시간 의존적 교량유지관리 모델

Time Dependent Maintenance Models of Bridges

양 승 이[1)]
Yang, Seung Ie

요 약 : 고속도로 건설은 여러 국가에서 거의 완료되었으며, 정부나 고속도로 관계기관은 유지관리쪽에 초점을 맞추고 있다. 교량을 효과적으로 유지관리하기 위해, 시스템 신뢰성을 이용한 교량의 잔존수명을 예측하는 것은 매우 시급하다. 그리고 시스템 신뢰성을 이용한 교량의 유지관리 모델을 개발하는 것은 필수적이다. 이 논문에서는 시스템 신뢰성과 라이프 타임 분포를 이용하여 예방 유지관리(Preventive Maintenance)와 사후 유지관리(Essential Maintenance) 모델을 개발하였다.

ABSTRACT : Construction of highway bridges is almost complete in many countries. Thus, the government and highway agencies are shifting from construction to maintenance. In order to maintain the bridges effectively, there is an urgent need to predict their remaining life span from the viewpoint of system reliability. As such, it is necessary to develop maintenance models based on system reliability concept. In this paper, preventive and essential maintenance models were developed using system reliability and lifetime distribution.

핵 심 용 어 : 교량, 시스템신뢰성, 잔존수명, 생애함수, 유지관리 모델
KEYWORDS : bridges; system reliability; remaining life; lifetime function, maintenance models

1. Introduction

The civil infrastructures are designed to serve the public. And no matter how well these are designed, they are deteriorating with time. The bridges are one of the important civil infrastructures. In order 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. There are two types of maintenance: Preventive and Essential. The preventive maintenance are performed on satisfactorily functioning components and the essential maintenance is performed on failed or malfunction components.

In order to compute the probability of failure of components or a system, the limit state functions are used. Because the computation of the system failure probability is not easy, usually upper and lower bounds are used.

In this paper, the lifetime distributions are used to compute the failure probability of components or a system instead of limit state functions. And, the lifetime distributions are used to predict the failure probability of the components or system. The types of maintenance models are clearly defined and explained. By using the concept of system reliability and lifetime, the maintenance models are developed.

2. Reliability Importance Factors

Structure function and Reliability function [Leemis 1995] are useful tools to describe the state of system with n components. Structure function defines the

1) 미국 콜로라도대학교 토목환경공학과 박사과정

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system state as a function of the component state. The structure function has two values as

$$\phi(\mathbf{x}) = \begin{cases} 0 & \text{if the system has failed} \\ 1 & \text{if the system is functioning} \end{cases} \quad (1)$$

where

$\phi(\mathrm{x})$ = Structure function

$\mathbf{x}$ = A system state vector, $\{x_1, x_2, \cdots, x_n\}$

x_i = The state of component i (0:component i failure, 1:component i is functioning.)

The structure function is deterministic. This assumption may be unrealistic for certain types of component system. So, reliability functions [Leemis 1995] are necessary to model the structures. x_i was defined to be the deterministic state of component i. Now, x_i has probability. The probability that component i is functioning is given by

$$p_i = P[x_i = 1] \quad (2)$$

Where

p_i = Probability that component i is functioning

which gives the reliability of component i. If there are n components, the reliability vector of the system can be written as

$$\mathbf{p} = \{p_1, p_2, \cdots, p_n\} \quad (3)$$

The system reliability is defined by

$$r = r(p) = P[\phi(x) = 1] \quad (4)$$

where

R = Quantity that can be calculated from the vector **p**

r(**p**) = Reliability function

$\phi(\mathrm{x})$ = Structure function

One of the lifetime distributions is a survivor functions. The survivor function is the generalization of reliability because the survivor function gives the reliability that a component or system is functioning at one particular time. The survivor function is expressed

$$S(t) = P[T \geq t] \qquad t \geq 0 \quad (5)$$

It is assumed that when $t \leq 0, S(t)$ is one. The survivor function has to satisfy three conditions. These are

1) $S(0) = 1$
2) $\lim_{t \to \infty} S(t) = 0$
3) $S(t)$ is non-increasing without any maintenance

Several functions are used as survivor functions. In this paper, the exponential distribution, Weibull distribution, Log-Logistic distribution, and Exponential Power distribution are used. These survivor functions are shown in table 1.

