시스템 신뢰성에 기초한 교량의 최적 유지관리 계획

Optimum Maintenance Strategy of Bridges Based on System Reliability

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요　　약 : 교량의 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 생애함수를 이용하여 예방 (Preventive) 유지관리 와 사후 (Essential) 유지관리 모델을 개발하였다. 이 논문에서 개발된 유지관리 모델을 이용해서 현존하는 교량에 대해 최적의 유지관리 계획을 구하였다.

ABSTRACT : Bridge construction is almost complete in many countries. Thus, the government and highway agencies change their focus from constructing to maintaining. Effectively maintaining bridges require predicting their lifespan using a system reliability viewpoint. Likewise, maintenance models based on the system reliability concept should be developed. Thus, this study developed maintenance models for preventive maintenance and essential maintenance using system reliability and lifetime distributions. The optimal maintenance strategy for an existing bridge was obtained using the developed maintenance models.

핵 심 용 어 : 교량, 시스템신뢰성, 잔존수명, 생애함수, 예방 유지관리 모델, 사후 유지관리 모델

KEYWORDS : bridges; system reliability; remaining life; lifetime function; preventive maintenance; essential maintenance

1. Introduction

About half of bridges in the United States are considered to be deficient and therefore are in need of repair or replacement. Half of these are functionally obsolete, and others do not have required strength [State 1989]. For these bridges, repairs and replacements are needed. In order to avoid the high cost of rehabilitation, the bridge rating must correctly report the present load-carrying capacity. The bridge rating is performed by AASHTO's method [Manual 1983, Condition 1994]. These manuals use level zero (Allowable Stress Design Rating) and level one (Load Factor Design Rating) safety checking requirement. In these safety checking methods (level zero and level one methods), the single component is used to check safety and to compute rating value, however, all bridges which are used or designed are a system of components.

The bridges are designed to serve the public. And no matter how well these are designed, they are deteriorating with time. One of the main concerns 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.

In this paper, as a new approach, the computer program, "LIFETIME", is developed by using system

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reliability concepts and lifetime functions. The program "LIFETIME" includes the maintenance models (Preventive and Essential Maintenance). Based on system reliability and maintenance cost, optimal maintenance strategy is obtained for an existing Colorado state highway bridge (E-17-AH).

2. System Reliability and Reliability Importance Factor with Lifetime Function

2.1 Structure Function and Reliability Function

Structure function [Leemis 1995] is a useful tool to describe the state of a system with n components. Structure function defines the system state as a function of the component state. In addition, it is assumed that both components and the system can either be functioning or failed. The state of component i, x_i, is assumed as

$$x_i = \begin{cases} 0 & \text{if component } i \text{ has failed} \\ 1 & \text{if component } i \text{ is functioning} \end{cases} \qquad (1)$$

for i = 1, 2, ..., n

The n component system can be expressed as a system state vector as following.

$$\mathbf{x} = \{x_1, x_2, \ldots, x_n\} \qquad (2)$$

Structure function, $\phi(\mathbf{x})$, expresses the system state vector $\mathbf{x}$ to zero or one. The structure function $\phi(\mathbf{x})$ for a given system state vector is

$$\phi(\mathbf{x}) = \begin{cases} 0 & \text{if the system has failed} \\ 1 & \text{if the system is functioning} \end{cases} \qquad (3)$$

As an example, the structure function is obtained for a 5-component system shown in Fig. 1. Also, Fig.1 shows the reduction steps. These reduction steps are also expressed as functions through Eq. (4) to Eq. (7).

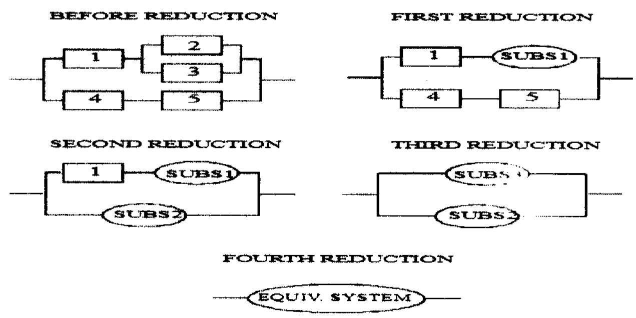


Fig. 1 Sequential Reduction Procedure

The first reduction step is a parallel system between components 2 and 3. Using the first reduction, the subsystem 1 is obtained and expressed as following.

$$\phi_{s1}(\mathbf{x}) = 1-(1-x_2)(1-x_3) \qquad (4)$$

The second reduction is a series system between components 4 and 5. This is expressed as following.

$$\phi_{s2}(\mathbf{x}) = x_4 x_5 \qquad (5)$$

The third reduction is also a series system between subsystem 1 and component 1.

$$\phi_{s3}(\mathbf{x}) = x_1 \phi_{S1} \qquad (6)$$

Using the fourth reduction, the structure function of this 5-component system is obtained.

$$\phi(\mathbf{x}) = 1-\{1-x_1[1-(1-x_2)(1-x_3)]\}(1-x_4x_5) \qquad (7)$$

The structure function is deterministic. This assumption may be unrealistic for certain types of components or 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 is a random variable. The probability that component i is functioning is given by

$$p_i = P[x_i = 1] \qquad (8)$$

Where

p_i = Probability that component i is functioning

In order to obtain the reliability function for a 5-component system shown in Fig. 1, the same procedure is necessary. But the component reliability function, p_i, is used in each step instead of component state x.

