RELIABILITY-BASED COMPONENT DETERIORATION MODEL FOR BRIDGE LIFE-CYCLE COST ANALYSIS

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Abstract

One major development in bridge life cycle cost analysis (LCCA) in recent years is to develop deterioration model for bridge components so that the times of repair/replacement throughout a component's life span can be properly determined. Taiwan also developed her own bridge LCCA model in 2003, integrating with the bridge inspection database in the local bridge management system (T-BMS). Under the framework of the local LCCA model, this study employs the reliability method in developing a deterioration model of bridge components. A component deteriorates through time in its reliability, which represents the probability of a component's condition index exceeds a user specified threshold. Model assumptions and rationale are described in the paper. The steps for applying the developed model are explained in detail. Results and findings are reported.

Keywords : Bridge, Life-cycle Management, Deterioration, Reliability

1. Introduction

As the average age of national bridge inventory grows older, many countries, especially those advanced ones, realize the importance of taking views of life span in making their decision on bridge management. More and more efforts are devoted in the development of better model for bridge life cycle cost analysis (LCCA). One major development in LCCA in recent years is to develop deterioration model for bridge components so that the times a component needs repair/replacement throughout its life span can be properly determined. The subjectivity in conventional LCCA can be decreased and accuracy of the results be improved. Taiwan also developed her own bridge LCCA model in 2003, integrating the local bridge and inspection database. Under the model framework, this study attempts to employ the reliability method and develop a deterioration model of bridge components. A component deteriorates through time in its reliability, which represents the probability a component's condition index exceeds a user specified threshold. A new condition index for bridge components is invented to accommodate the rating scheme in Taiwan's regular visual inspection. Model assumptions and rationale are described in the paper. The steps for applying the developed model are explained in detail. Conclusions are reported and future researches are suggested.

2. Literature Reviews

Depending on the theories or methods used, development of various bridge component deterioration models are categorized into three areas. There are (1) Markov Chain, (2) regression model and experimental test, and (3) reliability based.

2.1 Markov Chain

Many bridge component deterioration models were developed based on the Markov Chain theory (Glagola, 1992; Lin, 1999; Brϋhwiler et. al., 2001; Giuliano, 2002; Ehlen, 2003; Sundquist, 2003). The Markov Chain theory presumes that the condition of a component at time t+1 is a random variable, and its determination is only relevant of its condition at time t. Thus, a single-tier transform matrix can be formed with component conditions in two consecutive years, and used to compute the probabilities for a component to deteriorate to certain states in the next time period. This characteristic was found particularly beneficiary when the inspection data of bridge component were scarce. But with the accumulation of more and more bridge inspection data in many countries, the adequacy of the Markov Chain method for component deterioration prediction is challenged in recent years. Many researchers also look at alternative methods.

2.2 Regression Model and Experimental Test

Researchers in structural and material engineering have been developing deterioration models based on the experimental data obtained at laboratory (Daly, 2000; Rubakantha, 2000; Li and Cleven, 2000; Browne, 2001; Lin, 2001). Most of those experiments are conducted on a single impacting factor of deterioration, such as corrosion, chloride, cracks, and so on. In addition, some researchers employed historical inspection data or experts' opinion, and developed simple linear deterioration models for bridge components (Testa and Yanev, 2002; Huang e. al., 2003). They first determined the maximum and the minimum service life of a component, and assume a linear deterioration in the period.