Table 1 Survivor Function

Distribution	Survivor function
Exponential	$\exp(-\lambda t)$
Weibull	$\exp(-(\lambda_s t)^k)$
Log-logistic	$\frac{1}{1+(\lambda_s t)^k}$
Exponential- power	$\exp(1-\exp(\lambda_s t)^k)$

Where

λ = Failure rate

λ_s = Scale factor

κ = Shape factor

t = Time, $t \geq 0$

As an example of a three component series system, the reliability function is shown in equation 6 if each component has an exponential survivor function $e^{-\lambda t}$.

$$r(p) = e^{-\lambda t} \times e^{-\lambda t} \times e^{-\lambda t} = e^{-3\lambda t} \quad (6)$$

When reliability function is known, the reliability importance of each component in the system can be calculated. Reliability importance indicates the relative importance of component with respect to the system reliability. The reliability importance of component i in a system of n components is

$$I_r(i) = \frac{\partial r(p)}{\partial p_i} \tag{7}$$

where

p_i = Reliability of component i

for $i = 1, 2, \cdots, n$. The normalized reliability importance factor [Gharaibeh 1999, Gharaibeh et al. 1998] is defined as

$$I_r^0(i) = \frac{I_r(i)}{\sum_{i=1}^{n} I_r(i)} \tag{8}$$

where

$I_r^0(i)$ = Normalized reliability important factor

n = Number of component

The normalized reliability importance factor, I_r^0 is between 0 and 1. The definition of reliability importance emphasizes the impact of the i^{th} component on a system. The component with largest reliability importance is the component for which an increase in its reliability corresponds to the largest increase in the system reliability.

As an example, a four-component system is used to explain the reliability importance factors from Fig. 1 to Fig. 4. When the probability of failure for components 2, 3, 4 is fixed as 0.5 and that of component 1 varies from 0 to 1, the normalized reliability importance factors are shown in Fig. 1. In Fig. 2, the probability of failure of component 2 varies from 0 to 1 and that of components 1, 3, 4 are fixed. In Fig. 3, the probability of failure of component 3 varies from 0 to 1. In Fig. 4, the probability of failure for all components is varied at the same time from 0 to 1.

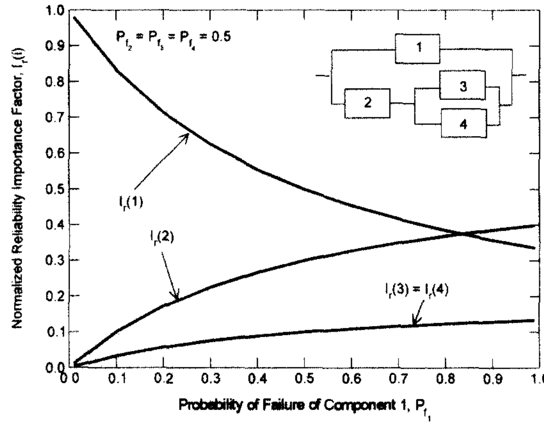

Fig. 1 Normalized Reliability Importance Factors for 4-Component System;

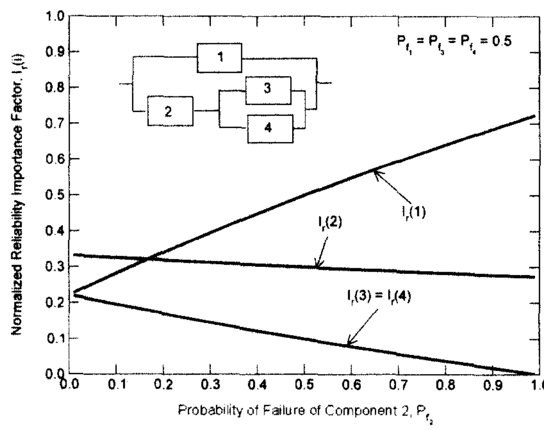

Fig. 2 Normalized Reliability Importance Factors for 4-Component System;