2.2 Lifetime Function

There are several lifetime functions to describe the evolution of the probability of failure. In this paper, survivor function is introduced and explained. The survivor function can be applied to both discrete and continuous lifetime.

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

$$S(t) = P[T \geq t] \qquad t \geq 0 \tag{9}$$

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

Exponential distribution, Weibull distribution, Log-Logistic distribution, and Exponential Power distribution are used as survivor functions. These are shown in Table 1.

Table 1. Survivor Functions

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

where

λ = Failure rate

κ = Shape factor

t = Time, $t \geq 0$

λ_s = Scale factor

2.3 Reliability Importance Factor

Reliability importance factor indicates the relative importance of component with respect to the system reliability. The reliability importance [Leemis 1995] of component i in a system of n components is

$$I_{r(i)} = \frac{\partial r(p)}{\partial p_i} \tag{10}$$

where

$r(p)$ = Reliability function

p_i = Reliability function of component i

for $i = 1, 2, 3 \ldots n$. The normalized reliability importance factor [Gharaibeh 1999, Gharaibeh et al. 1998] is defined as

$$I_r^0(i) = \frac{I_r(i)}{\sum_{i=1}^{n} I_r(i)} \tag{11}$$

The normalized reliability importance factor, I_r^0 is between 0 and 1. The definition of reliability importance emphasizes the impact of the component i on a system.

As an example, a four-component system is used to explain the reliability importance factors from Fig. 2 to Fig. 5. If the failure probability of 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. 2. In Figs. 3 and 4 the failure probabilities of components 2 and 3 vary, respectively. If failure probabilities of all components vary, the result is shown in Fig. 5.

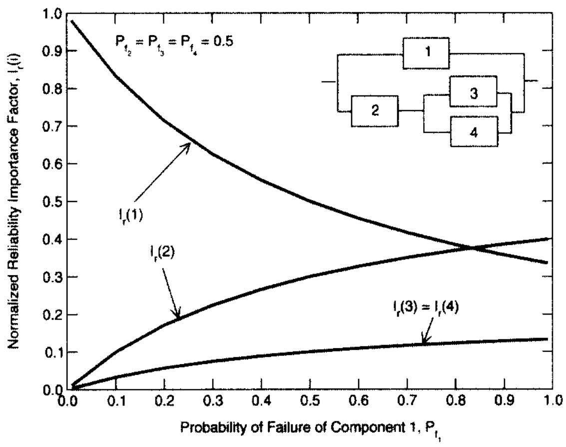


Fig. 2 Normalized Reliability Importance Factors; $0<P_{f1}<1$ and $P_{f2}=P_{f3}=P_{f4}=0.5$

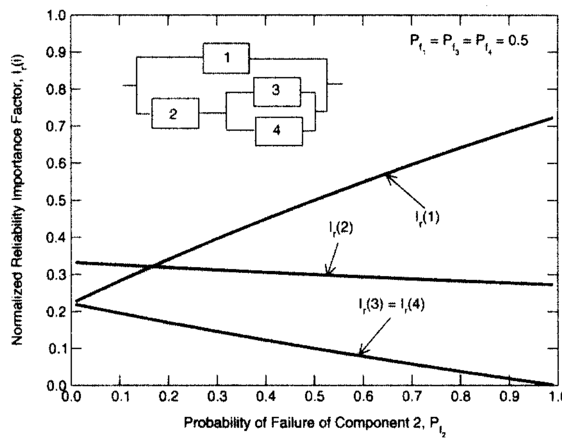


Fig. 3 Normalized Reliability Importance Factors; $0<P_{f2}<1$ and $P_{f1}=P_{f3}=P_{f4}=0.5$

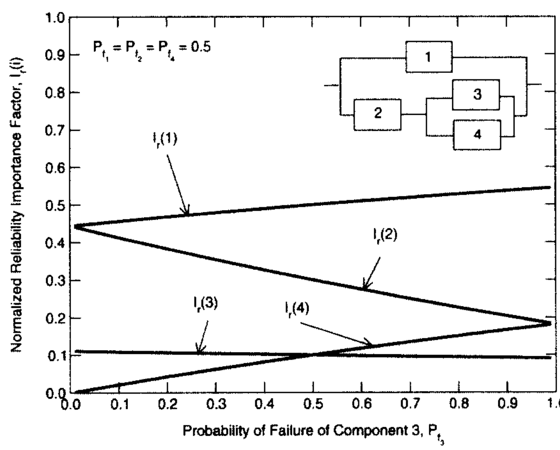


Fig. 4 Normalized Reliability Importance Factors; $0<P_{f3}<1$ and $P_{f1}=P_{f2}=P_{f4}=0.5$

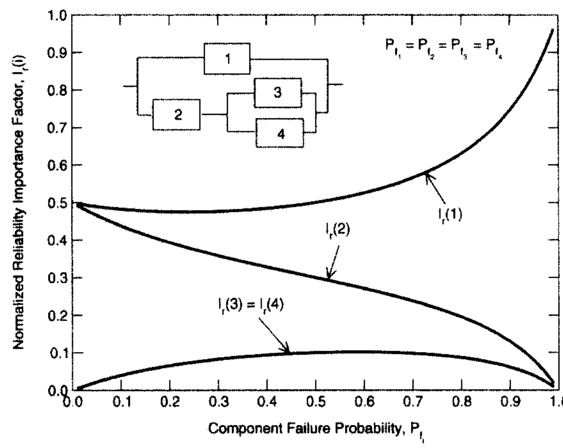


Fig. 5 Normalized Reliability Importance Factors; $P_{f1}=P_{f2}=P_{f3}=P_{f4}$

3. Maintenance Models

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 (scheduled) and Essential (unscheduled). The preventive maintenance are performed on satisfactorily functioning components and the essential maintenance is performed on failed or malfunction components.

