CHOICE OF INSPECTION STRATEGY FOR MARINE STRUCTURES BY DIFFERENT APPROACHES

Swilem A.M. Swilem
Department of Naval Architecture and Marine Engineering, Faculty of Engineering, Alexandria University, Alexandria, Egypt

In the present work, the choice of the inspection strategy for a structure is carried out based on three different approaches; Standard reliability approach, Cost minimization approach and Cost minimization with constraint on reliability approach. The inspection strategy of marine structures can be chosen by using life-time cost minimization, however, most of the cost items related to the cost analysis generally contain uncertainties in actual structures. A sequential cost minimization method developed by the author is employed to optimize the life-time cost. It is made clear that the stability of the life-time cost is maintained without losing the benefit of the cost minimization method by the use of the sequential cost approach. Cost minimization with constraint on reliability is developed in order to obtain an acceptable inspection strategy against the estimation errors of the parameters. In this analysis, the life-time cost optimization is carried out under the constraint that the failure probabilities of the members are controlled below the respective target values allowed for the members. First, initial target failure probabilities are assigned for each member. Then the criterion of the inspection planning is investigated by adjusting the parameters within the range of uncertainties. The initial values of the failure probabilities are changed until an acceptable result is obtained. The applicability of the proposed method is examined for a structure with several uncertain parameters.

في هذا البحث يتم اختيار خطة الفحص لأي منشأ بناء على مناهج مختلفة هي منهج المعوالية القياسية، منهج تقليل التكلفة ومنهج تقليل التكلفة مع تحديد المعوالية . من الممكن اختيار خطة الفحص للمنشات البحرية باستخدام طريقة تقليل تكلفة عمرها الافتراضي وقد تم تحقيق ذلك من خلال تتابع أقل التكلفة. تم تطوير منهج تقليل التكلفة مع تحديد المعوالية للحصول على خطة فحص مناسبة وذلك للتغلب على الأخطاء المتوقعة من المعاملات المستخدمة في طريقة تقليل تكلفة العمر الافتراضي. في هذا الصدد تم الحصول على التكلفة المثلي للعمر الافتراضي مع التحكم في قيم احتمالات انهيار أعضاء المنشأ بحيث تكون أقل من المسموح به. ففي البداية يتم تعيين قيم مبدئية لاحتمالات انهيار كل عضو في المنشأ حتى يتثنى استنباط خطة الفحص بضبط قيم المعاملات في حدود عدم التأكد ثم يتم تغيير القيم المبدئية لاحتمالات الانهيار حتى الحصول علي نتائج مرضية. وقد تم تطبيق هذه الطريقة علي أحد المنشات مع الأخذ في الاعتبار عدد من المعاملات في حدود عدم التأكد.

Keywords: Inspection strategy, Optimization, Uncertainties, Deteriorating structures.

INTRODUCTION

The structural safety and reliability against fatigue failure are important factors for ships and offshore structures. Structural reliability can be achieved by adopting suitable inspection, repair and maintenance policies. On the other hand, sufficient safety can be achieved by well-balanced use of several safety items at design, fabrication, inspection and repair maintenance stages. Each safety item has a certain cost, therefore, it is of importance to minimize the total expected cost during the life time of the structure and to keep the structural reliability at an acceptable level. From this viewpoint, life-time cost minimization can be considered as the optimal criterion for the choice of inspection strategy and repair maintenance of structures. In the present work, the choice of the inspection strategy was carried out based on three different approaches :-

(1) Standard reliability [1,2],
(2) Cost minimization [3], and
(3) Cost minimization with constraint on reliability.

In the first approach, a target failure probability [4] is assigned for the members of the structure. The inspection timing is decided when the failure probability of any member of the structure reaches the target failure probability. The inspection quality is decided such as to recover the failure probability and maintain the reliability at an acceptable target level.

In the second approach, the life-time cost minimization method is developed based on the sequential cost minimization method developed by the author [3]. The method aims to find appropriate inspection strategy for fatigue deteriorating structures. The cost evaluation equations were developed for all available inspection methods. The influence of inevitably uncertain parameters on the inspection strategy is considered. The predicted strategy based on this approach can be regarded as optimal [5].

In the third approach, the life-time cost minimization method is used in order to obtain an acceptable and optimal inspection strategy against the estimated errors and uncertainties. In this analysis, the life-time cost optimization is carried out with the constraint that the failure probabilities of the members are controlled below the respective target values allowed for the members. First, initial target failure probabilities are assumed for each member. Then the criterion of the inspection planning is investigated by adjusting the parameters within the range of uncertainties. The initial values of the failure probabilities are altered until an acceptable result be obtained.

In this study, the choice of the inspection strategy is carried out based on the above mentioned three aspects. Numerical example for a hypothetical structure with several uncertain parameters is carried out.

THE INSPECTION STRATEGY AND THE CORRESPONDING UNCERTAIN PARAMETERS

Structural safety during service can be achieved through enough considerations for several safety items related to inspection and repair maintenance. However, excessive safety assurance is economically not accepted, since the frequent inspection and repair actions usually cause rising of operating cost. It is thought that a structure has an optimal reliability level depending on the specification, inspection and repair cost, risk of an unexpected failure and so on. The best way to determine such reliability level is to employ decision making on the basis of life-time cost minimization [6].

However, most of the probabilities and the cost items required in the analysis generally contain several uncertain parameters. Working load on member, accuracy of structural analysis, accuracy of construction, risk of failure, deterioration in properties of member, initial defect condition of member, inspection capability, the rate of inflation, etc. include uncertainties. Therefore, it is doubtful whether the formulation of cost minimization approach will produce an optimal strategy. Traditionally, the experience and subjective judgment of experts were highly regarded for the inspection planning of ships and offshore structures.

Recently, new aspects have occurred in the field of structural maintenance. One is the developments of important structures such as large sized offshore structures, bridges and power plants. Risk of unexpected failure is quite large for these structures, also inspection and repair accompanies large economical losses due to service suspension.

In ship-building industry, lately, reconsideration on the risk of environmental pollution by the oil leakage of tanker has become necessary for several reasons. Further, the economical losses due to unexpected service suspension caused by member failure has become to be recognized as a serious problem in the operation management. Another problem is the tendency to pursuit the economical efficiency of structures. Life extension programs are considered for the aging ships, power plants, chemical plants, etc. due to economical reasons. Reliability assessment in deteriorating conditions are to be required for those structures. Further, improvements of maintenance strategy are necessary for aging structures to keep the reliability at an acceptable level [7].

Under such circumstances, inspection and maintenance planning relying only on experience and subjective judgment is becoming difficult. On the other hand, the objective evaluation of structural safety and the objective judgment for the appropriateness on maintenance have been recognized as important in several fields of structural engineering.

In order to make objective judgment, the reliability analysis method considering repeated inspections and the optimization method of inspection planning have to be developed [8,9]. However, the effort to decrease several uncertainties related to the planning is important. For example, the quantification of inspection capability and grasping the deterioration property of a member are inevitable subjects. Figure 1 shows the flow of the above mentioned procedure.

In this study, a cost minimization method with constraint on reliability is developed in order to choose an acceptable inspection strategy against the uncertain parameters. The following procedures are used to estimate the appropriate failure probability before making the final decision for the inspection planning. First, set up the constraint of reliability level based on cost minimization approach for a given structural model containing uncertain parameters and estimation errors. Then, primary inspection planning is estimated by performing cost minimization analysis under constraint that failure probabilities of the members are controlled below the respective target values. Second, the life-time cost optimization is achieved to obtain acceptable inspection plan against the estimated errors and inevitable uncertainties of parameters. Finally, the constraint of reliability is adjusted before taking the final decision for the inspection strategy. Figure 2 shows the flow chart of this procedure to estimate an appropriate failure probability for the members of the structure.

METHOD OF ANALYSIS

In this study. the estimation of the inspection strategy for fatigue deteriorating structure is carried out based on three different approaches, namely; Standard reliability, Cost minimization, and Cost minimization with constraint of reliability. Each approach has its own consistent formulations and assumptions.