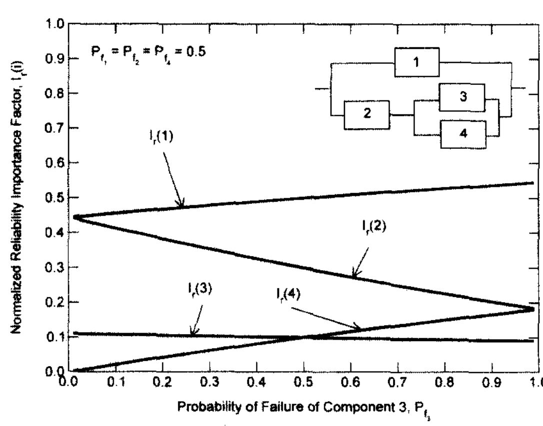

Fig. 3 Normalized Reliability Importance Factors for 4-Component System;

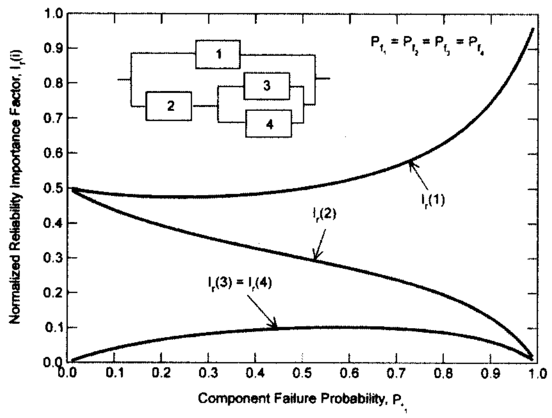

Fig. 4 Normalized Reliability Importance Factors for 4-Component System;

3. Preventive Maintenance Model

Maintenance is defined as any action which retains non-failed components in operational condition; and if they have failed, restore them to operational condition. It involves fixing up partial failures or incipient failures of independently operating subsystems of the system. The definition of maintenance implies two types of maintenance action: Preventive Maintenance or scheduled and Essential or unscheduled. The preventive maintenance are performed on satisfactorily functioning components and the essential maintenance is performed on failed or malfunction components.

There are two types of preventive maintenance depending on the maintenance action time. 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 "Pro-Active Maintenance". And, the maintenance action after time the damage starts is called "Re-Active Maintenance". The main purpose of pro-active maintenance is to increase the duration of time at which the damage starts. In Fig. 5, it is easy to show the effect of pro-active maintenance.

In the figure, the initial probability of failure is P_i and the time at which the damage initiates is t_0 without pro-active maintenance. If there is pro-active maintenance, the damage occurs after time t_p. Because

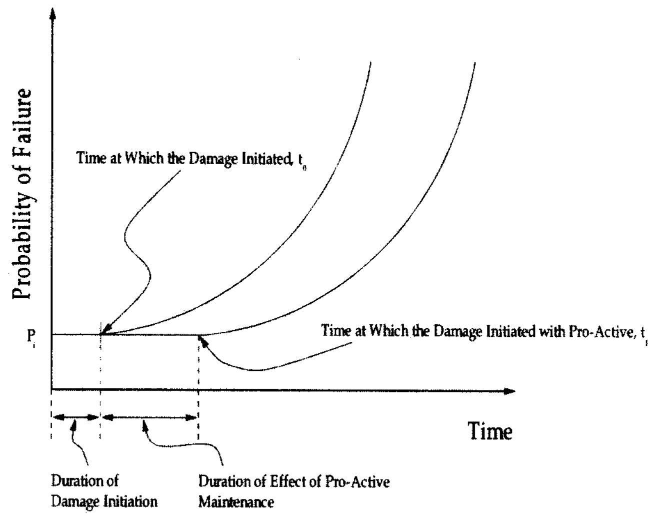

Fig. 5 Effect of Pro-Active Maintenance

of pro-active maintenance action, the damage initiation time is increased from t_0 to t_p.

In order to develop pro-active maintenance model, it is necessary to make the assumption. If there is enough data about pro-active maintenance action, it is much easier to develop the computer model. Unfortunately, there is not enough data about pro-active maintenance. So, to develop pro-active maintenance model, it is needed to talk very deeply with the maintenance experts, and the following assumption is made.

