COST-BASED INSPECTION STRATEGY FOR OFFSHORE STRUCTURES

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ABSTRACT

Inspection and maintenance play an important role in accomplishing a high level of structural reliability. Therefore, structural reliability can be improved by adopting some appropriate maintenance policies. In this study, a sequential cost minimization method and its consistent formulation previously developed has been modified to include the system probability of failure to estimate the inspection maintenance strategy of offshore structures. The method aims at finding an optimal inspection strategy for platform structures by making the total expected operating cost in the period between the present inspection and the next a minimum. The applicability of the proposed method is demonstrated through a computational example for a fixed offshore platform structure. In this paper, the failure of the platform is considered as a result of subsystem failures which are created in fatigue failure mode as the deteriorating damage of the members comprising the subsystem.

Keywords: Offshore Structures, Optimization, Inspection, System Probability of Failure, Markov Chain.

1. INTRODUCTION

Reliability and maintainability are considered as important tools for the fatigue deteriorating problems of marine structures. It is well-known that high structural reliability can be preserved by the use of inspection and maintenance. Therefore, structural reliability can be improved by adopting some appropriate maintenance policies. The structure maintenance after failure is usually costly and sometimes needs a long time. Then, it is a serious problem to determine when and how to maintain the structure before it fails. However, it is not wise to maintain the structure too often. From this view point, studies of inspection strategy of the fatigue deteriorating structures based on sequential cost minimization approach was carried out, see Ref. [1].

The total cost minimization is the optimal criterion of decision making for design and maintenance of structures. Therefore, the life-time cost optimization is considered the best strategy for the inspection and maintenance of structures. In this paper, the sequential cost minimization method previously developed[2] and its consistent formulation based on the subsystem probability of failure is modified considering the whole system probability of failure to find the optimal inspection strategy. In this method, the optimization variables are the inspection methods for each member set and the interval to the next inspection for the structure. The optimization is then repeatedly carried out at every inspection [2].

A computational example is carried out for a fixed platform. Such a platform is considered to be comprised of a number of structural sets (subsystems). Each set is formed of a variety of members. The example used is that of jacket-brace failure. Such failure due to fatigue crack initiation, propagation and continuous failure are treated as deterioration damage of the members. The Markov Chain Model (MCM) used by Refs. [3, 4 and 5] is employed to describe the entire probabilistic structure of the fatigue process. The procedure of repeated inspections is incorporated into the model. The applicability of the proposed method using whole system probability of failure for fixed offshore structures with perfect repair model is proved to be informative in maintenance and inspection planning.

2. PLATFORM PROBABILITY OF FAILURE

It is beyond the scope of this paper to include a detailed discussion of probability and reliability theories. However, to provide the background for the subsequent analysis, a brief outline of one method of determining the platform's probability of failure is outlined in this section. The details are given in Ref. [6].

2.1 *Member Failure*

A member is defined as any member of a member set (subsystem), such as deck leg, tubular joint, etc. Figure (1) shows an example of a fixed platform and the model used for the structural reliability analysis. It is assumed that the strength *R* of a member is a normally distributed random variable with mean $\bar{R}$ and standard deviation σ_R. In general, the probability of failure of a member under a given load *S* is :-

$$P_f = P\{R<S\} = P\ \{\frac{R-\bar{R}}{\sigma_R} < \frac{S-\bar{R}}{\sigma_R}\} \qquad (1)$$

where

$$\frac{R-\bar{R}}{\sigma_R} = t \text{ (standard normal variable)} \qquad (2)$$

Substituting Eqn. 2 into Eqn. 1 results in

$$P_f = P\ \{t < \frac{S-\bar{R}}{\sigma_r}\}$$

This means that the probability of failure of an element under a given load is the probability that the standard normal variable is less than the difference between the load *S* and the mean resistance $\bar{R}$ divided by the standard deviation σ_R of the resistance.

2.2 *Member Set Failure*

Failure of a typical fixed offshore platform can be the result of member set (subsystem) failures. Typical modes of failure in various subsystems are lateral deck collapse, axial pile-soil failure in pull-out or compression, weld failure in pile to jacket connections, tension or compression failure to brace members, tubular joint failure due to fatigue or punching shear, pile failure in bending or shear and lateral failure in soil. Using these modes, a typical platform can be modeled as a combination of various subsystems, as shown in Figure (1).