Reliability Basis Approach

If the choice of the inspection strategy is carried out based on reliability basis, a target failure probability is assumed for the members of the structure. The inspection timing is settled when the probability of failure of any member reaches the target probability of failure. The inspection quality is pre-determined to have either visual inspection or mechanical inspection during the service of the structure. Figure 3 shows the idea of the decision making processfor the inspection timing strategy if the reliability basis is considered in the analysis.

Cost Basis Approach

The sequential cost minimization method described in Appendix (I) is used to choose the inspection strategy in case that the analysis is carried out on cost basis. The method aims to find an optimal inspection strategy so that the total expected cost in the period between the present inspection and the next be minimum. The optimization parameters are the inspection qualities for each member set and the intervals between inspections. The optimization is repeatedly carried out at every inspection.

Cost Minimization with Constraint on Reliability Approach

If the inspection strategy is estimated based on cost minimization basis with constraint of reliability, the minimization process is performed under the constraint that the failure probabilities of the members are controlled below the respective target values for the members.

$$P_{F1}, P_{F2}, P_{F3} \leq \textit{target failure probability} \quad (1)$$

The initial values of the target failure probabilities are altered until an acceptable result be obtained. Life-time cost minimization method is used to investigate the inspection strategy of structures which contain uncertain parameters after adjusting the target probability of failure as well as the other parameters within the range of uncertainties.

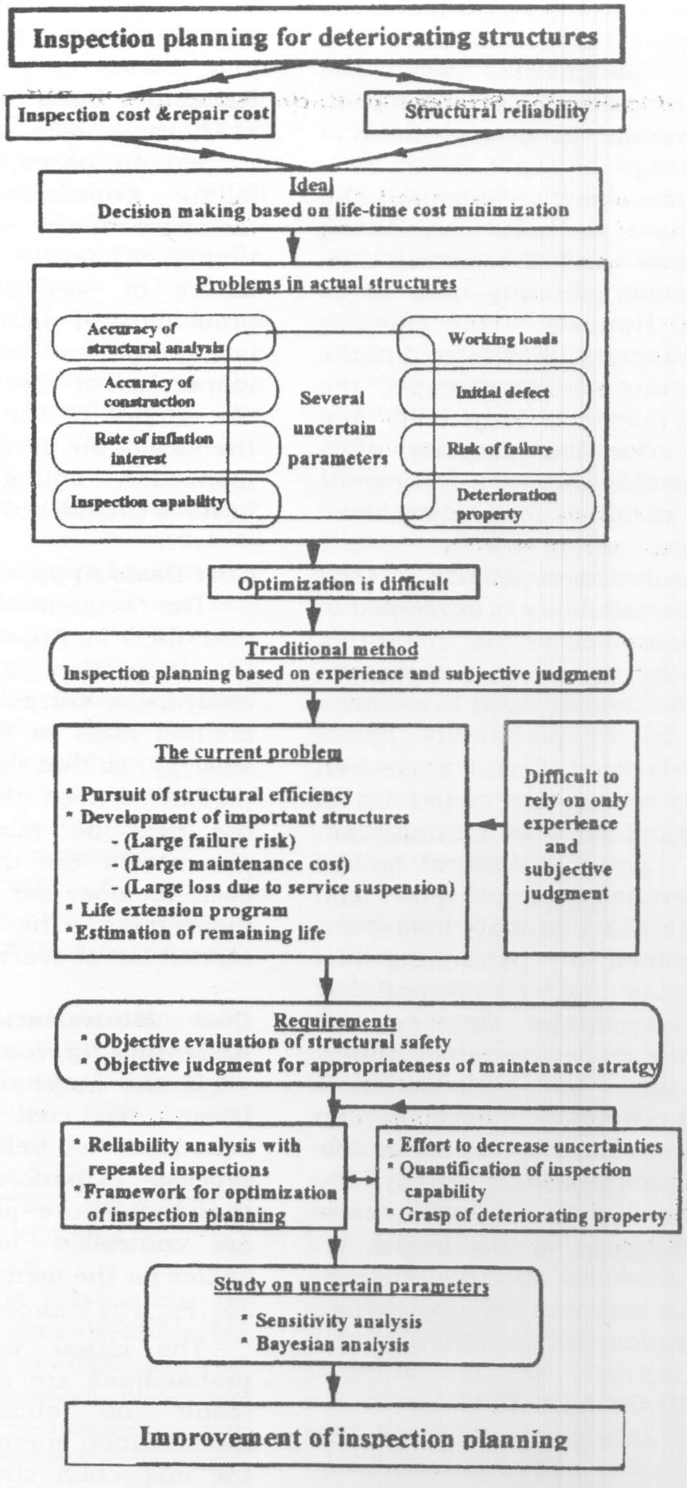


Figure 1 Inspection planning for deteriorating structures

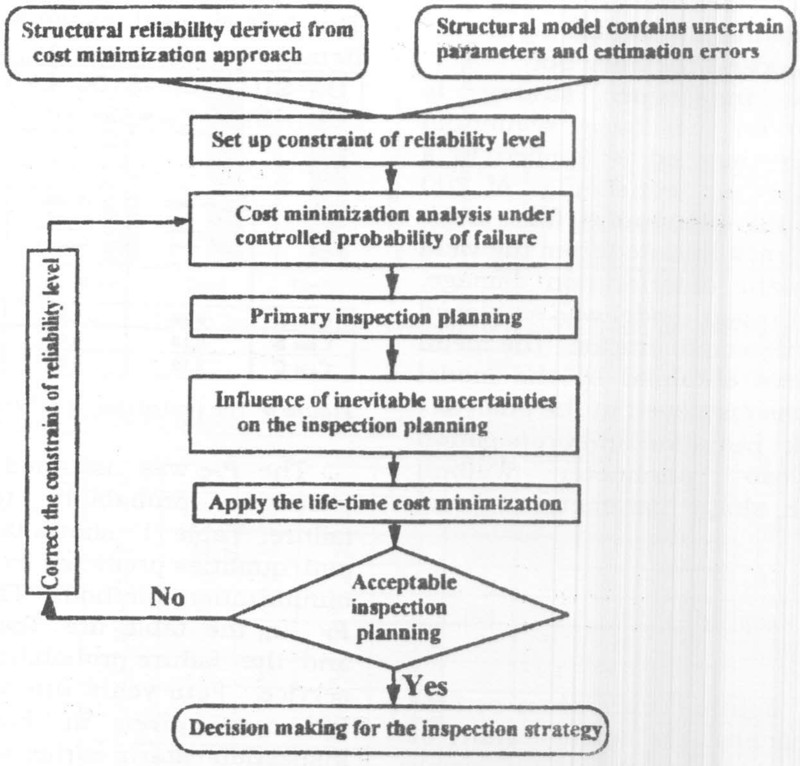


Figure 2 Method to determine an acceptable inspection strategy

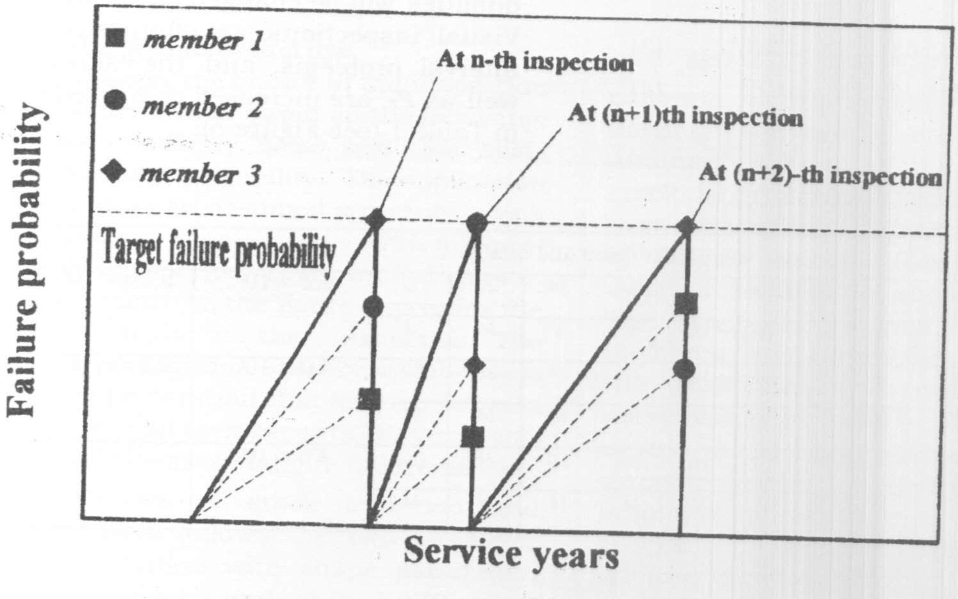


Figure 3 Effect of inspection timing in the strategy on reliability basis

NUMERICAL EXAMPLE

Analysis of a Structural Member Set

Choosing the inspection strategy is carried out based on cost basis, sequential cost minimization method is applied to a structural member set consisting of 200 structural elements with round fillet weld. Surface fatigue crack initiated from the weld toe is treated as the deterioration damage. Moreover, perfect repair model was employed to repair of the detected cracks. The mean crack growth curve obtained by the model fatigue test [10] was employed in the analysis. The fatigue crack initiation and propagation lives follow two parameter Weibull distributions with shape parameter 3.0 and 5.0, respectively.