Assumption

* The pro-active maintenance action interval, t_π, is deterministic.
* The damage initiation time, t_0, is deterministic.
* If there is the first pro-active maintenance action (t_π) before the time (t_0) at which damage initiates, the damage initiation time is increased as following.

$$t_{01} = t_0 + \frac{t_\pi}{2} \tag{9}$$

where

t_0 = damage initiation time without any pro-active maintenance effect

t_π = pro-active maintenance interval

t_{01} = damage initiation time with the first pro-active maintenance effect

* If there is the second pro-active maintenance action ($t_\pi + t_\pi$) before time at which the damage initiation time with first pro-active maintenance effect, the damage initiation time with the first pro-active maintenance effect is increased as following.

$$t_{02} = t_{01} + \frac{t_\pi}{2} \tag{10}$$

where

t_{02} = damage initiation time with the second pro-active maintenance effect

* This procedure is repeated until the cumulative pro-active maintenance interval exceeds the cumulative damage initiation time.

Based on these assumptions, the FORTRAN program is developed. The Fig. 6 shows the cumulative-time failure probability when the pro-active maintenance interval is 3 years and the damage initiation time is 15 years.

Each component has an exponential survivor function ($e^{-\lambda t}$), and it is assumed that each component is independent. There is an initial system failure probability, 10^{-7} . The failure rate, λ, is assumed

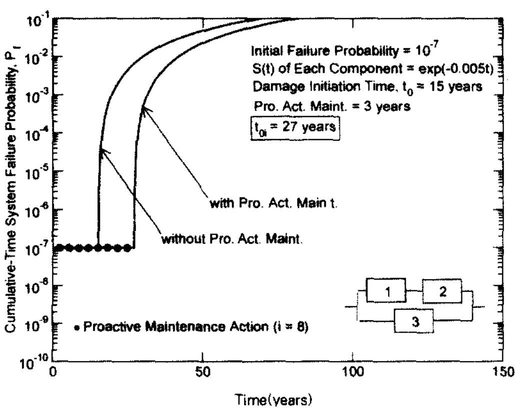

Fig. 6 Effect of Pro-active Maintenance

as 0.005/year for all component. Total number of pro-active maintenance action is 8. Because of pro-active maintenance, the damage initiation time has increased from 15 years to 27 years.

Re-active maintenance is performed on satisfactorily functioning components at regularly scheduled intervals, after the system or components start the damage. The main purpose of re-active maintenance is to increase the availability of either the system or components [Kececioglu 1995]. Availability is the probability that the system is operating satisfactorily at any time after the start of operation. If the failure rate of components or system increase with time, the availability decrease with time. If the failure rate of components or system do not change with time, the availability of components or system don't change with time. If the failure rate of components or system decrease with time, the availability of components or system increase with time.

Failure during service life may be much expensive than re-active maintenance, since they interrupt the service. The re-active maintenance actions do not increase significant improvement of the reliability of components or system, but that extends the service life and improves the level of service.

In this paper, the mathematical re-active maintenance model is used from Kececioglu [1995]. If the re-active maintenance is performed every time interval, the survivor function with that re-active maintenance is given by

$$S_{t_p}(t) = [S(t_p)]^j S_t(\tau) \tag{11}$$

where

S_t = Survivor function

S_{tp} = Survivor function with re-active maintenance interval t_p

j = Number of maintenance action

t = $jt_p + \tau$

$0 \leq \tau \leq t_p$

Based on Equation 11, the survivor function is plotted for two-component parallel system. Each component is assumed as independent. In Fig. 7, the survivor function of each component has exponential distribution, and failure rate is 0.01/hour for each component.

Fig. 7 was plotted based on equation 11. From the figure, it is possible to see that when re-active maintenance is performed, the slop of cumulative-time survival probability is the same as that of cumulative-time survival probability at which the system starts the service. This means that when re-active maintenance is performed on a system, the degradation speed is retarded to original level (the system starts the service). This can be explained by time dependent failure rate. In the Fig. 8, the cumulative time failure probability is shown for one component whose survivor function is Weibull. The scale factor (λ_s) is assumed as 0.005/year and shape factor (x) is assumed as 2.5. The re-active maintenance interval is 20 years. For these two cumulative time failure probabilities, the failure rate is plotted in Fig. 9. From Fig. 9, it is seen that whenever there is re-active maintenance, the failure rate is retarded to original level.