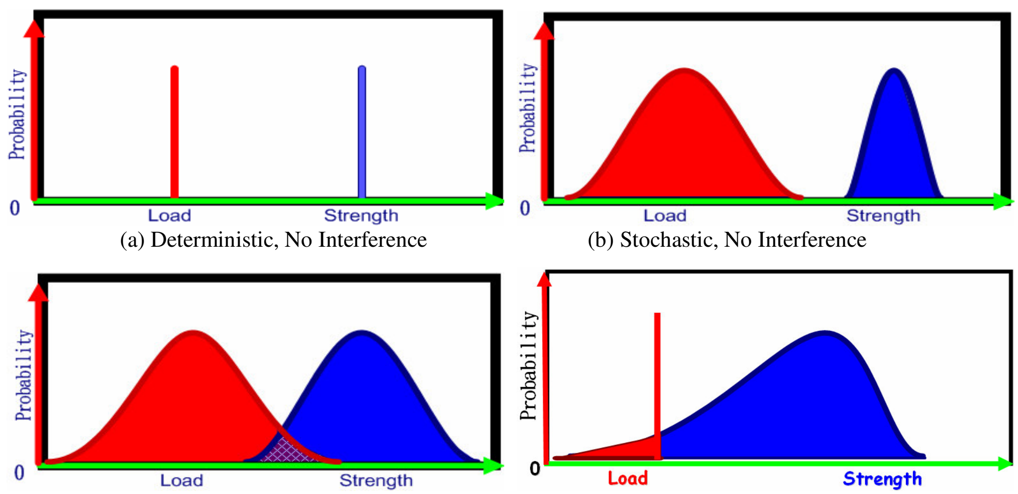
2.3 Reliability Based Models

Research in introducing the reliability method for developing bridge deterioration models has somewhat been active in recent years. Many research studies can be found in literature (Carlsson et. al., 2000; Cremona, 2000; Frangopol et. al., 2000; Lark and Mawson, 2000; Matsushima, 2000; Smith-Pardo and Ramirez, 2000; Kawamura, 2001; Nowak and Szerszen, 2001; Lan 2002; Cheung and Noruziaan, 2003). Most of those studies require experiment data from major bridge inspection, and usually focus on one deterioration factor. In addition, many of them developed their models using certain bridge component, such as deck, pier, as the study object. Only very few of those models are developed for conducting bridge life cycle cost analysis.

3. Reliability-based Component Deterioration Model

3.1 Concept and Reliability

Reliability is the probability for a product to perform adequately under certain stress level during its age or mission time. An example frequently used to illustrate the concept is strength vs. load. A product will fail if strength less than load. Figure 1(a) shows a deterministic strength and a deterministic load. Since load is less than strength, the possibility of failure is zero and the reliability is high. In Figure 1(b), both strength and load are a distribution. Since there is no overlapping between the two distributions, the possibility of failure is again zero. But if the two distributions overlap, as shown in Figure 1(c), they interfere with each other and the area of interference represents a distribution of failure. Finally, Figure 1(d) shows a deterministic load and a distribution of strength. The reliability equals to the probability in the right part of the distribution where the strength is greater than the load.



(a) Deterministic, No Interference
(b) Stochastic, No Interference
(c) Interference Pattern 1
(d) Interference Pattern 2

Figure 1: Illustration of Basic Principals of Reliability

A bridge component deteriorates yearly in its lifetime. It is a combined result of many possible factors, such as corrosion, chloride, cracks, and so on. Although arguable, this research takes a view that results of bridge visual inspection represent the combined acting effect of these factors. A condition index, based on the visual inspection data, is developed in this research to assess the condition of a bridge component. Basically a visual inspection is required in every two years for bridges in Taiwan.

For a bridge component, the condition in each year should be a random variable and has a distribution. It is like the “strength” in Figure 1(d). Normally a Maximum Acceptable Condition Level can be set to determine if a bridge component is failure or not. It is like the “load” in Figure 1(d). Thus, the reliability of a component in a particular year is determined by assessing the probability that its condition is greater than the specified Maximum Acceptable Condition Level. As bridge ages every year, the reliability of a component decreases every year.

3.2 Assumptions

There are a few assumptions for developing the model：

1. Bridge component (e.g. beam, deck, pier, footing, expansion joint, and guard rail) of same material and similar style, when exposed to similar environment conditions (e.g. climate zone, earthquake zone, river system, distance to seashore, etc.) and to the same level of traffic, has the same deterioration pattern. Those components are defined as similar component.