$$f_N(N) = \frac{\alpha}{\beta} \times \left(\frac{N}{\beta}\right)^{\alpha-1} \times \exp\left\{-\left(\frac{N}{\beta}\right)^{\alpha}\right\} \qquad (2)$$

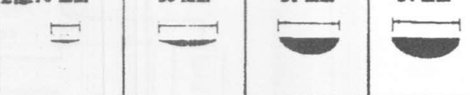
The member failure occurs when surface crack length reaches the plate width of 80mm. Figure 4 shows the initial crack conditions for three cases analyzed. The capability of visual and mechanical inspections was assumed to be a function of surface crack length as follows [3]

$$POD(VI) = 1.0 - \exp\{-0.025 \times (2a - 10.0)\} \qquad (3)$$

$$POD(MI) = 1.0 - \exp\{-0.10 \times (2a - 10.0)\} \qquad (4)$$

The following values are assumed for the cost items:

C_{VI}=\$10	C_{MI}=\$100	C_{RD}=\$$10^3$	C_{ASD}=\$$10^6$
C_{SSD}=\$$10^4$	C_{RF}=\$$5 \times 10^5$		C_{CF}=\$$2 \times 10^8$



	2a=10 mm	20 mm	21 mm	24 mm
Case A	0.10	0.00	0.00	0.00
Case B	0.10	0.05	0.05	0.00
Case C	0.10	0.05	0.03	0.02

Figure 4 The probability of existence of initial defect

The P_{FC} was assumed to be 0.01 as the transition probability to a catastrophic failure. Table 1 shows the inspection timing and qualities predicted by the sequential cost minimization method. The values of C_{OP} and P_F in the table are the accumulated costs and the failure probabilities during 32 years' service. Four years' interval is selected for all the cases given in Figure 4. The first inspection starts earlier when the probability of initial crack condition becomes high (case C).

If the inspection interval is pre-fixed for the member set at two years, the inspection qualities will be changed as shown in Table 2. Visual inspections are often selected in fixed interval problems, and the values of C_{OP}'s as well as P_F are increased compared with those in Table 1 (see Figure 5).

Table 1 Results if inspection planning

Case	Selected inspection years and qualities								COP, US$	Pf
Case A	4	8	12	16	20	24	28	32	3.2 × 10	2.06 × 10
	N	N	N	N	V	V	M	M		
Case B	4	8	12	16	20	24	28	32	4.0 × 10	2.27 × 10
	N	V	M	M	M	M	M	M		
Case C	4	8	12	16	20	24	28	32	4.6 × 10	2.57×10^{-4}
	M	M	V	V	M	M	M	M		

M: Mechanical inspection
V: Visual inspection
N: No inspection

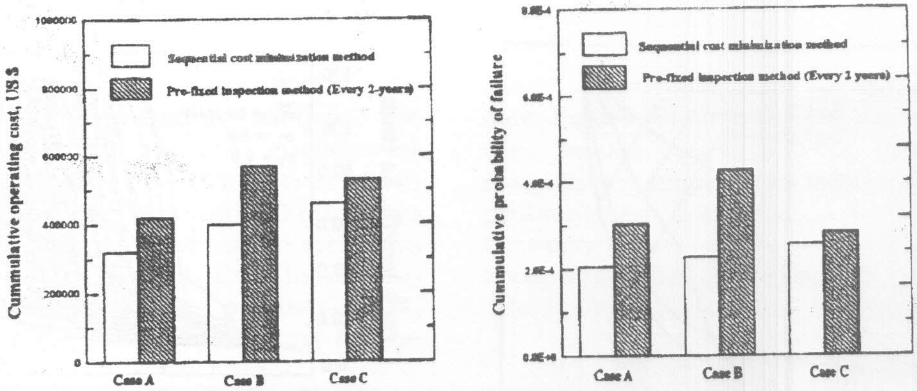


Figure 5 Comparison between sequential cost minimization method and pre-fixed inspection method

Table 2 Results of inspection planning (Fixed interval inspection)

Case	Selected inspection years and qualities									C_{op} US$	P_f
Case A	2	4	6	8	10	12	14	16	18	4.2×10^5	3.04×10^{-4}
	N	N	N	N	N	N	N	N	N		
	20	22	24	26	28	30	32				
	N	V	V	M	M	M	M				
Case B	2	4	6	8	10	12	14	16	18	5.7×10^5	4.28×10^{-4}
	N	N	N	N	V	V	V	M	V		
	20	22	24	26	28	30	32				
	V	V	M	V	V	M	V				
Case C	2	4	6	8	10	12	14	16	18	5.3×10^5	2.83×10^{-4}
	N	V	M	V	V	V	V	V	V		
	20	22	24	26	28	30	32				
	V	V	V	V	V	M	V				

M: Mechanical inspection
V: Visual inspection
N: No inspection

Analysis of a Whole Structure

In this paper, the choice of the inspection strategy is carried out based on the following; cost basis, reliability basis and cost basis with constraint on reliability. The application is carried out on an assumed structure which consists of four member sets with different mean fatigue properties as shown in Figure 6. The crack length in the figure expresses the observable length at the inspection. The mean crack propagation lives for member sets 1 and 2 are shorter than that for member sets 3 and 4. For all member sets, 60 years was assumed as the mean fatigue failure life $\overline{N_f}$. The distribution of crack initiation and propagation lives follows the two parameter Weibull distribution with shape parameter, $\gamma(N_C)=4.0$ (for set 1 and set 2), 3.0 (for set 3 and set 4), $\gamma(N_P)=5.0$, respectively. The contents of the fatigue properties for each member set are given in Table 3. The assumed values of the initial and critical crack lengths are 10 mm and 120 mm for all sets, respectively. Figure 7 shows an example of fatigue sample functions generated for member set 3 by the Markov Chain model [5]. The contents of cost items, number of members, the target failure probability, and the ***POD*** curves for each member set are summarized in Table 4. The crack conditions at the initial state and after the repair are given in Table 5. Replacement model was employed to the repair method of the detected cracks. Three interval inspections are allowed for the structure, one year, two years and four years.