In this paper, this re-active maintenance is defined as "Perfect Re-Active Maintenance". When there is perfect re-active maintenance on a system, all components of the system take re-active maintenance at the same time to retard the system failure rate to original level. The perfect re-active maintenance model is programmed. As an example, the following figures show the cumulative-time failure probability with perfect re-active maintenance.

In Fig. 10, the perfect re-active maintenance is performed every 50 years on three component system. In Fig. 11, there are just three times perfect re-active maintenance. If maintenance intervals are different, the result is shown in Fig. 12. At the first time, the maintenance interval is 50 years and the second maintenance interval is 100 years. And, last maintenance interval is 20 years.

In real case, the perfect re-active maintenance may be happened more in Mechanical area not in Civil

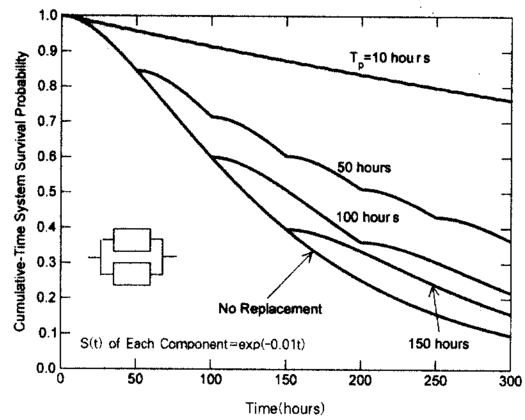

Fig. 7 Cumulative-Time System Survivor Function with Re-active Maintenance for Exponential Distribution of Each Component