3.1 Preventive Maintenance Model

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 "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 Fig. 6, it is easy to show the effect of proactive maintenance.

In the figure, the initial probability of failure is P_i and the damage initiation time is t_0 without proactive maintenance. If there is no proactive maintenance action, the damage starts at t_0. If there is proactive

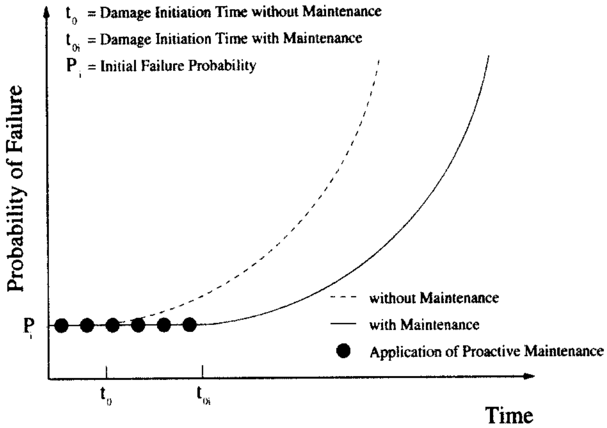


Fig. 6 Effect of Pro-Active Maintenance

maintenance, the damage occurs after time t_{0i}. Because of proactive maintenance effect, the damage initiation time is increased from t_0 to t_{0i}.

In order to develop a proactive maintenance model, it is necessary to make the assumption based on an existing data. Unfortunately, data on proactive maintenance are rarely limited. Therefore, to develop a proactive maintenance model, expert opinion is needed. The assumption made in this paper are as follows:

Assumption

- The proactive maintenance action interval, t_π, can be treated as deterministic or random variable.
- The damage initiation time, t_0, can be treated as deterministic or random variable.
- When there is the first proactive maintenance action (t_π) before the time (t_0) at which damage initiates, the damage initiation time is increased as following.

$$t_{0i} = t_0 + i \times \frac{t_\pi}{2} \qquad (12)$$

where

t_{0i} = damage initiation time with maintenance effect
t_0 = damage initiation time without considering maintenance effect
i = number of maintenance actions
t_{pi} = maintenance action time interval

- The process in Eq. 12 is repeated until the cumulative proactive maintenance time exceeds the damage initiation time with maintenance effect as follows

$$i \times t_\pi > t_{0i} \qquad (13)$$

Based on these assumptions, the FORTRAN program is developed. Fig. 7 shows the result if the proactive maintenance interval is 3 years and the damage initiation time is 15 years.

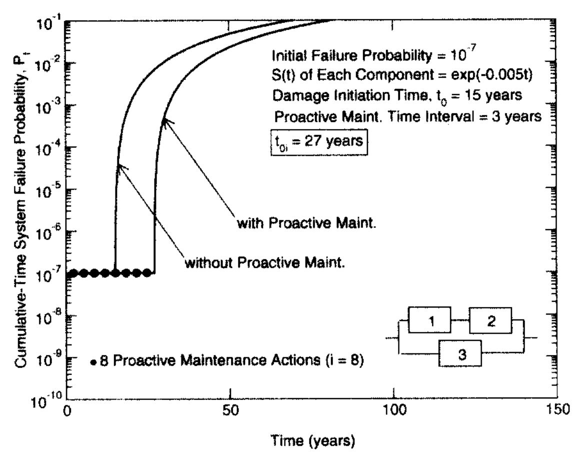


Fig. 7 Effect of Pro-Active Maintenance for a Three Component System (Deterministic Pro-active Maintenance Interval and Deterministic Damage Initiation Time)

Table 2. Proactive Maintenance Effect

Damage Initiation Time without Maintenance (years)	Proactive Maintenance Time Interval (years)	Mean of Damage Initiation Time (with Proactive Maintenance) (years)	Standard Deviation of Damage Initiation Time (with Proactive Maintenance) (years)
15	Log-normal (3, 0.5)	27.7	0.58
Log-normal (15, 0.5)	Log-normal (3, 0.5)	27.8	1.12

In this example, each component is independent, and both proactive maintenance interval and damage initiation time are deterministic as 3 years and 15 years, respectively.

The initial failure probability of the system is 10^{-7}. According to assumptions, the number of proactive maintenance action is 8 and total 12 years are increased by proactive maintenance. If proactive maintenance interval and damage initiation time are random, the results are shown in Table 2.