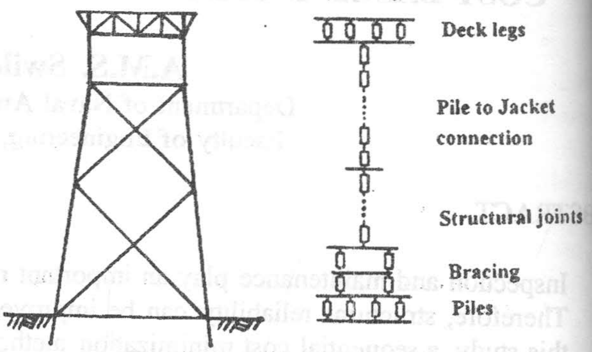

Figure 1. Structural example of an offshore platform.

Such a model is more complex than a simple series or parallel model. Consequently, the true failure probability should be bounded by two extreme forms of behavior. One Simplified subsystem model is a fatigue redundant model as applied to diagonal braces of a jacket. After a diagonal-brace member has failed, progressive failure occurs as the structure is unzipped, thereby, loosing in stages its ability to resist the applied loads. Since there are a large number of failure sequences even in simple structures, a simplification is to assume merely that the member with the highest crack length is the first to fail. In the next stage, again the member with the highest crack length is assumed to fail and so on. To partially account for the fact that only one failure sequence is considered, the failure probability contribution of all members, not just a critical member is included at each stage[6]. Assuming uncorrelated failure of structure elements, the probability of failure of such a subsystem may be taken as:-

$$P_{FT} = P_{f1} \text{ x } P_{f2} \text{ x} \ldots, \text{ x } P_{fn} = \sum_{i=1}^{n} P_{f1} \qquad (4)$$

Where;

P_{f1}= Probability of failure of any brace member failing in the original subsystem.

P_{f2}= Probability of failure of any brace member failing after first member has failed.

P_{fn}= Probability of failure of the final stage, after which the subsystem is statically unstable. (i.e, $P_{f(n+1)} = 1.0$).

Where "P_{fi}" are functions of probabilities of failure of the elements comprising the system. For example, if the subsystem is comprised of "*m*" members with different risk values, "$P_f^{(j)}$", an upper bound on P_{fi} may be given as:-

$$P_{fi} \leq 1 - \sum_{j=1}^{m} \{1 - P_f^{(j)} \tag{5}$$

2.3 *System Failure*

The next step is to combine the failure probabilities of the various subsystems to compute the total system probability of failure. Assume that the system is a series combination of "n" subsystems. Assuming independence of failure modes, an upper bound of the probability failure "P_F" can be expressed as:-

$$P_F \leq 1.0 - \{(1.0-P_{fT1})(1.0-P_{fT2})....(1.0-P_{fTn}) \tag{6}$$

Where "P_{fTn}" is the probability of failure of the *nth* subsystem.

As stated above, these failure probabilities are based on a given load. The overall probability of failure of the structure for a specified service life (20 years, 30 years, etc.) is computed by combining the load distribution for the same period with the system failure probabilities, i.e.,

$$P_o = \int [P_F | S] f_s(s) ds \tag{7}$$

for a continuous load distribution, where $[P_F | S]$ is the "P_F" of Eqn. (6) for a given load "*S*" and "$f_s(s)$" is the density function of the loading.

The system probability of failure calculated above is combined with the sequential cost minimization method [2] to estimate the optimal inspection and maintenance strategy for deteriorating offshore structure. In the next section , the sequential cost minimization method is presented briefly. Reader should refer to Ref. [2] for details.

3. THE SEQUENTIAL COST MINIMIZATION METHOD

The optimal inspection strategy can be achieved by the appropriate selection of inspection interval, inspection method, repair quality and so on. The sequential cost minimization method is used to estimate the suitable inspection strategy for fatigue deteriorating structures by using cost minimization approach and reliability theory. The proposed method has three main steps to follow :-

1- Estimation of the total expected operating cost for structure.

2- The selection of the optimal inspection method for a member set.

3- Selection of the appropriate inspection interval for a structure.

3.1 *Estimation of the Total Expected Operating Cost for Structure*

As stated before, the structure comprises a variety of member sets which consist of different numbers of members (see Figure (2)). It was assumed, for the formulation of the problem, that all the structural members in each set have the same strength property and are subjected to the same loading condition. It is also assumed that each member has a possibility of failure due to the deterioration damage. When any member fails, the service of the structure is always suspended urgently until the failed member is to be repaired. Before the structure returns to service, the member failure might be developed into a catastrophic failure with a certain probability. Inspections are repeatedly carried out during the service life to find the damage when it is small. The detected damages are perfectly repaired. At a certain inspection during service, the total expected operating cost for the structure in the succeeding inspection interval is classified into two main groups : 1) costs necessary in the present inspection, and 2) risks (expected costs) during the service period until the next inspection (see Figure (3)). The former consists of the following cost items :-

- C inspection or *CINS* : Inspection cost for each member set.
- C repair or *CREP* : Expected repair cost of the detected damages during the inspection.
- C scheduled system down or *CSSD*: Loss due to the service suspension caused by the present time inspection and repair maintenance. This includes the losses for scheduled system down, system warming up and system downtime during the inspection and

repair maintenance actions.

