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생애 주기 비용을 이용한 철도교량의 최적유지관리

The Optimal Maintenance Strategy of a Rail Road Bridge by Using Life Cycle Cost

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Abstract

Nowadays, most of bridge networks are complete or close to completion. The biggest challenge railroad/highway agencies and departments of transportation face is the maintenance of these networks, keeping them safe and serviceable, with limited funds. To maintain the bridges effectively, there is an urgent need to predict their remaining life from a system reliability viewpoint. And, it is necessary to develop the maintenance models based on system reliability concept. In this paper, maintenance models are developed for preventive maintenance and essential maintenance by using system reliability and lifetime distributions. The proposed model is applied to an existing railroad bridge. The optimal maintenance strategy of this bridge is obtained in terms of service life extension and cumulative maintenance cost.

Keywords : Rail Road Bridge (철도교량), System Reliability (시스템신뢰성), Lifetime Function (생애함수), Maintenance Model (유지관리 모델), Optimization (최적화)

1. Introduction

Nowadays, most of bridge networks are complete or close to completion. The biggest challenge railroad/highway agencies and departments of transportation face is the maintenance of these networks, keeping them safe and serviceable, with limited funds. One of the main concerns bridge engineers have is whether the reliability of the bridge remains above the required safety level or not at the end of expected lifetime. To increase the service life, it is necessary to properly maintain the bridge, and the most effective maintenance strategy is required because of limited funds.

To predict and obtain the remaining life of the bridges and optimal maintenance strategy, it is necessary to develop the maintenance models based on system reliability concept. There are two types of maintenance : Preventive and Essential. The preventive maintenance is performed on satisfactorily functioning components and the essential maintenance is performed on failed and malfunction components.

In this paper, the program "LIFETIME", which was developed using system reliability and lifetime functions, is used to predict the remaining life and obtain optimal maintenance strategy of the existing railroad bridge.

2. Lifetime Distribution Function

The probability of survival, Ps of a deteriorating component under no maintenance decreases with time to according to a function dependent on the type of component, quality of construction, and environmental conditions, among others. Ps can be approximated by various lifetime distribution functions (LDFs) [1]. These functions must satisfy the following conditions:

$$P_s = 1 \quad at \quad t = 0$$

$$P_s = 0 \quad at \quad t \to \infty$$

$$P_s(t) \quad is\ nonincreasing\ without\ maintenance$$

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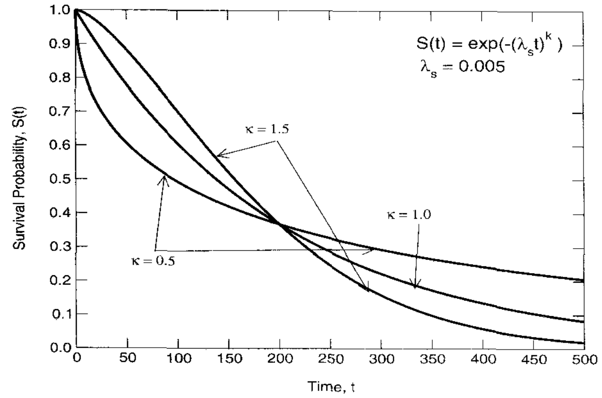


Fig. 1. Weibull Survivor Function

There are several lifetime functions to describe the evolution of the probability of failure. In general, Exponential distribution ($e^{-\lambda t}$) and Weibull distribution $e^{-(\lambda_s t)^{\kappa}}$ are used as survivor functions. λ is a failure rate, κ is a shape factor and λ_s is a scale factor. For instance, Weibull distribution is shown in Fig. 1.

3. Maintenance Models

To keep structures safe and increase service life of them, maintenance actions are usually necessary. Maintenance is defined as any action which retains non-failed components in operational condition; and if they have failed, restore them to operational condition. The definition of maintenance implies two types of maintenance action: Preventive Maintenance or scheduled and Essential or unscheduled. The preventive maintenance is performed on satisfactorily functioning components and the essential maintenance is performed on failed or malfunction components.