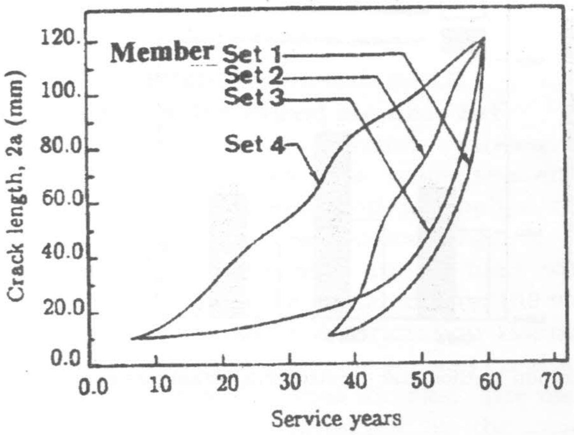


Figure 6 Mean properties of crack growth curves for the members with different fatigue properties

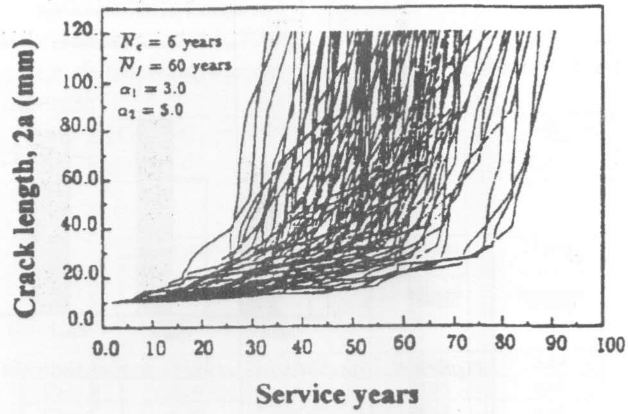


Figure 7 Fatigue samples function generated by the Markov chain model (set 3)

Table 3 Fatigue property of each member set

Member set	$\overline{N_C}$ years	$\overline{N_P}$ years	Weibull shape parameter Nc	Weibull shape parameter Np
Set 1	36	24	4	5
Set 2	36	24	4	5
Set 3	6	54	3	5
Set 4	6	54	3	5

a_o=10.0 mm, a_{max}= 120.0 mm

Table 4 Condition of analysis

Condition of analysis	Member set			
	Set 1	Set 2	Set 3	Set 4
No. of members	100			
C_{VI}(US$/member)	50			
C_{MI}(US$/member)	200			
C_{RD}(US$/damage)	1000			
C_{RF}(US$/failure)	10^5			
C_{CF} (US$)	10^8			
P_{FC}	0.001	0.01	0.010	0.10
C_{SSD}(US$)	50,000			
C_{ASD}(US$)	500,000			
POD curves	VI : POD = 1.0-ex{-0.025(2a-10.0)} MI : POD = 1.0-ex{-0.010(2a-10.0)}			

Table 5 Crack condition before the start of service and after repair

Member Set	Crack condition	0.00 mm	10.0 mm	20.0 mm
Set 1	Initial state	80 %	10 %	10 %
Set 2	After repair			
Set 3	(Replacement model)	80 %	10 %	10 %
Set 4				

Using the cost basis as the criterion for sequential cost minimization method, the selected inspection timing and qualities for the structure are shown in Table 6 in which seven inspections are required. Four years interval is always selected for all the members sets. It is noticed that the first inspection timing becomes late for the member set 4, because the crack detection is easy for the crack growth property of that member set (see Figure 6). Figure 8 shows the change of the failure probabilities of members in respective inspection intervals. The failure probabilities are maintained in the range between 10^{-6} and 2×10^{-4} which are acceptable from the reliability viewpoint.

Table 6 Results of inspection planning on cost basis

Member	Selected inspection years and qualities									
Set	4	6	8	10	12	16	18	22	26	28
Set 1	M	M	V	M	M	M	M	M	V	M
Set 2	V	V	V	V	M	V	V	V	V	V
Set 3	M	V	M	V	M	V	M	M	M	V
Set 4	V	V	V	V	V	V	V	V	V	V

M : Mechanical inspection
V : Visual inspection

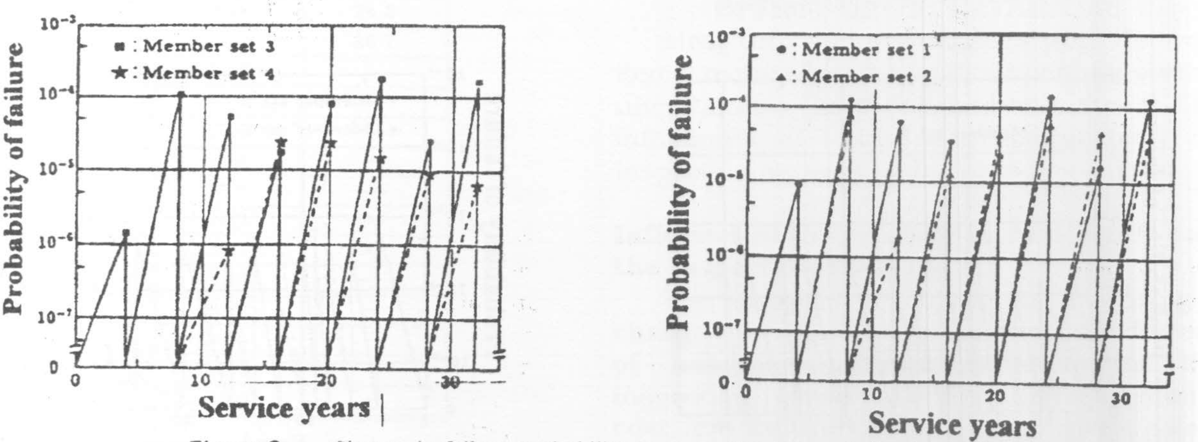


Figure 8 Change in failure probability in respective intervals (cost basis).

f the inspection planning is selected based on cost basis with constraint on reliability for the same structure, the choice of inspection timing and qualities for that structure will be changed as shown in Table 7 where twelve inspections are necessary. Visual inspection with short interval inspections are always selected. The inspection timing for member set 4 based on cost minimization with constraint on reliability is started earlier than those when the analysis is carried out on cost basis only.

If the allowable inspection methods are either visual inspection or mechanical inspection, then the selected inspection qualities and timing will be changed as shown in Table 8. The estimated operating cost during 30 years' service will become $\$9.5 \times 10^5$ compared to $\$9.4 \times 10^5$ form Table 7.

The change of the failure probabilities of members in respective inspection intervals is shown in Figure 9. Form the figure, it is seen that the failure probabilities for member sets 1 and 2 as well as member set 3 are maintained under 10^{-5}. For member set 4, the failure probability is maintained under 10^{-6}.

Table 7 Inspection planning on cost basis with constraint of reliability

Member set	Selected inspection years and qualities											
	4	6	8	9	10	12	14	16	20	24	25	29
Set 1	M	M	N	V	M	V	M	M	M	N	M	V
Set 2	N	V	V	N	V	V	V	V	M	N	V	N
Set 3	M	V	V	V	V	M	N	M	M	V	M	V
Set 4	N	N	N	N	N	V	V	V	V	N	M	N

M : Mechanical inspection
V : Visual inspection
N : No inspection

Table 8 Inspection planning on cost basis with constraint of reliability (VI and MI methods only)

Member set	Selected inspection years and qualities						
	4	8	12	16	20	24	28
Set 1	M	M	M	M	V	M	V
Set 2	N	M	V	V	V	V	V
Set 3	V	M	M	V	V	M	V
Set 4	N	N	N	V	V	V	V

M : Mechanical inspection
V : Visual inspection

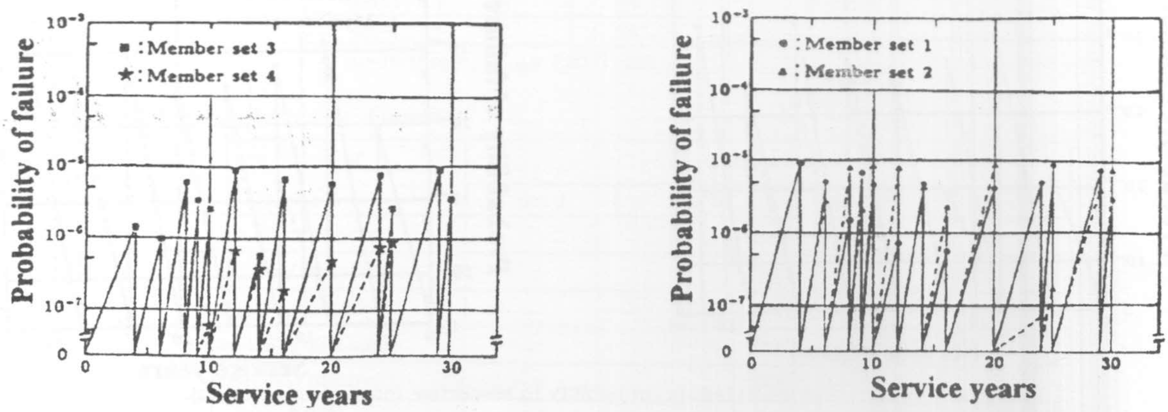


Figure 9 Change in failure probability in respective inspection intervals (cost basis with constraint of reliability).