The expected costs consist of the following cost items :-

- C Member failure or *CMBF* : Expected loss due to a member failure. This includes repair cost of failed members, loss due to the service suspension caused by member failure, and other economical losses accompanied with the accidental system down.
- C Catastrophic failure or *CCTF* : risk against a catastrophic failure which may occur starting from member failure with a certain probability.

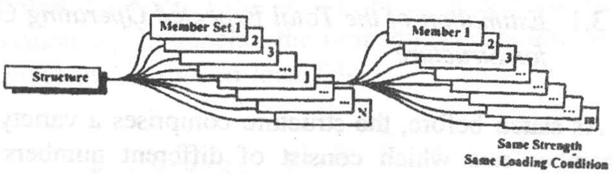

Figure 2. Representation of structure, member sets and members.

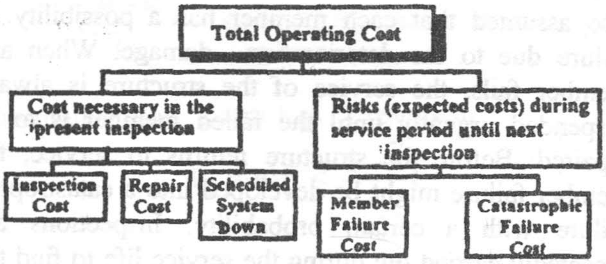

Figure 3. Cost required for structure in an inspection interval.

The total expected operating cost for the whole structure in an inspection interval, from time *t* to time *t+S*, denoted by *CT(t,t+S)*, can be written as,

$$C_T\,(t,t+S) = \sum_{j=Set\,1}^{Set\,N} C_j(t,t+S)+C_{SSD} \qquad (8)$$

Where,

$$C_j\,(t,t+S) = C_{INS}+C_{REP}+C_{MBF}+C_{CTF} \qquad (9)$$

N is the number of member sets that the structure comprises of and C_j (t,t+S) is the expected operating cost for member set *j* in the inspection interval *(t,t+S)*. Certainly, this value changes depending on the applied inspection method and the inspection interval *S*.

3.2 *The Selection of the Optimal Inspection Meth for a Member Set*

The selection is repeatedly carried out at ever inspection from the following five inspection method [2]:-

1- No inspection (*NO*).
2- Visual inspection (*VI*) method.
3- Mechanical (precise) inspection (*MI*) method.
4- Visual and conditional mechanical inspectio (*V&M*) method.
5- Sampling mechanical inspection (*SM*) method.

3.3 *The Selection of the Appropriate Inspection Interval for a Structure*

The proposed method is basically applicable to selec the appropriate inspection interval when there are tw or more choices of inspection interval allowed for th structure. For simplicity, assume that two inspectio intervals are allowed for the structure, once a year an once every two years. The following procedures the could be used to select the appropriate inspectio interval [7]:-

1- First, set the inspection interval for one year *(t,t+* and select the optimal inspection metho for each member set of the structure.
2- Evaluate the total expected operating cost for th structure following Eqn.(8) in the period betwee the time *t* and time *t+1* : CT(*t,t+1*).
3- Repeat 1) and 2) for the inspection interval after th next, (*t+1,t+2*), to evaluate CT(*t+1,t+2*).
4- Sum up these two costs for the structure and obtai the total expected operating cost in the period fro the inspection time *t* to time *t+2*:

$$C_T(t,t+2) = \sum_{j=Set\,1}^{Set\,N} C_j\,(t,t+1) + C_j(t+1,t+2) + 2C_{SSD} \quad (1$$

5- Secondly, change the inspection interval to tw years *(t,t+2)*, and carry out the selection of th optimal inspection method for each member set.
6- Then evaluate the total expected operating cos during two years adding a system down cost for th present inspection at time *t*. The total operating cos

is given by the following equation.

$$C_T(t,t+2) = \sum_{j=\mathrm{Set}\,1}^{\mathrm{Set}\,N} C_j(t,t+2) + C'_{SSD} \qquad (11)$$

7- Finally, the choice of the optimal inspection interval for the structure is to be done by comparing these costs evaluated by the above two equations (see Figure (4)).