2. Results of visual inspection represent the actual condition of a component.
3. By deleting those inspection data that were taken after repair, or show a better condition in the immediate following year, the remaining inspection data represent the deterioration of a bridge component.
4. The condition of a component in each year is a random variable, which follows a Normal distribution.

3.3 Condition Index

Currently a DER&U (Degree, Extent, Relevancy, and Urgency) rating system is adopted for visual inspection in Taiwan, to assess the condition of a bridge component as well as the whole bridge. Normally the visual inspection of a bridge is conducted once every two years in Taiwan. Each bridge component is inspected and rated in DER&U. Table 1 shows the rating scheme.

Table 1**:** Rating Scheme of DER&U System

Degree		Extent		Relevancy		Urgency	
0:	No Such Item	0:	Can't Assess	0:	Can't Assess	0:	Can't Assess
1:	Good	1:	<10%	1:	Minor	1:	Routine
2:	Fair	2:	<30%	2:	Small	2:	Within 3 Years
3:	Bad	3:	<60%	3:	Medium	3:	Within 1 Year
4:	Severe	4:	Over 60%	4:	Major	4:	Immediately

In the DER&U methodology, "D" stands for degree of deterioration; "E" represents extent of the deterioration; "R" implies relevancy to safety and serviceability of the deterioration; and "U" depicts urgency for repairing of the deterioration. All of these ratings are numerically rated on an integer scale from 1 to 4; a smaller digit means less important, or little degree, of deterioration of an inspected component of the bridge.Among the four indices, D and E are more related to the structurally physical condition of a component. R indicates the relevancy of a component's condition to the sound performance of the bridge, both structurally and functionally. The U rating is to determine if immediate remedial actions are required for a component. For purpose of developing a deterioration model, a new condition index (NCI) employing the rating of D and E is created in this research and is shown as Formula 1.

$$NCI = D + \frac{E-1}{4} \qquad \text{Eqn. (1)}$$

According to many inspectors in bridge authorities in Taiwan, an inspector will normally determine the D rating of a component first, and then the rating of E. The NCI is designed in a way that each of the four grades in D is subdivided into 4 grades employing the rating of E. However, since grade 1 of D means a component is in good condition, no further sub grade by E is applied. Therefore, there are totally 13 grades (1-13) in the new condition index, as shown in Table 2.

Table 2: NCI Grades

D Rating		1	2				3				4			
E Rating			1	2	3	4	1	2	3	4	1	2	3	4
NCI	Index	1	2	2.25	2.50	2.75	3	3.25	3.50	3.75	4	4.25	4.50	4.75
	Grade	1	2	3	4	5	6	7	8	9	10	11	12	13

3.4 Formulation of Input Parameters

1. Definition of "failure"

As shown in Figure 2, whenever the NCI of a component goes beyond the user specified Maximum Acceptable Condition Level, the component is considered to have failed the requirement. The Maximum Acceptable Condition Level can be a maintenance standard set by the managing authority. Proper remedial actions are taken at this time.

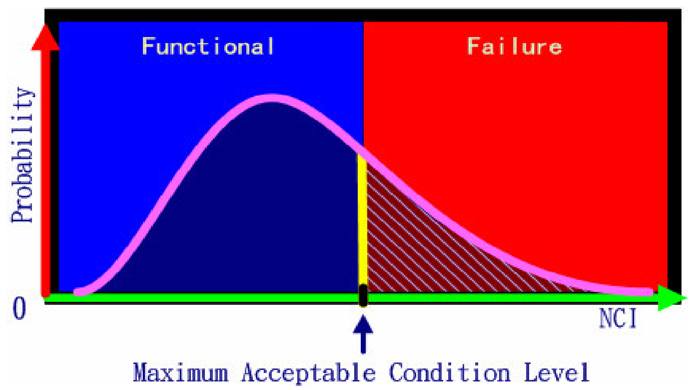


Figure 2: Definition of Failure in the Developed Model

2. Definition of reliability index β

Reliability index β measures the probability of a component not being failure or being functional. As shown as Formula 2 and in Figure 3, it can be defined as the number of standard deviation the mean value is away from the specified Maximum Acceptable Condition Level. The greater the β of a component, the smaller the probability of it being failure. β is used in the developed model to indicate the reliability of a bridge component. Without repair/rehabilitation/replacement, reliability of a component will decrease gradually every year.

