Super-structure	Whole bridge
Alternative-1	-	-	-	Strengthen-ing (7yrs.)		-	Retrofit (17 yrs.)
Alternative-2	-	Repair	-	-	-	-	Retrofit (17 yrs.)
Alternative-3	-	Repair	Repair		Repair (11yrs.)	Replacement (25yrs.)	Retrofit (29 yrs.)

elaborate LCC optimum strengthening design can be conducted using the TISRA model.

6. Conclusion

Recently, the demand on the practical application of LCC effectiveness in design and rehabilitation is rapidly growing in civil engineering practice. However, in spite of impressive progress in the researches on the LCC, the most researches have only focused on the theoretical point but did not fully incorporate the critical issues for the practical implementation. Thus, this paper demonstrated that approximate but practical LCC assessments using appropriate LCC models could be effectively used for the LCC-effective design and rehabilitation of bridge structure.

Based on the investigation of various kinds of LCC models available so far for the LCC assessment of design and rehabilitation of bridges, hierarchical definitions of LCC models such as DLCCA/PLCCA, TISRA, and TVSRA was defined as depending upon the characteristics of applied problems for LCC assessment. And then, an integrated LCC system model is introduced with an emphasis on data/uncertainty assessment and user-friendly knowledge-based database for its successful implementation. In order to demonstrate the LCC effectiveness for design and rehabilitation of real bridge structures using DLCCA and PLCCA in practice, illustrative examples for determine LCC-effective optimal bridge type at conceptual design stage and optimal maintenance strategy of an existing bridge based on visual inspection are demonstrated. Applications using TISRA and TVSRA also have been performed by the author, which can be found in the available references.[2),3)] From the first example, PLCCA can be used more reasonable and reliable decision making for selection of optimal bridge type. Also, in second example, it may be stated that DLCCA using results of condition assessment of existing bridge can be applied effectively to determine optimal maintenance strategy. Finally, from the LCCA examples, it is clearly demonstrated that indirect cost and discount rate are considered as important factors for rational LCC assessment.

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