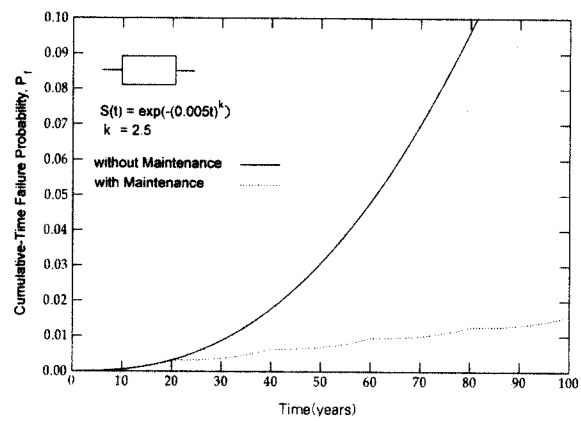

Fig. 8 Cumulative-Time Failure Probability for One Component

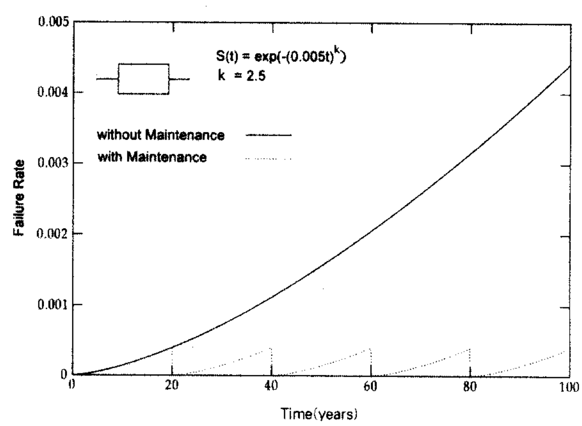

Fig. 9 Comparison of Failure Rate

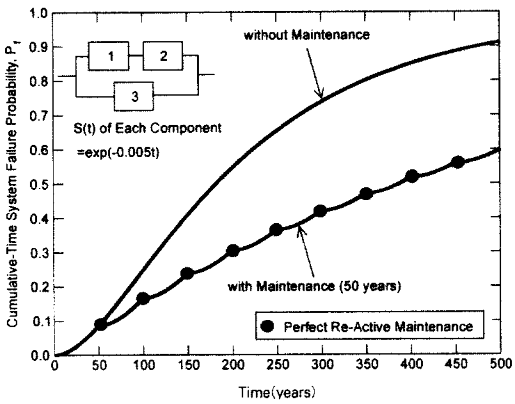

Fig. 10 Perfect Re-Active Maintenance on 3-Component System

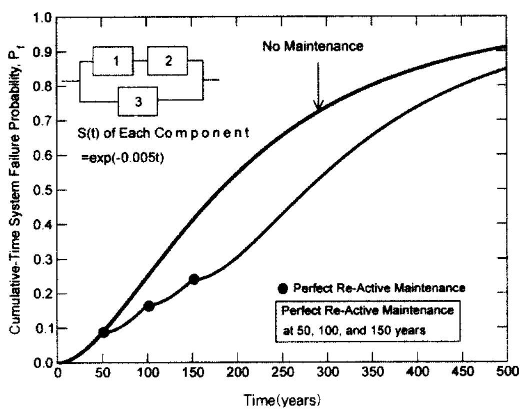

Fig. 11 Three Times of Perfect Re-Active Maintenance on 3-Component System

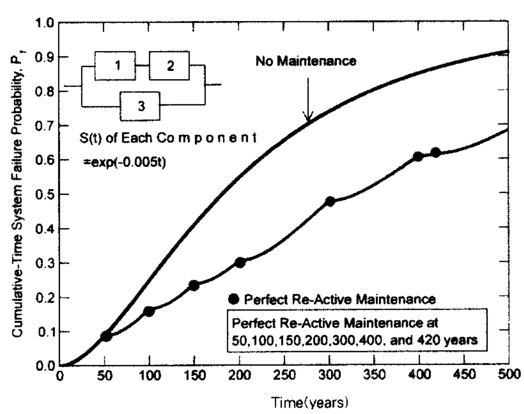

Fig. 12 Perfect Re-Active Maintenance on 3-Component System with Different Maintenance Interval

area. If there are just one, two, or partial re-active maintenance, the equation 11 cannot be used to compute the system reliability because it increases the availability of all component in a system. In order to develop the partial re-active maintenance model, reliability importance factor is used. The basic equation is following.

$$S_{t_{pp}}(t) = S_t + (S_{t_p}(t) - S_t) \times I_r^0(i) \qquad (12)$$

where

$S_{t_{pp}}(t)$ = survivor function with component i re-active maintenance

S_t = survivor function

S_{t_p} = survivor function with re-active maintenance interval t_p

I_r^0 = normalized reliability importance factor of component i

More general equation of partial re-active maintenance is written as following.

$$S_{t_{pp}}(t) = S_t + (S_{t_p}(t) - S_t) \times \sum_j I_r^0(j) \qquad (13)$$

where

j = Components with re-active maintenance

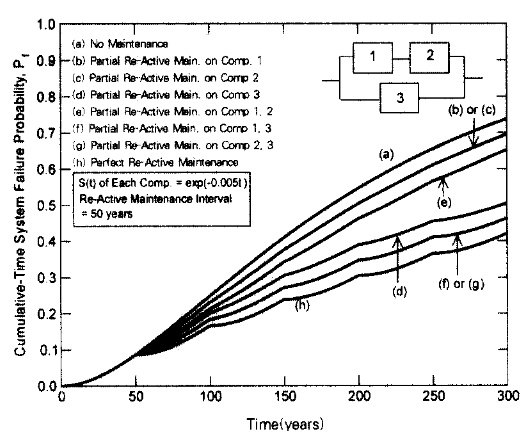

Fig. 13 Partial Re-Active Maintenance on 3-Component System with Exponential Survivor Function of Each Component

Fig. 13 show the application of partial re-active maintenance.

Each component has exponential distribution ,and it is independent. The failure rate is assumed as 0.005/year for each component. The (h) in this figure shows failure probability with the perfect re-active maintenance and the (a) is the failure probability without any maintenance. (b) and (c) show the probability of failure with the partial re-active maintenance of component 1, and 2 and (d) is the partial re-active maintenance of component 3. (f) and (g) show the partial re-active maintenance of compone nts 1, 3 and components 2, 3, respectively.

4. Essential Maintenance

The essential maintenance is performed on failed or malfunctioning components. Such maintenance is performed at unexpectable intervals because the time to any 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 paper, it is assumed that the essential maintenance is performed on components, or system by only replacing them.

Based on an assumption just mentioned, the computer model of essential maintenance is developed. The 3-component system shown in Fig. 14 is used to explain the essential maintenance model.