$$\beta = \frac{Maximum\ Acceptable\ Condition\ Level - \mu}{\sigma}$$ Eqn.

(2)

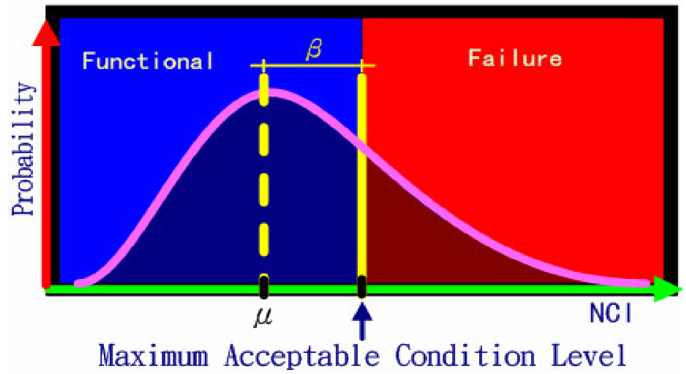


Figure 3: Illustration of Reliability Index β

3. Specification of Minimum Acceptable Reliability

For a Maximum Acceptable Condition Level, the Minimum Acceptable Reliability determines the time proper remedial actions should be taken for repair or rehabilitation of a component. The greater the specified Minimum Acceptable Reliability, the lesser the possibility of a component being failure, or the possibility of a component's condition exceeding the Maximum Acceptable Condition Level. Depending on the degree of risk the decision maker is willing to bear, he/she can decide on the Minimum Acceptable Reliability.

3.5 Computation and Regression

The following lists the steps for computation of the reliability-based deterioration curve of bridge component Xi:

Step 1: Identify similar bridges and collect the historical visual inspection data of component Xi from database in local bridge management system.

Step 2: Compute the condition index NCI (Formula 1) for each inspection data.

Step 3: According to the age of component Xi when the inspection was conducted, group the NCI by age and compute the mean value μj and the standard deviation σj of NCI at year j.

Step 4: Compute the reliability index βi (Formula 2) of component Xi at year j.

Step 5: Conduct regression of βj to develop the deterioration equation. The equation represents the deterioration of component Xi in terms of its reliability. Figure 4 illustrates the regression result.