Reactive maintenance is performed on satisfactorily functioning components at regularly scheduled intervals, after either the system or components starts the damage. The main purpose of reactive 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 increases with time, the availability decrease with time. If the failure rate of components or system does not change with time, the availability of components or system doesn't change with time. If the failure rate of components or system decreases with time, the availability of components or system increases with time. The reactive 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 reactive maintenance model is adapted from Kececioglu [1995]. If the reactive maintenance is performed every time interval, t_p, the survivor function is given by

$$S_{t_p}(t) = [S(t_p)]^j S_t(\tau) \tag{14}$$

where

$S_{t_p}(t)$ = Survivor function with reactive maintenance time interval t_p

j = number of maintenance actions

$0 \le \tau < t_p$

Based on Equation 14, the survivor function is plotted for a two-component parallel system. Each component is independent, and its survivor function is exponential distribution. The failure rate is assumed as 0.01/year for each component. The figure shows the difference between survival probability with or without reactive maintenance (different reactive maintenance intervals).

Fig. 8 was plotted based on equation 14. From these figures, it is possible to see that when reactive maintenance is performed, the slope of cumulative-time survival probability is the same as that of cumulative-time survival probability at which the system starts the service. This can be explained by time dependent failure rate. In Fig. 9, the cumulative time failure probability is shown for one component whose survivor function is Weibull ($e^{-(\lambda_s t)^\kappa}$). The

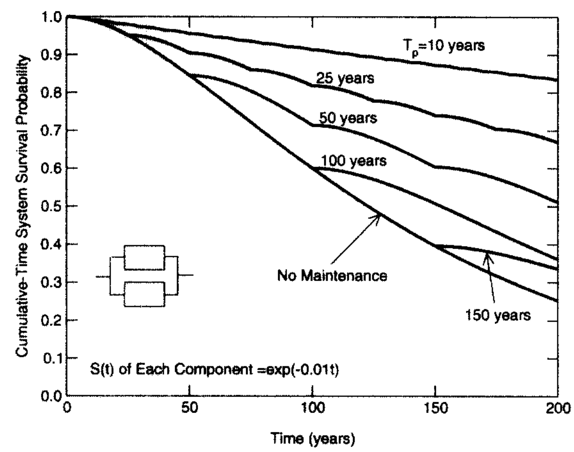


Fig. 8 Cumulative-Time System Survivor Function with Reactive Maintenance for Exponential Distribution of Each Component

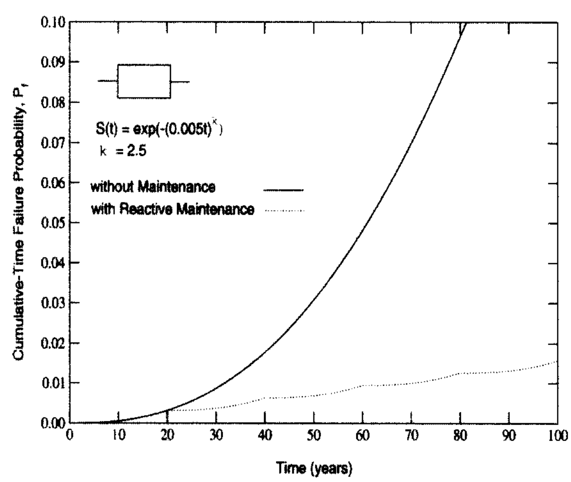


Fig. 9 Cumulative-Time Failure Probability for One Component

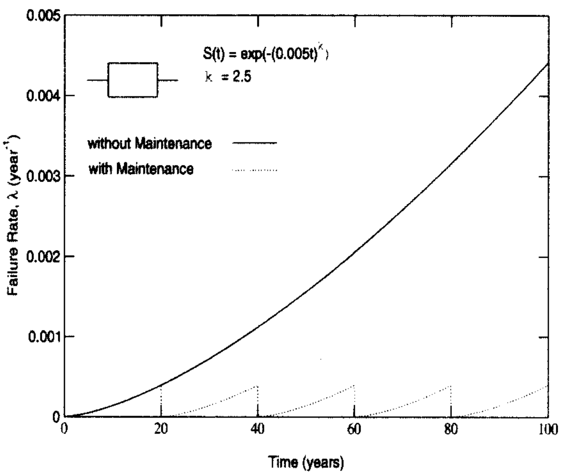


Fig. 10 Comparison of Failure Rate

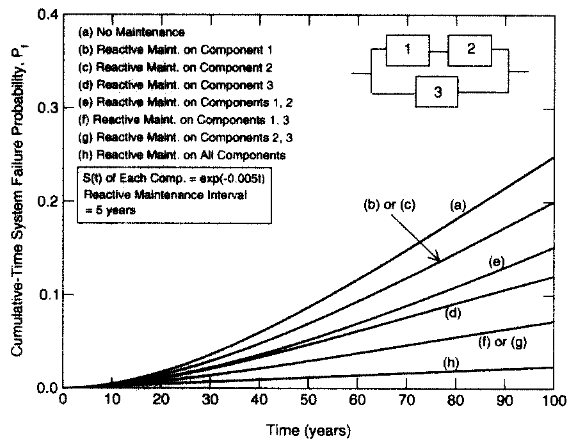


Fig. 11 Partial Reactive Maintenance on 3-Component System with Exponential Survivor Function of Each Component

scale factor (λ_s) is assumed as 0.005/year and shape factor (κ) is assumed as 2.5. The reactive maintenance interval is 20 years. For these two cumulative time failure probability, the failure rate is plotted in Fig. 10. From Fig. 10, it is seen that whenever there is reactive maintenance, the failure rate is retarded to original level.