If the standard reliability analysis is performed for the same structure to choose the inspection planning, then the selected inspection timing is shown in Table 9 in which visual inspection VI and mechanical inspection MI are performed for the structure, respectively. It is noticed that 20 inspections are necessary during 30 years' service if VI method is used, however, 8 inspections are necessary if MI method is performed. It makes clear that if the analysis is performed on reliability basis, either mechanical inspection with long intervals or visual inspection with short intervals are selected, respectively. The change of the failure probabilities of members in respective inspection intervals is shown in Figure 10 for member sets 1 and 3. Form the figure, it is noticed that the failure probabilities are maintained within the range of 10^{-5}. Figure 11 shows the cumulative operating costs expected for the structure during 32 years' service and calculated by cost basis, reliability basis and cost basis with constraint on reliability, respectively. The expected cumulative operating cost on cost basis is usually minimum. However, not only the cost aspect, but also the reliability aspect should be taken in consideration. Therefore, the decision making for the stable inspection strategy can be obtained if the analysis of cost basis with constraint or reliability is performed.

Table 9 Inspection planning on reliability basis

No. of inspections	Inspection years VI for all the member set	Inspection years MI for all the member set
1	4.2	4.2
2	5.0	6.5
3	5.8	9.5
4	6.7	13.0
5	7.7	16.7
6	8.7	20.5
7	9.8	24.8
8	11.0	28.7
9	12.3	--
10	13.7	--
11	15.0	--
12	16.3	--
13	17.7	--
14	19.2	--
15	20.7	--
16	22.2	--
17	23.8	--
18	25.5	--
19	27.3	--
20	29.0	--

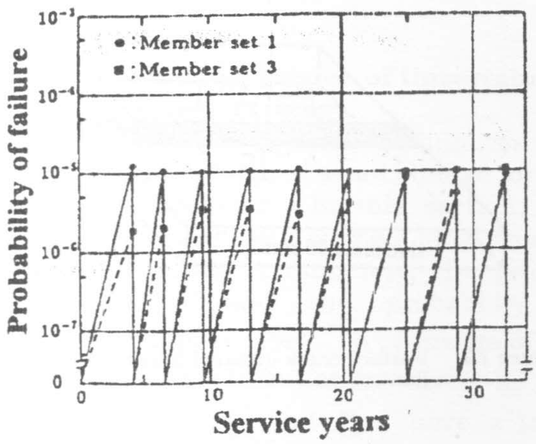


Figure 10 Change in failure probability in respective inspection intervals. (Raliab lity basis)

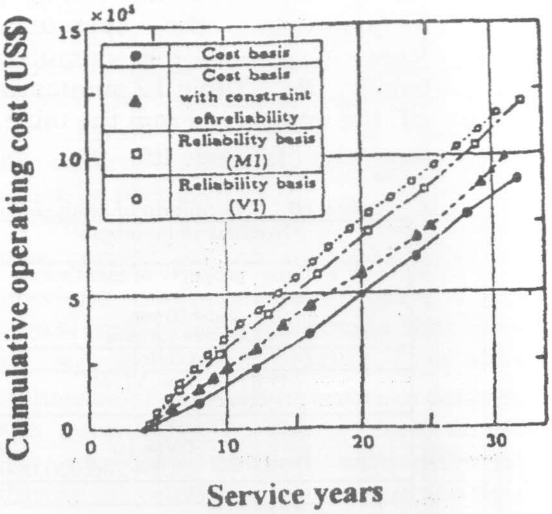


Figure 11 Comparison of cumulative operating cost among three inspection plans

EFFECT OF UNCERTAINTIES

Most of the probabilities and the cost items required in the analysis contain several uncertainties in the actual structures. The influence of uncertain parameters on inspection strategy is discussed as follows :-

Influence of Uncertainty in Parameters on the Inspection Planning

The analysis is carried out by giving a change for individual parameters, the degrees of influence of each parameter on the inspection content, the cumulative operating cost and failure probability are investigated. A single member set consisting of 200 members of welded joints shown in Figure 12 was chosen for the analysis. Table 10 shows the fatigue property, initial defect condition, inspection capability and cost contents of the welded joints. These values were chosen as the basic condition of the analysis. Table 11 summarizes the results of inspection planning for the basic condition, in which the cumulative operation cost during 22 years' service and the cumulative failure probability of the member are shown as well as the inspection timing and qualities.

The analysis was carried out by changing the individual parameters to half or to twice of the original value. The sensitivities of each parameter were investigated from the viewpoints of the degree of influence on the inspection planning, the cumulative operating cost, C_{OP}, and the cumulative failure probability P_f. Table 12 summarizes the result of the analysis. From the table, it is seen that the fatigue life $\overline{N_C}$, $\overline{N_P}$, inspection cost C_{VI}, C_{MI}, schedule system down cost C_{SSD} and inspection capability (***POD***) are sensitive on the inspection planning, the cumulative operating cost, C_{OP}, and the cumulative failure probability P_f. Among them, the most sensitive parameter is the fatigue life.

Table 10 Condition of analysis for butt weld joints

Number of members	200
Fatigue property of members 2ao=10*mm* 2amax=120*mm*	Nc=50 years Weibull shape parameter : 3 Np=20 years Weibull shape parameter : 4
Initial defect	PID=0.01
POD Curves, VI, MI	PODV= 1.0-exp{-0. 20(2a-3.0)} PODM=1.0-exp{-0.40(2a-1.0)}
Cost items (US$) CVI= 10 CMI=100 CSSD=20,000 CCF= 200,000,000 CASD= 1,000,000	
PFC	0.01

Table 11 Results of inspection planning

Parameters		Inspection years and qualities									COP, US$	Pf
Basic	P_{FC}	4	8	10	12	14	16	18	20	22	3.42 × 10[illegible]	9.7 × 10[illegible]
Cond	0.05	M	M	M	V	V	V	V	M	V		

M: Mechanical inspection
V: Visual inspection
N: No inspection

Table 12 Result of changing parameters

Parameter		Number of inspections during 22 years' service			C_{op}	P_f
		VI	MI	Total	$\times 10^5$ $	$\times 10^{-5}$
C_{VI} C_{MI}	1/2	3	5	8	2.79	4.2
	1	4	4	8	3.42	4.9
	2	7	1	8	4.96	12.0
C_{RD}	1/2	4	4	8	3.40	4.9
	1	4	4	8	3.42	4.9
	2	4	4	8	3.55	4.9
C_{RF}	1/2	4	4	8	3.42	4.9
	1	4	4	8	3.42	4.9
	2	4	4	8	3.44	4.9
C_{ASD}	1/2	4	4	8	3.42	5.0
	1	4	4	8	3.42	4.9
	2	4	4	8	3.50	4.9
C_{SSD}	1/2	18	0	18	2.59	1.2
	1	4	4	8	3.42	4.9
	2	0	5	5	4.93	4.2
C_{CF}	1/2	2	3	5	3.25	5.0
	1	4	4	8	3.42	4.9
	2	3	5	8	3.91	4.3
P_{FC}	1/2	3	4	7	3.22	5.0
	1	4	4	8	3.42	4.9
	2	3	5	8	3.91	4.3
P_{ID}	1/2	1	5	6	3.46	5.2
	1	4	4	8	3.42	4.9
	2	7	4	11	3.93	5.0
POD	Bad	13	2	15	4.50	3.5
	Med	4	4	8	3.42	4.9
	Good	0	5	5	2.72	1.5
$\overline{N}_c$ $\overline{N}_p$	1/2	4	14	18	8.70	10.5
	1	4	4	8	3.42	4.9
	2	3	1	4	1.63	0.8

POD(VI)=1.0-exp{$-d_1$(a-1.0)}
POD(MI)=1.0-exp{$-d_2$(a-1.0)}
Bad : d_1=0.15, d_2=0.30
Medium : d_1=0.20, d_2=0.40
Good : d_1=0.30, d_2=0.60

When the fatigue life $\overline{N_C}$, $\overline{N_P}$ becomes half, mechanical inspections are frequently applied with short interval. When $\overline{N_C}$, $\overline{N_P}$ becomes twice, visual inspections with long interval are preferred. At the same time, both of the cumulative operating cost, C_{OP}, and the cumulative failure probability, P_f, are highly affected by the fatigue life.