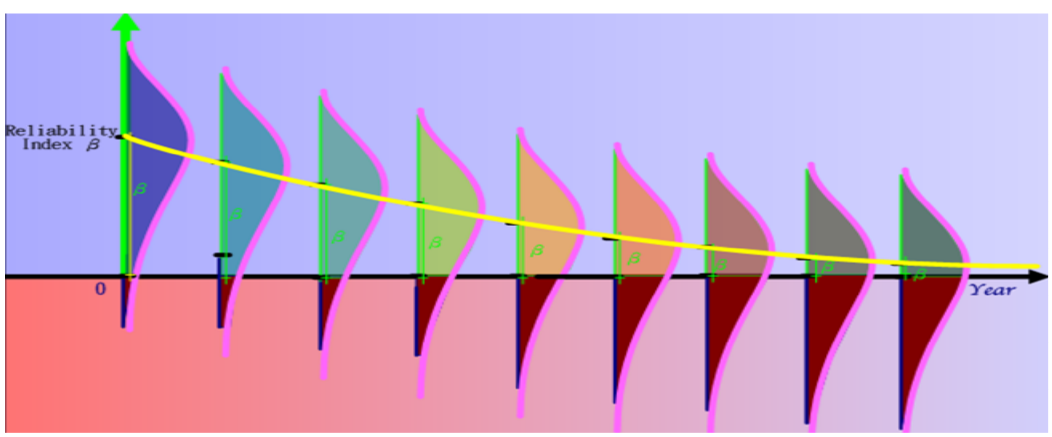


Figure 4: Regression of Reliability Index

Step 6: Conduct regression of the mean value μ j and the standard deviation σ j . They are needed when the reliability of the component reaches the Minimum Acceptable Reliability and proper remedial actions have to be decided. The regression equations of μ j and σ j are used to determine the exact condition (NCI) of a component so that proper remedial actions can be decided. In addition, they are used for observing their respective development as the component ages. Figure 5 illustrates the regression results.

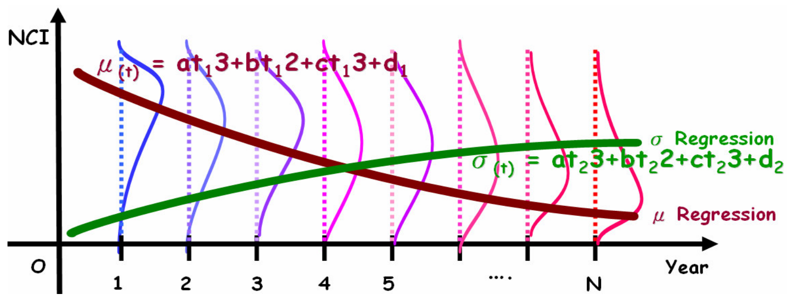


Figure 5: Regressions of Mean Value and Standard Deviation

4 Case Study

4.1 Project Information

An agency in northern Taiwan is planning to build a new bridge. This 10-span prestressed concrete bridge has a length of 500 m and a width of 20 m. Its distance to shore is between 1km and 2km. In addition, the northern part of Taiwan is in an A earthquake zone (There are two zone categories in Taiwan; category A is prone to earthquakes) so the bridge has to be designed accordingly. The component of deck is employed as a subject for demonstrating the use of the developed reliability-based model.

Table 3 lists the criteria employed in this study to identify similar bridges from the Taiwan Bridge Management System. 53 similar bridges are identified. Their ages range from 1 to 46 years. Between the years of 1999-2003, there are totally 3,411 records of span inspection of the 53 bridges. Nonetheless, records belong to the following two categories were eliminated to comply to the model assumptions. There are totally 1,651 records remained.

1. for a bridge span, those inspection records taken after a repair action,
2. for a bridge span without any repair action, the inspection records show an improving condition in two consecutive years.

Table 3: Criteria for Selecting Similar Bridges

Items	Criteria
Climate	Northern Area
Earthquake Zone	Zone A
Distance to shore	1km~2km
Location Zone	Rural
Bridge Length	100m~500m
A bridge crossing river?	Yes (Tang-shuei River)

According to interviews with engineers in several local highway managing authorities, the condition of a component is considered acceptable as long as it is not worse than an inspection result of D=2 and E=3. When the condition of a component is worse than D=2 and E=3, it is likely to jeopardize the level of service condition, or in some cases the safety level. Therefore, the user specified Maximum Acceptable Condition Level in this case is defined as NCI=4 (D=2, E=3).

4.2 Regression of the Deterioration Equation

Figure 6 shows the regression of the reliability index. The R-square is only 0.67 and obvious not very high. By employing the same set of data as used for regression in Figure 6, regressions of the mean value μ and the standard deviation σ are conducted. Figure 7 shows the results. They are used to predict the deteriorated condition (NCI) of a component so that the times for taking proper remedial actions can be decided throughout a component's service life. Life cycle cost can then be computed.