Preventive maintenance actions can be divided in proactive and reactive maintenance actions.. Usually, after the civil infrastructures are built, there may be no damage in several years from the time they start to be in use. If the maintenance action is applied before the time damage starts, this maintenance action is called "Proactive Maintenance". And, the maintenance action after time the damage starts is called "Reactive Maintenance". The main purpose of proactive maintenance is to increase duration of time at which the damage starts.

In order to develop a proactive maintenance model, it is necessary to make different assumptions based on existing data. Unfortunately, data on proactive maintenance are very limited. Therefore, to develop a proactive maintenance model, expert opinion is needed. In this study, it is assumed that each proactive maintenance action (i.e. applied before damage initiation) postpones the time of damage initiation under no maintenance, t_0, by a period equal to half of the interval between applications of maintenance as follows [2]

$$t_{0i} = t_0 + i\frac{t_{pi}}{2} \tag{1}$$

Where

t_0 = Damage initiation time without any proactive maintenance effect
t_{pi} = Proactive maintenance interval
t_{0i} = Damage initiation time with maintenance effect
i = Number of maintenance actions

Reactive maintenance is performed on satisfactorily functioning components at regularly scheduled intervals, after the system or components start the damage. The main purpose of reactive maintenance is to increase the availability of either the system or components [3].

In this paper, the mathematical reactive maintenance model is used from [3]. When the reactive maintenance is performed every t_p time interval, the survivor function with that reactive maintenance is given by

$$S_{t_p}(t) = [S(t_p)]^j S_t(\tau) \tag{2}$$

Where

S_t = Survivor function
S_{t_p} = Survivor function with reactive maintenance interval t_p
j = Number of maintenance action
t = $jt_p + \tau$
τ = $0 \le \tau \le t_p$

The essential maintenance is performed on failed or malfunctioning components. Such maintenance is performed at unexpectable intervals because the time to any

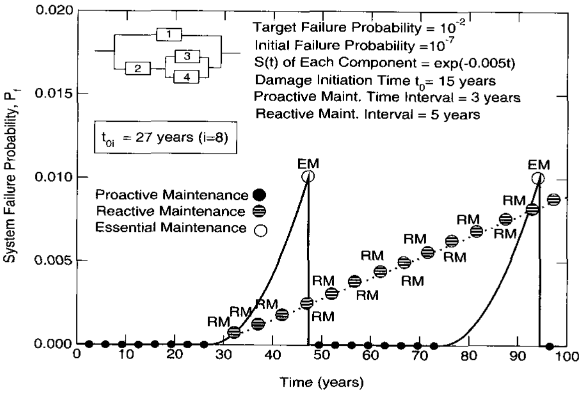


Fig. 2. System Failure Probability with Maintenance Actions

specific component's failure cannot be established. The main purpose of essential maintenance is to restore such components to safe function within the shortest possible time by replacing components. In this study, the essential maintenance actions considered are the replacement of one, several, or all components of a system, resulting in the restoration of the condition of such components to their initial values (at t=0) and of the probability of failure to its initial value.

As an example of the effect of preventive maintenance and essential maintenance actions on a four-component system is shown in Fig 2. The initial failure probability of the system is 10^{-7} and the survivor functions of each component are exponential with failure rate 0.005. The solid line includes proactive maintenance and essential maintenance. The dashed line includes proactive maintenance and reactive maintenance. These results show that the use of proactive and reactive maintenance actions postpone the time of application and reduce the number of applications of EM actions, reducing the lifetime maintenance cost of deteriorating structures.

4. Case Study of Optimum Maintenance Strategy : P.S.C. Railway Bridge

The bridge has simple span and a length is 24.9 m. The deck consists of 35 cm of reinforced concrete. The slab is supported by six P.S.C concrete girders. The design load is L22. The cross section of the rail road bridge is shown in Fig. 3.