In this paper, this reactive maintenance is defined as "Perfect Reactive Maintenance". When there is perfect reactive maintenance on a system, all components of a system take reactive maintenance at the same time to retard the system failure rate to original level.

If there are just one, two, or three components which need to have the reactive maintenance on a multi-component system (say, n>4), equation 14 cannot be used to compute the system failure probability because it increases availability of all components. In order to develop reactive maintenance model when not all components in a system need to have maintenance, reliability importance factor explained in section 2.3 is used. The equation for partial reactive maintenance [Yang 2002] is as follows:

$$S_{t_{rp}}(t) = S_t(t) + [S_{t_p}(t) - S_t(t)] \times \sum_{jj} I_r^0(jj) \qquad (15)$$

Eq. 15 explains that if there is reactive maintenance on several components in a system, the difference between reliability without perfect reactive maintenance and reliability with perfect reactive maintenance is computed and the portion of reliability importance factor for this difference are added to the reliability without perfect reactive maintenance.

Fig. 11 shows the application of partial reactive maintenance.

The 3-component system is used, and each component has exponential distribution and is independent. The reactive maintenance time interval is 5 years. The failure rate is assumed as 0.005/year for each component. The (h) in this figure shows failure probability with the perfect reactive maintenance and the (a) is the failure probability without any maintenance. And, (b) to (g) show the failure probability with partial reactive maintenance. The (b) and (c) show the probability of failure with the partial reactive maintenance of components 1, and 2 and (d) is the partial reactive maintenance of component 3. (f) and (g) show the partial reactive maintenance of components 1, 3 and components 2, 3, respectively.

3.2 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. 12 is used to explain the essential maintenance model.

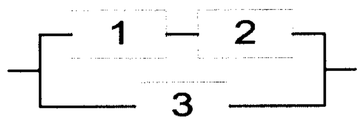


Fig. 12 3-component System

Each component has exponential distribution. It is assumed that all components are independent and their failure rate is 0.0005/year. The survivor function of system C3 is

$$S(t)=1-\ [1-\exp(-0.0005t)\exp(-0.0005t)]\times [1-\exp(-0.0005t)] \quad (16)$$

When the essential maintenance is performed on component 1 at year 10, the survivor function at year 10 is written as following.

$$S(t)=1-\ [1-\exp(-0.0005\times 0)\exp(-0.0005\times 10)] \times [1-\exp(-0.0005\times 10)] \quad (17)$$

After this essential maintenance, when the essential maintenance is performed on component 2 at year 20, the survivor function at year 20 is

$$S(t)=1-\ [1-\exp(-0.0005\times 10)\exp(-0.0005\times 0)] \times [1-\exp(-0.0005\times 20)] \quad (18)$$

And, there is an essential maintenance for all components at year 40, the survivor function at year 40 is

$$S(t)=1-\ [1-\exp(-0.0005\times 0)\exp(-0.0005\times 0)] \times [1-\exp(-0.0005\times 0)] \quad (19)$$

The failure probability of the system is shown in Fig. 13 with the effect of essential maintenance.

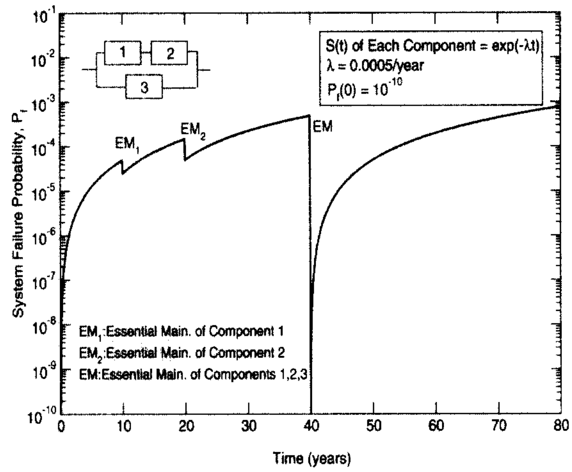


Fig. 13 Probability of Failure with the Essential Maintenance

4. Optimum Maintenance Strategy of Case Study

4.1 Colorado State Bridge E-17-AH

Bridge E-17-AH is located on 40th Avenue (State Highway 33) between Madison and Gardfield Streets in Denver. The bridge has three simple spans of equal length (43.83 *ft*) and a total length of 137.3 *ft*. The deck consists of 9.0 *in.* of reinforced concrete and a 3.0 *in.* surface layer of asphalt. The east-west bridge has two lanes of traffic in each direction with an average daily traffic 8,500 vehicles. The roadway width is 40 *ft.* with 5 *ft.* pedestrian sidewalks and handrailing on each side. The bridge offers 22.17 *ft.* of clearance for the railroad spur that runs underneath. There is no skew or curvature. The slab is supported by nine standard-rolled, compact, and non-composite steel girders. The girders are stiffed by end diaphragms and intermediate diaphragms at the third points. Each girder is supported at one end by a fixed bearing and an expansion bearing at the other end. The bridge is shown in Figs. 14 and 15.