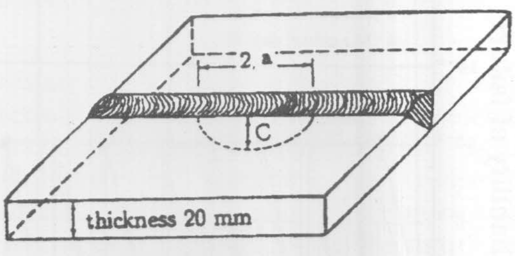


Figure 12 Surface crack initiated from butt welding joint

When the inspection cost C_{VI}, C_{MI} becomes twice, the rate in use of visual inspection is increased. As a result, the failure probability of the member increases. When schedule system down C_{SSD} becomes half, visual inspections are frequently applied with short interval. However, when the C_{SSD} becomes twice, mechanical inspections with long interval are suggested.

When the inspection capability (***POD*** curves) is good in quality, mechanical inspections with long interval are selected. On the other hand, visual inspections with short interval are preferred for the bad inspection capability.

With respect to the insensitive parameters, repair cost C_{RD}, C_{RF}, accidental system down cost C_{ASD}, and transition probability to a catastrophic failure P_{FC} have slight effect on the inspection planning, the cumulative operating cost and the cumulative failure probability.

Further, the initial defect condition, P_{ID}, and the risk against a catastrophic failure, C_{CF}, are insensitive on the cumulative operating cost, but sensitive on the inspection content and the cumulative failure probability. Large cumulative failure probability is allowed when the risk against a catastrophic failure becomes half, because the anxiety of catastrophic failure is decreased.

The quantitative property of the sensitivities obtained in the above analysis agrees well with reasoning of engineers who are familiar with the inspection planning of actual structures.

Influence of a Large Degree of Uncertainty on the Inspection Strategy

In the previous section, the analysis was carried out by giving a small change for the individual parameter. In this section, the analysis is carried out giving a large change for two uncertain parameters, the fatigue failure life $\overline{N_f}$ and the probability of catastrophic failure P_{FC}. . $\overline{N_f}$ consists of the mean fatigue crack initiation lives $\overline{N_C}$ and $\overline{N_P}$ respectively. $\overline{N_f}$ and P_{FC} have a large influence on inspection contents such as inspection qualities, inspection intervals, cumulative operating cost and cumulative probability of failure. The initial uncertainty of P_{FC} is usually maintained during the whole service life, because a catastrophic failure is a rare event. Therefore, a wide range of uncertainty of P_{FC} at the inspection planning must be prepared.

For the fatigue failure life, The analysis was carried out changing the $\overline{N_f}$ used in previous example from 60 years to 45 and 75 years, respectively. It means that the change in $\overline{N_f}$ is 15. Figure 13-a shows the influence of estimation errors of fatigue life on the cumulative operating cost calculated by the proposed method with different basis during 30 years' service. From the figure it is clear that the uncertainty of the cumulative operating cost is large if the calculation is performed on cost basis only. However, the uncertainty in the operating cost can be reduced if the cost basis with constraint reliability is used. Figure 13-b shows the cumulative operating cost during 30 years' service for three inspection plans with different values of $\overline{N_f}$. In the figure, the values of C_{OP}'s are influenced by the change of $\overline{N_f}$ specially if the cost basis is used in the analysis.

For the probability of catastrophic failure P_{FC}, the analysis was carried out changing the P_{FC} used in the previous section to one fifth and five times, respectively. Figure 14-a shows the influence of P_{FC} on the cumulative operating cost calculated by the proposed methods with different basis during 30 years' service. Figure 14-b shows the cumulative operating cost during 30 years' service for three inspection plans with different values of P_{FC}. In the figure, the values of C_{OP}'s are influenced dramatically by the change of P_{FC} in case of cost basis. The more P_{FC} increases, the more frequently and precisely the inspections are carried out. However, if inspection planning is carried out following the reliability basis or cost basis with constraint of reliability, the change of C_{OP} is relatively very small.

Curve	$(\overline{N}_c, \overline{N}_p)$ years			
	Set 1	Set 2	Set 3	Set 4
a	(27,18)	(27,18)	(4.5,40.5)	(4.5,40.5)
b	(45,30)	(45,30)	(7.5,67.5)	(7.5,67.5)

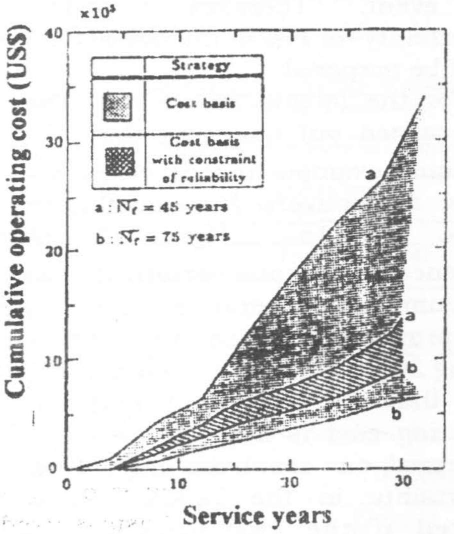


Figure 13-a Influence of estimation error of fatigue life on cumulative operating cost

Curve	$(\overline{N}_c, \overline{N}_p)$ years			
	Set 1	Set 2	Set 3	Set 4
a	0.005	0.05	0.05	0.5
b	0.0002	0.002	0.002	0.02

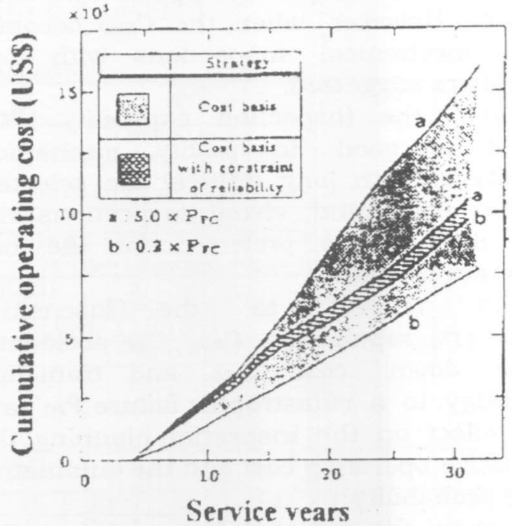


Figure 14-a Influence of estimation error of P_{FC} on cumulative operating cost

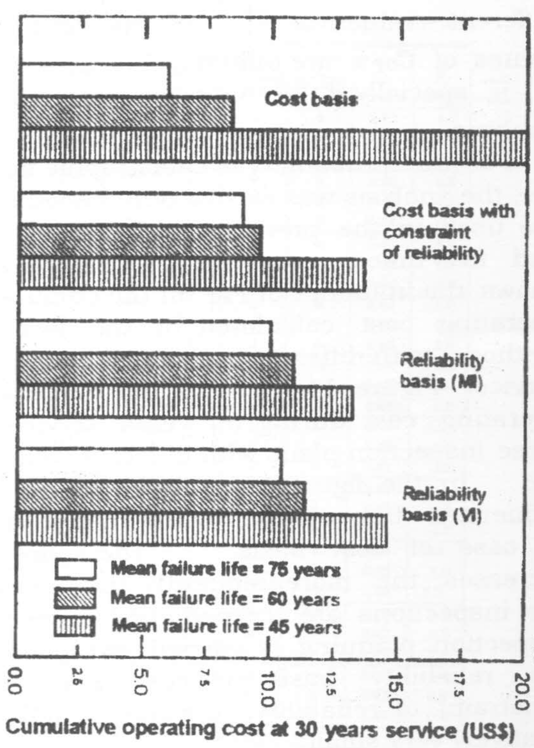


Figure 13-b Comparison of C_{OP} among three inspection plans. (Influence of estimation error of N_C and N_P)