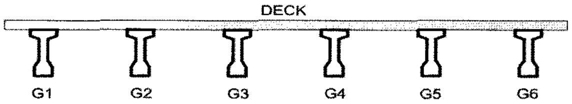
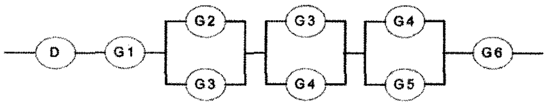
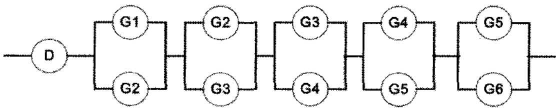


Fig. 3. Cross Section of the Rail Road Bridge

System I



System II



System III

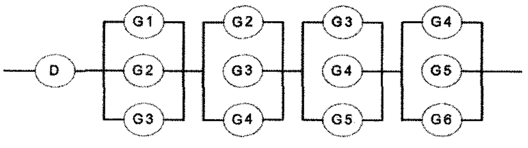


Fig. 4. System Failure Modes

Due to nonlinearity in multi-girder bridge types, single girder failure doesn't cause the bridge failure. If one girder fails on bridge, the load redistribution takes place and the bridge is capable to carry additional loads. The multi-girder bridges are modeled as combination of series and parallel systems in system reliability analysis. System failure modes are considered ; System I: Any one girder failure or deck failure causes the bridge failure ; System II: Failure of any external girder or any two adjacent internal girders or deck failure cause the bridge failure ; System III: Any two adjacent girder failures or deck failure cause the bridge failure ; System IV: Any three adjacent girder failures or deck failure cause the bridge failure.

These failure models are shown in Fig. 4 for the rail road bridge. With these failure modes, the reliability analysis is performed.

Where

D = Deck failure
G1 and G6 = Exterior girder failure
G2, G3, G4, G5 = Interior girder failure

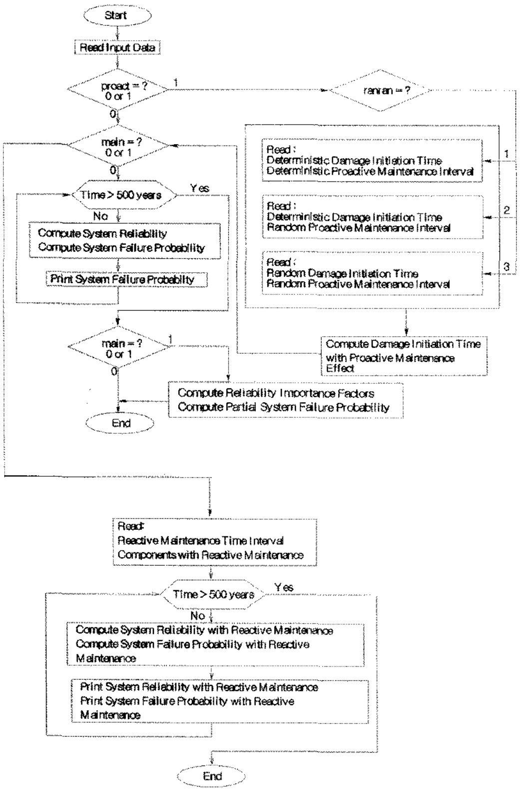


Fig. 5. Flow Chart

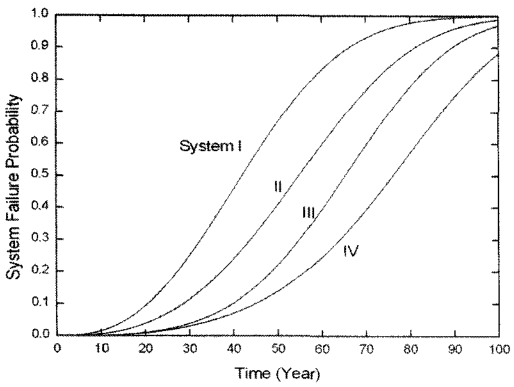


Fig. 6. System Failure Profile of Each System

The program LIFETIME was developed by using lifetime functions and system reliability concepts. The flow chart of the program is shown in Fig. 5.

Using program LIFETIME [2, 4-6], the probability of system failure for each failure mode is predicted and shown in Fig. 6 [6].

The optimal maintenance method was borrowed from Estes [7]. In the thesis, only essential maintenance actions were used to obtain the optimal maintenance strategy. Possible maintenance options are presented in Table 1.