Each component has exponential distribution. It is assumed that all components are independent and their failure rate is 0.005/year. The survivor function of the system is

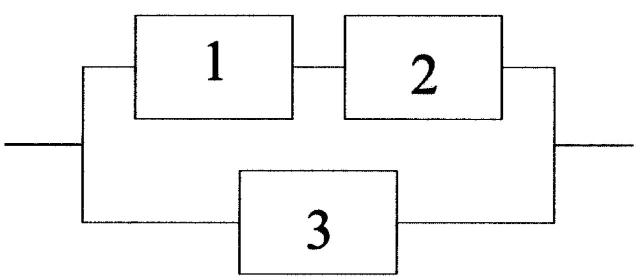

Fig. 14 Three Component System

$$\begin{aligned} S(t) &= 1-[1-S_1(t)S_2(t)][1-S_3(t)] \\ &= 1-(1-e^{-0.005t}e^{-0.005t})(1-e^{-0.005t}) \end{aligned} \tag{14}$$

where

$S_i(t)$ = survivor function of component i

If the essential maintenance is performed on component 1 at year 100, the survivor function at year 100 is written as following.

$$\begin{aligned} S(t) &= 1-[1-S_1(t)S_2(t)][1-S_3(t)] \\ &= 1-(1-e^{-0.005\times 0}e^{-0.005\times 100}) \\ &\quad (1-e^{-0.005\times 100}) \end{aligned} \tag{15}$$

After this essential maintenance, if the essential maintenance is performed on component 2 at year 150, the survivor function at year 150 is

$$\begin{aligned} S(t) &= 1-[1-S_1(t)S_2(t)][1-S_3(t)] \\ &= 1-(1-e^{-0.005\times 50}e^{-0.005\times 0}) \\ &\quad (1-e^{-0.005\times 150}) \end{aligned} \tag{16}$$

And, if the essential maintenance is performed on components 1, 2, and 3 at year 400, the survivor function at year 400 is

$$\begin{aligned} S(t) &= 1-[1-S_1(t)S_2(t)][1-S_3(t)] \\ &= 1-(1-e^{-0.005\times 0}e^{-0.005\times 0}) \\ &\quad (1-e^{-0.005\times 0}) \end{aligned} \tag{17}$$

The failure probability of essential maintenance effect is shown in Fig. 15. From this result, it is shown that the survivor function is not cumulative when there is essential maintenance.

5. Application of Maintenance Model

The preventive maintenance and essential maintenance are programmed. In this section, the applications will