4.2 Data Collection

Each lifetime distribution has each its parameters (failure rate, scale factor and shape factor), and these should be obtained from data analysis to predict the

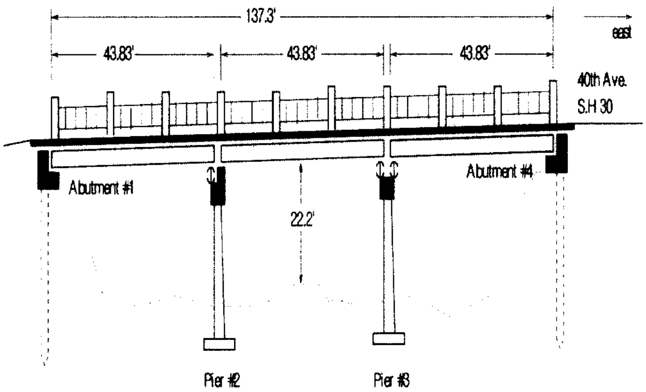


Fig. 14 Colorado State Bridge E-17-AH :Profile (Estes 1997)

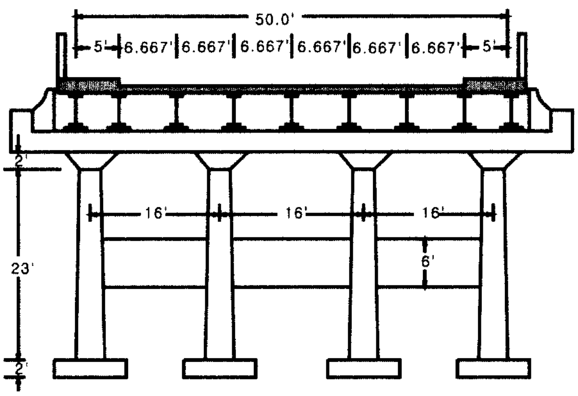


Fig. 15 Colorado State Bridge E-17-AH :Cross Section (Estes 1997)

failure probability of real bridges.

The data from Maunsell Ltd. [Maunsell 1999] is used for bridge components. In Maunsell's report [1999], the serviceable life is defined to be the time taken for a significant defect requiring attention to be recorded at an inspection. According to defect severity, four levels are classified.

- Severity1 : no significant defects
- Severity2 : minor defects of a non urgent nature
- Severity3 : defects which shall be included for attention within the next annual maintenance program
- Severity4 : the defect is severe and urgent action is needed

Data analysis was conducted for severity 3 and 4. Weibull distribution was selected as best fit for each bridge component and its parameters were summarized in the report [Maunsell 1999].

Tables 3 and 4 contain the parameters of Weibull distribution for Severity 3 and 4.

4.3 Modeling of Colorado State Bridge E-17-AH

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. The following failure modes are considered.

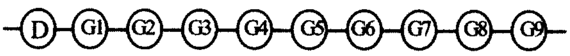
- System I : Any one girder failure or deck failure causes the bridge failure.

Table 3. Parameters of Weibull Distributions of Serviceable Life for Severity 3 Defects(Adapted from Maunsell 1999)

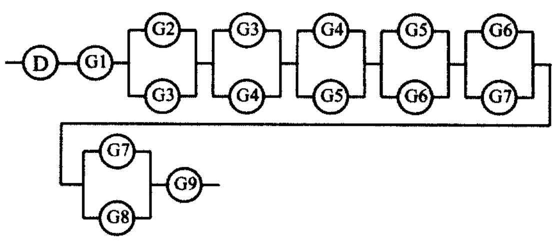
Category Structure forms	Description	x Years	$1/\lambda_s$ Years	MODE Years
A1	Arches, concrete	2.44	41.28	33
A2	Slab decks	1.40	56.12	22
A3A	RC beam and Slab, slabs	2.98	27.73	24
A3B	RC beams and Slab, Beams	2.88	30.26	26
A4A	Composite, slabs	2.84	37.72	32
A4B	Composite, beams	1.47	26.66	12
A5A	Pretensioned slabs	1.70	68.74	40
A5B	Pretensioned beams	1.41	69.45	28
A6A	Post tensioned, slabs	2.62	51.55	42
A6B	Post tensioned, beams	3.29	23.97	21

Table 4. Parameters of Weibull Distributions of Serviceable Life for Severity 4 Defects(Adapted from Maunsell 1999)

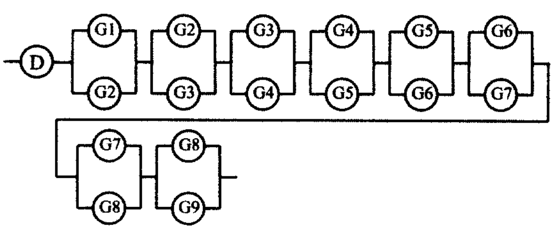
Category Structure forms	Description	x Years	$1/\lambda_s$ Years	MODE Years
A1	Arches, concrete	Insufficient Data for Analysis		
A2	Slab decks	2.37	130.50	103
A3A	RC beam and Slab, slabs	3.76	83.36	76
A3B	RC beams and Slab, Beams	1.66	228.50	119
A4A	Composite, slabs	2.91	98.98	85
A4B	Composite, beams	2.86	94.70	81
A5A	Pretensioned slabs	1.90	223.39	119
A5B	Pretensioned beams	3.19	80.23	71
A6A	Post tensioned, slabs	3.03	104.20	91
A6B	Post tensioned, beams	2.60	100.83	83



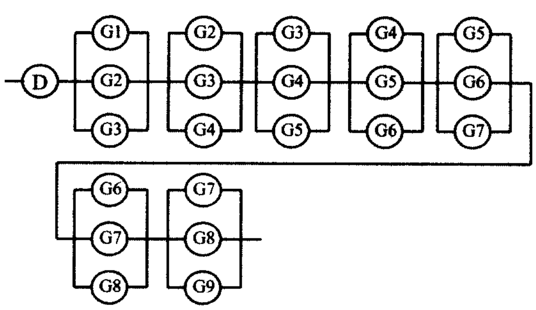
a) System I



b) System II



c) System III



d) System IV

Fig. 16 Failure Modes

Where
D = Deck failure
G1 and G10 = Exterior girder failure
G2, G3, G4, G5, G6, G7, G8, and G9
= Interior girder 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. 16 for Bridge E-17-AH. With these failure modes, the reliability analysis is performed.