Table 1. Costs for Maintenance Options

Replacement Option	Replacement Cost
0: Do nothing	₩ 0
1: Replace Deck	₩ 250,000,000
2: Replace exterior girders and deck	₩ 259,000,000
3: Replace superstructure	₩ 277,000,000

The costs presented in table 1 were obtained from bridge engineers.

In order to obtain the optimal maintenance strategy, it is necessary to establish the minimum acceptable system failure probability. In this paper, the minimum acceptable system failure probability is assumed as 10^{-2}. The target service life is assumed as 75 years. So, all possible feasible combinations of repair options are tried to increase the service life to 75 years with the target failure probability 10^{-2}.

The costs are computed as a present value cost. The present value cost is the value of cost incurred at some future time expressed as the amount that would be equivalent if that cost were incurred now [8]. The present value cost is computed as

$$PV = \frac{C_{rep}}{(1+\nu)^n} \tag{3}$$

PV = Present value cost
Crep = Maintenance cost
n = Number of years in the future when the repair will be made
ν = Discount rate

The discount rate is used to calculate the equivalent present value of a future cost. Historically, discount rate has been around 2-3 % [9]. In this paper, 2 % of the discount rate is used.

In the application of optimal method, the Bridge System I is ignored because the series system is impossible to be in real situation. The optimal maintenance strategies for the second, third, and fourth failure modes are obtained.

A system failure probability of the second failure model reaches the target failure probability 10-2 at year 12. All

Table 2. The First Maintenance Action

	Extended Service Life (ESL)	Costs(₩)	Cost/ESL(₩)
Option 1	1.2	197,123,294	164,269,412
Option 2	11.3	204,219,732	18,072,543
Option 3	11.9	218,412,610	18,354,001

Table 3. The Optimal Maintenance Strategy

Failure Model	Optimal Maintenance Strategy	Maintenance Cost(₩)
II	2-3-2-3-2-3-2	66,496,136
III	3-3-3	12,856,830
IV	1-3-1	12,114,910

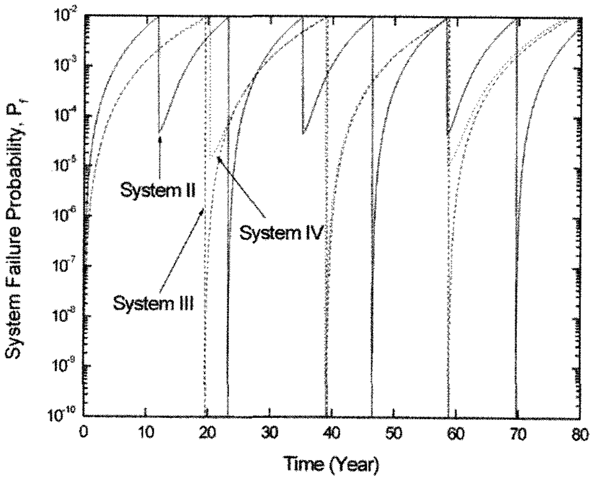


Fig. 7. System Probability : All Systems

maintenance options listed in Table 2 are tried at year 12. Costs and extended service life are computed and optimal maintenance is chosen. For the first maintenance at year 12, the result is in Table 2. In this calculation, 2 % discount rate is used.

The optimal maintenance is option 2 for the first maintenance action. In the same way, maintenance actions are applied until the service life of the bridge is reached at year 75. The optimal maintenance strategy is option 2-3-2-3-2-3-2. For failure models 3 and 4, the results are in Table 3.

The system failure probabilities with maintenance actions for all failure models are shown in Fig. 7.

5. Conclusion

The main purpose of this paper was to predict the system probability of the railway bridge and obtain optimal maintenance strategies. Lifetime functions and system reliability models were used.

(1) The types of maintenance were clearly defined and assumptions were made for each maintenance type. When preventive maintenance was performed, only availability was considered. For essential maintenance, instead of availability, replacement was considered. Both preventive and essential maintenance can increase the service life of structural systems.

(2) The LIFETIME program can be applied to any structural system which can be expressed as a combination of series-parallel components, to predict the probability of survival of the system and obtain the optimal maintenance strategy. The program LIFETIME developed in this paper can be applied to a bridge network, and the optimal maintenance strategy for the bridge network can be obtained.

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