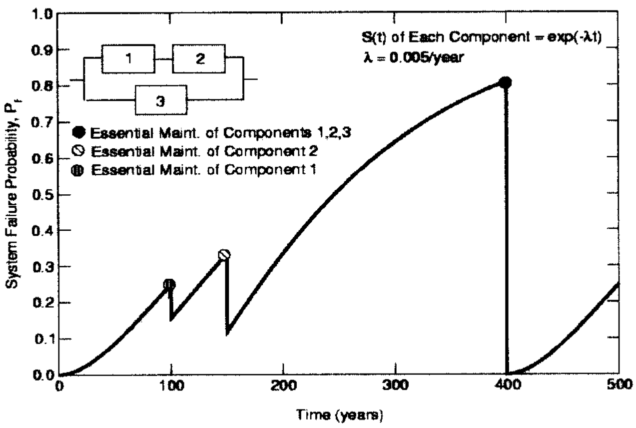

Fig. 15 Essential Maintenance on 3-Component System

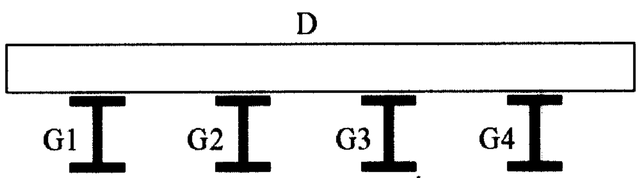

Fig. 16 Bridge Cross Section

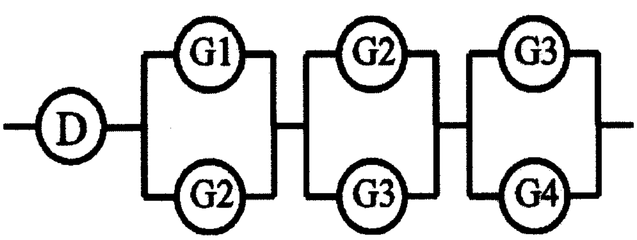

Fig. 17 Bridge Failure Mode

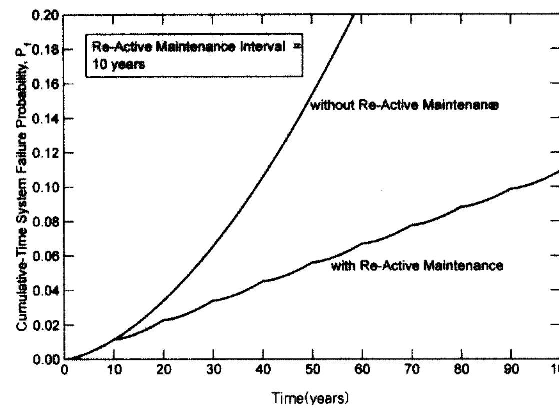

Fig. 18 Cumulative-Time System Failure Probability

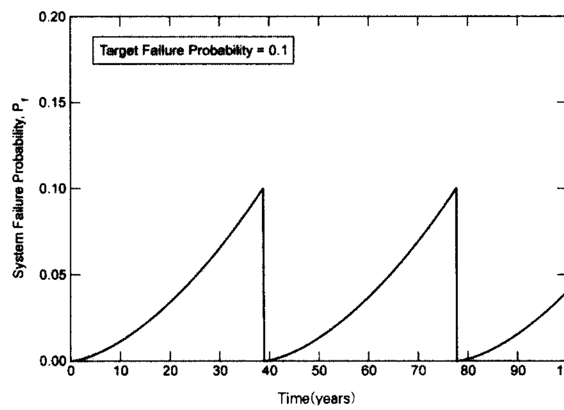

Fig. 19 System Failure Probability with a Target Failure Probability 0.1

be shown.

As an example, a composite bridge shown in Fig. 16 is used. The bridge has a deck and four steel girders. The lifetime distribution is assumed as Weibull survivor function for each bridge component (deck and girders). The scale factor and shape factor of a concrete deck and steel girders are assumed as 0.005/year and 1.5, respectively. The failure mode of the bridge is assumed that any two adjacent girder failures or deck failure cause the bridge failure. The failure mode is shown in Fig. 17.

where
D = deck failure
Gi = failure of girder i

If the re-active maintenance interval is 10 years, the probabilities of failure with re-active maintenance and without re-active maintenance are shown in Fig. 18.

If there is a target failure probability 0.1, the system failure probability is shown in Fig. 19.

In Fig. 19, when the system failure probability reaches the target failure probability 0.1, all components in a bridge are replaced.

6. Conclusion

Based on the concept of system reliability and lifetime function, the FORTRAN program was developed for each maintenance models. The availability is considered for preventive maintenance and the replacement is considered for essential maintenance.

Using the essential maintenance model developed in this paper, the optimum maintenance strategy can be obtained. In the application, if the system failure probability reached the target failure probability, all components in a system were replaced. However, in real case, it may be possible to choose the options (replace deck or interior girders or exterior girders, etc.).

The main concern of the preventive maintenance is to calculate the optimum preventive maintenance interval. Using preventive maintenance, the reliability of the bridge can not be increased, but the service life of the bridge can be increased.

The maintenance models developed in the paper can be applied to any structure which is expressed as a combination of series and parallel systems.

References

1. Leemis, L. M., (1995). Reliability, probabilistic models and statistical methods, Prentice-Hall, New Jersey, p 319.
2. Kecveciolu, D. (1995). "Maintainability, Availability and Operational Readiness Engineering", Vol 1, Prentice-Hall Inc., Washington D.C.
3. Gharaibeh, E.S., (1999). "Reliability and Redundancy of Structural System with Application to Highway Bridges", Ph.D Thesis, University of Colorado at Boulder.
4. Gharaibeh, E.S., Frangopol, D.M., and Shing, P.B., (1998). "Structural Importance Assessment of Bridge Members", A Reliability based Approach, Canadian Society of Civil Engineers, 2:1221-1233.

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