4.4 Optimal Maintenance Strategy

The optimal maintenance method was borrowed from Estes [1997]. In this thesis, possible maintenance options shown in Table 5 were tried to obtain the optimal maintenance strategy.

In order to obtain the optimal maintenance strategy, it is necessary to establish the minimum acceptable system failure probability. In this paper, the minimum

Table 5. Maintenance Options (Adapted from Estes 1997)

Replacement Option	Replacement Cost
0: Do nothing	$ 0
1: Replace D)deck	$ 225,600
2: Replace exterior Girder	$ 229,200
3: Replace exterior girders and deck	$ 341,800
4: Replace superstructure	$ 487,100

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 [Cost 2001]. The present value cost is computed as

$$PV = \frac{C_{rep}}{(1+\nu)^n} \tag{20}$$

where

PV = Present value cost
C_{rep} = Maintenance cost
n = Number of years in the future when the repair will be made
υ = 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 % [Weston and Brigham 1981]. In this paper, 2 %, 4 %, 6 %, and 8 % of the discount rates are used. As an example, if there is an replacement of the superstructure of the bridge at year 100, the present value cost with 2 % discount rate is computed by using equation 20 and Table 5 as following.

$$PV = \frac{\$487,100}{(1+0.02)^{100}} = \$67,236 \tag{21}$$

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. Figs. 18 and 19 are the optimal maintenance strategy and the profile of the failure probability for the bridge system II.

In Fig. 17, all possible combinations of repair options are shown for Bridge System II. It can be seen that the system failure probability reaches the target

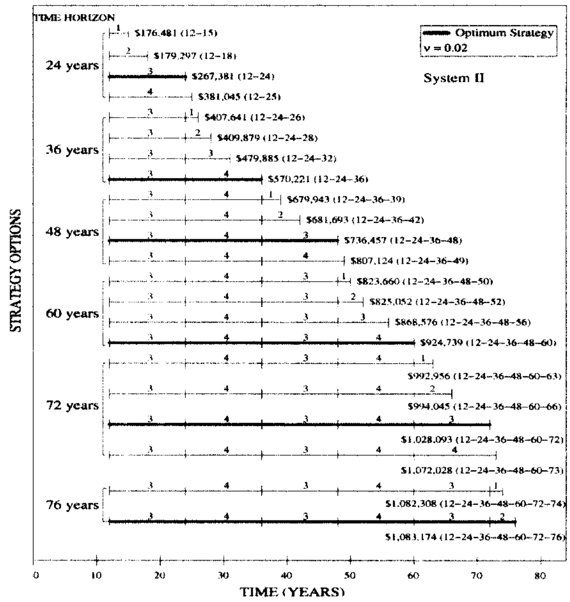


Fig. 17 Optimal Maintenance Strategy for the Second Failure Mode

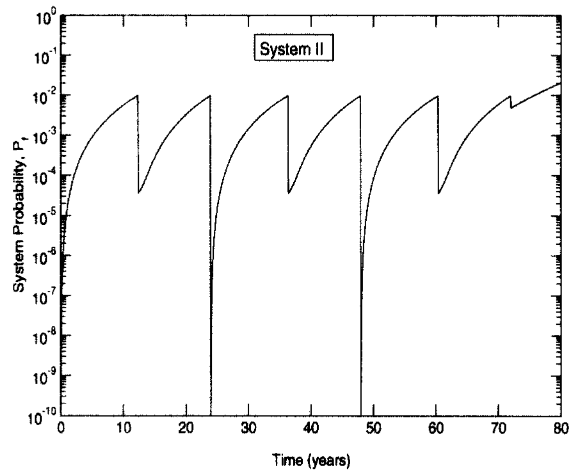


Fig. 18 Failure Probability Profile of Optimal Maintenance Strategy for the Second Failure Mode

failure probability 10^{-2} at year 12. At that year, all possible options listed in Table 5 are tried to compare the extended lifetime and compute the present value cost for each option. According to the first replacement, the option 3 is the best choice. After the first replacement, the system reaches the target failure probability at year 24. Again, the all options listed in Table 5 are tried. The best choice of the second replacement is an option 4 since it extends the system lifetime very long comparing with other options. This is continued until the service life is beyond 75 years.