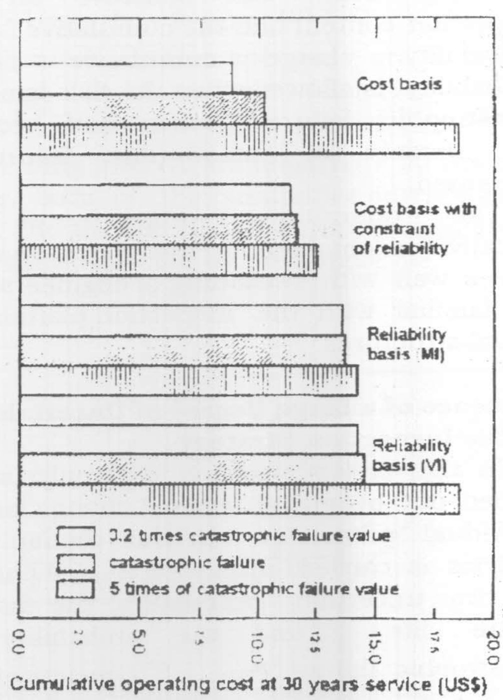


Figure 14-b Comparison of C_{OP} among three inspection plans. (Influence of estimation error of N_{FC})

From the above discussion it can be concluded that the optimal decision making for the estimation of the inspection and repair maintenance strategy can be achieved by performing the calculation on cost basis with constraint of reliability.

CONCLUSIONS

From the above presentation, the following conclusions can be drown:

1. In the inspection planning problem, not only the cost aspect, but also reliability aspect should be taken into consideration. From this viewpoint, the decision making for an acceptable inspection planning can be obtained by performing the analysis on cost minimization basis with constraint on reliability.
2. The cost minimization approach has an effect to reduce the uncertainty of the estimated operating cost when a large uncertainty exists in the failure risk of members as well as the fatigue failure life.

NOMENCLATURE

$A(0)$ An initial state vector.
$A_{AI}(t)$ The state vector right after inspection and repair.
$A_{BI}(t)$ The failure probability distribution right after the elapsing of time t.
$a_M(t+1)$, $a_M(t)$ The absorbing terms of the state vector at the time $t+1$ and time t, respectively.
a_R The limiting crack length.
C_{ASD} Financial loss due to service suspension caused by accidental system down.
C_{CF} The risk of a catastrophic failure.
C_{INS} Inspection cost for each member set.
$C_j(t,t+\tau)$ Expected operating cost for member set j in the inspection interval $(t,t+\tau)$.
C_{MBF} Expected loss due to a member failure.
C_{OP} Total cumulative operating cost.
C_{RD} The repair cost of a damaged member detected by visual or mechanical inspection. This value is a function of degree of damage and elapsed service time.
C_{RF} Repair cost of a failed member.
C_{SSD} Financial loss due to the service suspension.
$C_T(t,t+\tau)$ Total expected operating cost for the whole structure in an inspection interval, from time t to time $t+\tau$.
C_{VI}, C_{MI} The visual and mechanical inspection costs for a member, respectively.
C_{ZMI} When a damage is detected by visual inspection, if that defect is again inspected mechanically for sizing or examining the repair method, the value of C_{ZMI} equals C_{MI}. Otherwise C_{ZMI} is zero.
D Delectability vector ($1 \times M$, row vector).
$E[N_c]$ The mean of the crack initiation property.
L The state vector in which the crack already exceeds the limiting crack size a_R.
I Unit matrix ($M \times M$).
N Number of member sets.
$\overline{N_c}$ Mean fatigue crack initiation.
$\overline{N_f}$ Mean fatigue failure life.
NO, VI, MI No inspection, visual inspection, mechanical inspection, respectively.
$\overline{N_p}$ Mean fatigue crack propagation.
N The number of duty cycles in the time t($n=t/\Delta t$, Δt is the time of a duty cycle).
M The total size of the matrix.
m The number of members in the member set.
m_1, m_2 Number of equations for crack initiation and crack propagation stages, respectively.
P Basic $M \times M$ probability transition matrix.
P_{DM} Probability of defect detection by mechanical inspection.
P_{DV} Probability of defect detection by visual inspection.
P_{FC} The probability of a catastrophic failure of a structure.
P_f Cumulative probability of failure.
P_{F1}, P_{F2}, P_{F3} The probabilities of member failure in the succeeding inspection interval

under the conditions that **NO**, **VI** and **MI** methods are applied at the present inspection, respectively.

P_{sizing} The probability of detection for crack sizing for the members which have detected cracks in the previous inspections.

P_{SV} The probability that a member has not experienced repair and failure until the present inspection.

R Repair vector, ($1 \times M$, row vector).

τ Inspection interval (τ =1 or 2 or 4 years)

$\sigma^2 N_c$ The variance of the crack initiation property.

APPENDIX (I) SEQUENTIAL COST MINIMIZATION METHOD (SHORT REVIEW)

The optimization of the inspection strategy can be achieved by the appropriate selection of inspection intervals, inspection methods and repair qualities. The sequential cost minimization method has three steps to follow [3]:-

1. Estimation of the total expected cost of structure.
2. The selection of the optimal inspection method for a member set.
3. Selection of the appropriate inspection interval for a structure.

The sequential cost minimization method has the following assumptions :-

1. All the structural members in each member set have the same strength property and are subjected to the same loading condition.
2. Each member has a possibility of failure due to the deterioration damage. When any member fails, the service of the structure is always suspended until the failed member is repaired. Before the structure returns to service, the member failure might develop into a catastrophic failure with a certain probability.
3. Inspections are repeatedly carried out during the service life to find the damage while it is small. The detected damages are perfectly repaired.

At a certain inspection during service, the total expected operating cost of structure in the succeeding inspection interval is classified into two main groups: costs necessary in the present inspection, and risks(expected costs) during the service period until the next inspection. The total expected cost for the whole structure in an inspection interval, from time t to time $t+\tau$, denoted by $C_T(t,t+\tau)$, can be written as.

$$C_T(t,t+\tau) = \sum_{j=1}^{SetN} C_j(t,t+\tau) + C_{SSD} \quad \text{(I-1)}$$

Where,

$$C_j(t,t+\tau) = C_{INS} + C_{REP} + C_{MBF} + C_{CTF} \quad \text{(I-2)}$$

The estimation of the total expected operating cost of structure, the selection of the optimal inspection method for a member set and the selection of the appropriate inspection interval for a structure are explained in detail in Reference [3]. The selection is repeatedly carried out at every inspection from the following three inspection methods:-

- No inspection (*NO*).
- Visual inspection (*VI*) method.
- Mechanical (Precise) inspection (*MI*) method.

Cost Evaluation Equations

To estimate $C_j(t,t+\tau)$ corresponding to each member set for the above mentioned three inspection methods, the cost evaluation equations are developed. In the formulations, the following assumptions were made.

- The detection of defects in visual or mechanical inspection is probabilistic.
- Costs due to the service suspension caused by accidental system down are to be taken into consideration. Member failure does not necessarily mean a collapse of the structure. However, the service of the structure is suspended urgently and the failed member is to be repaired. This accidental system down requires considerably larger cost than that of scheduled (pre-determined) system down.

- A member failure may result in a catastrophic failure with a certain transition probability. When the catastrophic failure occurs, the cost is due not only to the loss of the structure but also to the losses received from different portions of society such as owners, client, insurance, related industries and so on.

The expected operating cost for a member set in an inspection interval $(t, t+\tau)$ is evaluated[3] by the following equations for the three inspection methods.