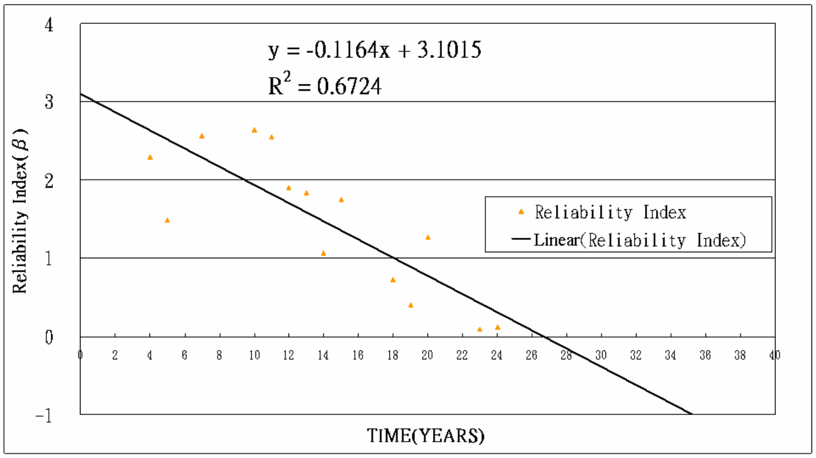


Figure 6: Regression of Reliability Index of Decks with Further Data Treatment

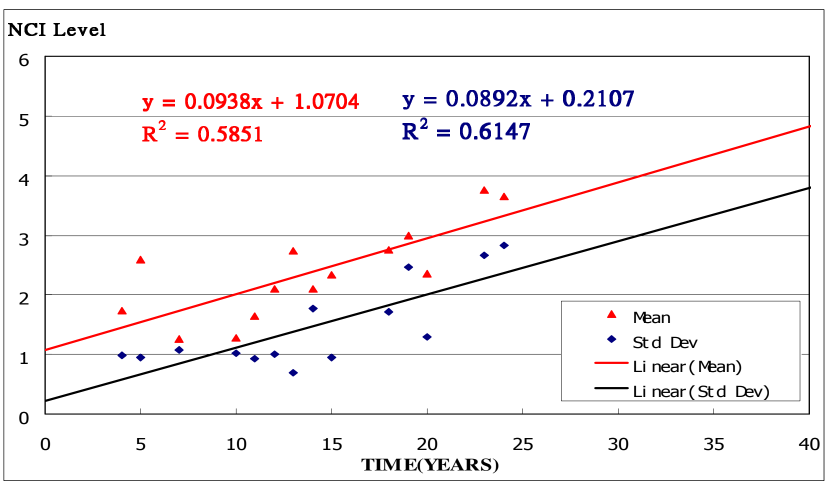


Figure 7: Regressions of the Mean Value μ and the Standard Deviation σ

5. Conclusion and Future Research

5.1 Conclusions

A reliability-based deterioration model of bridge components is developed in this research, for the purpose of bridge life cycle cost analysis. The developed model features the followings.

1. It is reliability based, which can simulate more closely the deterioration of bridge

components in the real world and provides more accurate prediction of times for taking remedial actions in a component's lifetime. The accuracy of a bridge life cycle cost analysis can be improved as a result.

2. It employs the historic visual inspection data. Although arguable, the visual inspection data represents the combined acting effect of many factors and provides a more "complete" assessment of a bridge component's condition. In addition, for the purpose of conducting life cycle cost analysis, employment of the visual inspection data in the deterioration model should be more cost effective than that of the major inspection data.
3. A new condition index NCI is created and employed in the developed model. The new index accommodates the condition rating system in visual inspection in Taiwan, and is more specific in indicating the condition of a bridge component.

5.2 Future Research

1. This research assumes Normal distribution for a component's condition index at a particular year. Different distributions, such as Lognormal, Triangular, Weibull, and so on, can be tested in the future.
2. For a component requiring remedial actions, future research can be conducted to identify the proper remedial actions for the component at different condition levels, and to evaluate their respective effects on enhancing the reliability.
3. Future research is needed for developing system reliability of the whole bridge, in related to the reliability of individual components.

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