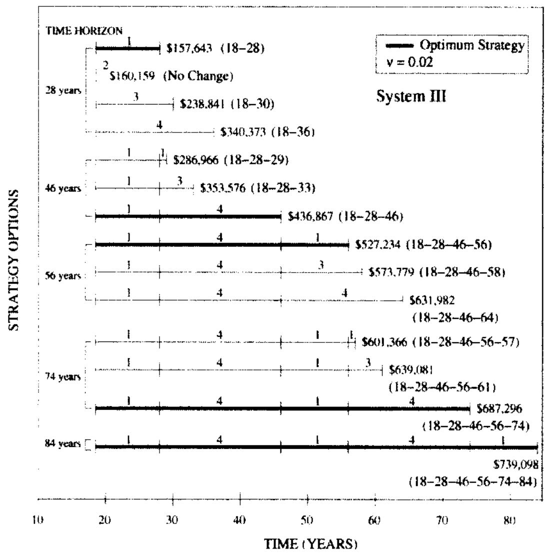


Fig. 19 Optimal Maintenance Strategy for the Third Failure Mode

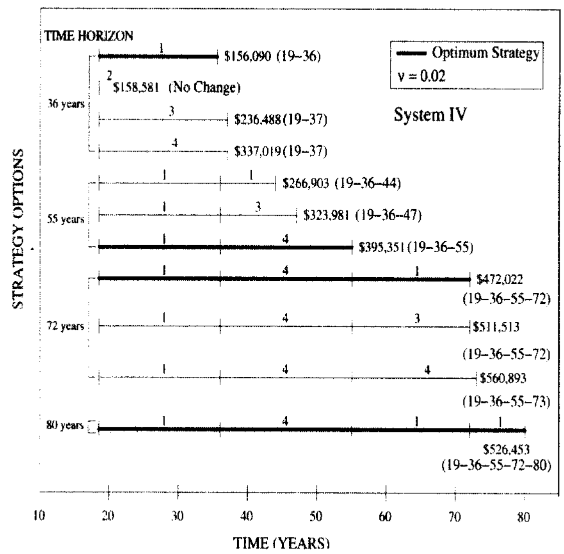


Fig. 21 Optimal Maintenance Strategy for the Fourth Failure Mode

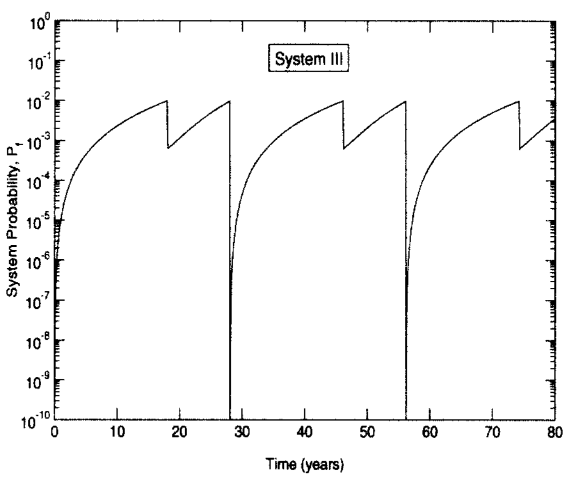


Fig. 20 Failure Probability Profile of Optimal Maintenance Strategy for the Third Failure Mode

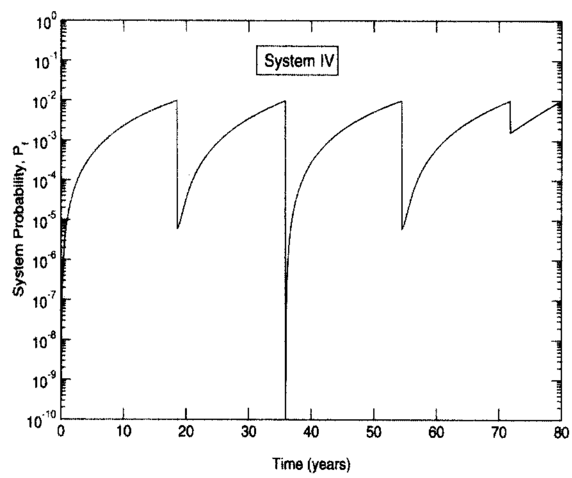


Fig. 22 Failure Probability Profile of Optimal Maintenance Strategy for the Fourth Failure Mode

Table 6. Optimal Maintenance Cost with Different Discount Rates

Bridge System	Optimal Maintenance Cost (U.S. $)				
	v = 0%	v = 2%	v = 4%	v = 6%	v = 8%
II	2,228,800	1,083,174	601,910	370,528	245,476
III	1,651,000	739,099	375,560	209,997	125,682
IV	1,163,900	526,453	268,039	149,320	88,949

The result is shown in Fig. 17. The sequential replacement options are 3 - 4 - 3 - 4 - 3 - 2. The present cost is computed using discount rate 2 %. The system failure probability with optimal strategy is shown in Fig. 18.

The same method is applied to Bridge Systems III and IV. Figs. 19 and 20 are for Bridge System III and Figs. 21 and 22 are for Bridge System IV.

The optimal maintenance cost with different discount rates are shown in Table 6.

5. Conclusion

The main purpose of this paper was to predict the time-dependent component and system probability of survival using lifetime functions and obtain optimal maintenance strategies. Lifetime functions and system reliability models were used. Finally, the existing Colorado bridge E-17-AH was used to predict the time-dependent system probability and obtain the optimal maintenance strategy using life-cycle cost.

(1) Using structure function and reliability function, the system can be expressed as a combination of series-parallel components. The reliability importance factor can be used to evaluate the importance of the components in a system.

(2) 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.

(3) 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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