No inspection (NO)

$$C_j(t, t+\tau \mid NO) = G \times P_{F1} \times C_F \tag{I-3}$$

Visual inspection (VI) method

$$C_j(t, t+\tau \mid VI) = G \times \{C_{VI} + P_{DV} \times (C_{ZMI} + C_{RD}) + (1 - P_{DV}) \times P_{F2} \times C_F\} \tag{I-4}$$

Mechanical inspection (MI) method

$$C_j(t, t+\tau \mid MI) = G \times \{C_{MI} + P_{DM} \times C_{RD} + (1 - P_{DM}) \times P_{F3} \times C_F\} \tag{I-5}$$

In the above equations,

$$C_F = (1 - P_{FC}) \times (C_{ASD} + C_{RF}) + P_{FC} \times C_{CF}$$
$$G = m \times P_{SV} \tag{I-6}$$

The probabilities appearing in the cost evaluation equation are calculated by Markov Chain Model (Appendix II).

APPENDIX (II)

Probability Estimation Using Markov Chain Model

The probabilities appearing in the cost evaluation equations are calculated by the Markov Chain Model . Basically, in the simplest Bogdanoff and Kozin stationary Markov Chain Model[11], an initial state vector ***A(0)*** and a duty cycle independent basic transition matrix ***P*** are sufficient to describe the structure. The probability distribution right after the elapsing of time ***t***, $A_{BI}(t)$, is obtained by :-

$$A_{BI}(t) = A(0) \times P^n \tag{II-1}$$

Where ***n*** is the number of duty cycles in the time ***t*** and ($n=t/\Delta t$, where, Δt is the time of a duty cycle). $A_{BI}(t)$ and ***A(0)*** are ***M***-dimensional vectors representing the probability distributions with respect to pre-defined ***M*** states. ***P*** is the basic $M \times M$ probability transition matrix. The fatigue crack initiation and propagation processes are incorporated into the transition matrix of a single MCM[12]. The probability of member failure is also considered in the absorbing term of the matrix :-

$$A(0) = \{\overbrace{a_1(o).a_2(0).....a}^{m_1}\underbrace{_{m1}(0)......a_{M-1}(0).0}_{m_2}\} \tag{II-2}$$

$$P = \begin{bmatrix} p_1 & q_1 & 0 & \cdots & & & & & 0 \\ 0 & p_1 & q_1 & 0 & \cdots & & & & 0 \\ 0 & \cdots & p_1 & q_1 & 0 & \cdots & & & 0 \\ \cdots & \cdots & \cdots & p_2 & q_2 & \cdots & & & 0 \\ 0 & \cdots & \cdots & \cdots & p_2 & q_2 & & & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & & & \cdots \\ & & & & & p_2 & q_2 & & 0 \\ & & & & & & p_2 & q_2 & 0 \\ & & & & & & & p_2 & q_2 \; 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 1 \end{bmatrix} \tag{II-3}$$

The total size of the matrix is (***M=m₁+m₂-1***).

The probabilities P_1, q_1, p_2, and q_2 are determined using the mean and variance of the crack initiation and propagation property of the structural member, respectively [13].

The probability that the member survives until the time of the present inspection without any experience of repair P_{SV} can be expressed as.

$$P_{SV} = \sum_{m=1}^{M-1} a_m(t) \tag{II-4}$$

The detection probabilities for a crack of any length by the visual inspection P_{DV} is calculated by the following equations.

$$P_{DV} = A_{BI}(t) \times D^T \tag{II-5}$$

The detection probabilities for all crack conditions are represented by D, ($1 \times M$) row vector.

$$D = \{\overbrace{d_1.d_2(0).....d}^{m_1}\underbrace{_{m1}.....d_{M-2}.d_{M-1}.0}_{m_2}\} \tag{II-6}$$

The state vector right after the inspection can be given by the following equation.

$$A_{AI}(t) = A_{BI}(t).(C_1 + C_2) \tag{II-7}$$

where,

$$C_1 = I - diag.(d_m) \tag{II-8}$$

and,

$$C_2 = D^T.R \tag{II-9}$$

$$R = \{ \overbrace{r_1, r_2 \ldots\ldots r_{m1}}^{m_1}, \underbrace{r_{m_1-1} \ldots\ldots r_{M-2}, r_{M-1}, 0}_{m_2} \} \quad \text{(II-10)}$$

The repair vector is represented by R, $(1x\ M)$ row vector, in which:-

$$\sum_{m=1}^{M-1} r_m = 1.0 \quad \text{(II-11)}$$

The failure probabilities P_{F1}, P_{F2} and P_{F3} are calculated as follows. If no inspection, visual inspection or mechanical inspection is carried out in the present inspection, the corresponding state vector at the next inspection after an interval (τ) becomes :-

$$A_{BI}(t+\tau)=A_{BI}(t+\tau \mid \textbf{No Inspection})=A_{AI}(t).P^k$$
$$A_{BI}(t+\tau)=A_{AI}(t+\tau \mid \textbf{visual Inspection}).P^k$$
$$A_{BI}(t+\tau)=A_{AI}(t+\tau \mid \textbf{mechanical Inspection}).P^k$$

(II-12)

where,

$$P_{F1}, P_{F2}, P_{F3} = \{a_M(t+\tau)-a_M(t)\} \quad \text{(II-13)}$$

Where k is the number of duty cycles in the next inspection interval ($k=1/\Delta t$).

REFERENCES

1. H. Itagaki and N. Yamamoto, "Bayesian Reliability on Ship Structural Members", J. of the Society of Naval Architects of Japan, Vol. 158. pp. 629, (1985), (in Japanese).
2. Y. Fujimoto, H. Itagaki, S. Itoh and M. Asada, "Bayesian Reliability Analysis of Structures With Multiple Component", Int., Conf. on Structural Safety and Reliability (ICOSSR789). Vol. 3, pp. 2143 (1989).
3. Y. Fujimoto, A.M. Swilem, M. Iwata and K. Nagai "Inspection Planning of Deteriorating Structures Based on Sequential Cost Minimization Method", Journal of the Society of Naval Architects of Japan, Vol. 170, pp. 755-768, (1991).
4. P.T. Christensen and M.J. Baker, "Structural Reliability Theory and Its Application", Spring-Verlag, (1982).
5. A.M. Swilem, Swilem, "Influence of Inevitable Uncertainties on Inspection Planning for Structures", Alexandria Engineering Journal, Vol. 37, No. 3, pp. A185-A193, (1998).
6. Y. Fujimoto, and A.M. Swilem, "Improvement of Fatigue Design and Inspection Maintenance for Structures Based on Life-Time Cost Optimization", Trans. of West-Japan Society of Naval Architects, Vol. 83. pp. 215-225, (1992) (in Japanese).
7. J.N. Yang and W.J. Trapp, "Reliability Analysis of Aircraft Structures Under Random Loading and Periodic Inspections", AIAA Journal, Vol.12, No. 12, pp. 1623, (1974).
8. H.O. Madesen and J.D. Solensen, "Probability-Based Optimization of Fatigue Design, Inspection And Maintenance", Proceedings 4th International Symposium on Integrity of Offshore Structures, Elsevier Applied Science, pp.421, (1990).
9. A. Tsurui, A. Sako and T. Tanaka, "Effect of Repeated Inspections on Structural Reliability Defradation", J. of the Society of Materials Science, Japan Vol. 39, No. 441, pp. 748, (1990), (in Japanese).
10. H. Kawano, T. Kawasaki, D., Sakai, S. Noda, A. Fushimi and K. Hagiwara, "Some Consideration of Reference Stress Definition in Fatigue Strength Analysis", Trans. of the West-Japan Society of Naval Architects, No. 83, pp. 207-214, (1992) , (in Japanese).
11. J.L. Bogdanoff and F. Kozin, "Probabilistic Models of Cumulative Damage", John Wiley (1985).
12. Y. Fujimoto, A. Ideguchi and M. Iwata, "Reliability Assessment for Deteriorating Structures by Markov Chain Model", J. of the Society of Naval Architects of Japan, Vol. 166, pp. 303, (1989) , (in Japanese).
13. Y. Shimada, T. Nakagawa and H. Tokuno, "Application of Markov Chain to the Reliability Analysis of Fatigue Crack Propagation Process with Non-Destructive Inspection", J. of The Society of Materials Science, Japan, Vol. 34, No. 378, pp. 327, (1984), (in Japanese).

Received August 29. 1999
Accepted December 18. 1999