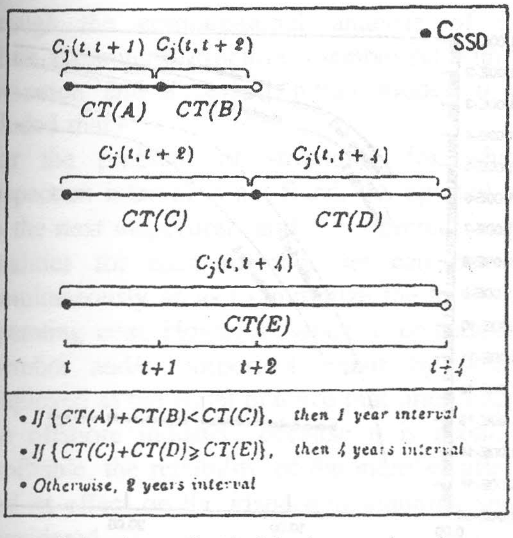

Figure 4. Selection of suitable inspection interval.

In the above procedure, if one year is chosen as the cost minimum, then the inspection methods selected in the *1st* procedure are applied for each member set. Then the same procedure as those described from (1) to (7) are repeated at the inspection time of the next year. Else, if two years are selected, then the inspection methods chosen in the *5th* procedure are applied and the same procedures from (1) to (7) are repeated at the inspection time of two years later. Figure (4) shows the selection procedure of inspection interval for the case that three inspection intervals of once a year, once every two years and once every four years are allowed for the structure.

3.4 *Cost Evaluation Equations*

The estimation of the total expected operating cost corresponding to each member set for the above mentioned five inspection methods, and the cost evaluation equations are given in Ref. [2]. The Markov Chain Model [4] used for the estimation of the probabilities appearing in the cost evaluation equations are also evaluated in Ref. [2].

4. COMPUTATIONAL EXAMPLE

In order to examine the applicability of the proposed method, a computational example was performed for a jacket platform with a hypothetical structural member set. The example used is that of jacket-brace failure due to fatigue deterioration. It must be understood that a structural analysis was not performed for this example and the "numbers" used in these computations are merely assumed values. The assumed platform structure consists of five member sets, deck legs (member set 1), pile to jacket connections, (member set 2), structural joints (member set 3), bracing (member set 4), and piles (member set 5) as shown in Figure (1). Each member set of the assumed platform structure has statistically identical strength properties and is subjected to the same loading condition. The distributions of fatigue crack initiation and propagation lives follow the two parameter Weibull distribution with shape parameter, τ equal to 3 and 4, respectively to accelerate the crack initiation :-

$$f_N(N) = \frac{\gamma}{\beta} \mathrm{x} \left(\frac{N}{\beta}\right)^{\gamma-1} .\exp\left\{-\left(\frac{N}{\beta}\right)^{\gamma}\right\} \; N \geq 0 \qquad (12)$$

The mean crack growth curve is described by Paris' equation with stress intensity factor range ΔK calculated by linear elastic fracture mechanics. The surface length/dratio of the crack was assumed to be constant during the crack growth. Member failure was defined when the crack depth reaches the plate thickness. Both inspection interval and inspection methods for each member set were chosen as the optimization variables. The probability of initial defects, PID, was considered in the first term of the crack propagation terms of the initial state vector. The distribution of the initial defect size was not considered in this study.

The cost items are assumed for the platform structures as follows:- Catastrophic failure cost $C_{CF} = 3.0 \mathrm{~X~} 10^8$ US\$, $C_{SSD} = 10^7$ US \$, Accidental system down cost $C_{ASD} = 3.0 \mathrm{~X~} 10^5$US\$, Visual inspection cost C_{VI}=5.0 US\$, Mechanical inspection cost C_{MI} = 50.0 US\$. The repair cost of a failed member C_{RF} as well as the repair cost of the damaged member C_{RD} detected by visual or mechanical inspection is given as a function of degree of damage, elapsed service life and member position in the platform structure[2].

The capability of the visual inspection and also the mechanical inspection are given as follows[2]:-

$$POD(VI) = 1.0 - \exp\{0.1 \times (a-5.0)\},$$
$$POD(VI) = 1.0 - \exp\{0.1 \times (-0.4x(a-1.0)\} \quad (13)$$

Figure (5) shows the inspection capability for both visual and mechanical inspections in term of crack depth. The minimum cracks that can be detected are 1 *mm* and 5 *mm* by mechanical inspection and visual inspection, respectively. The whole probabilistic structure of the fatigue processes and the inspection procedures were simulated by Monte Carlo simulation.

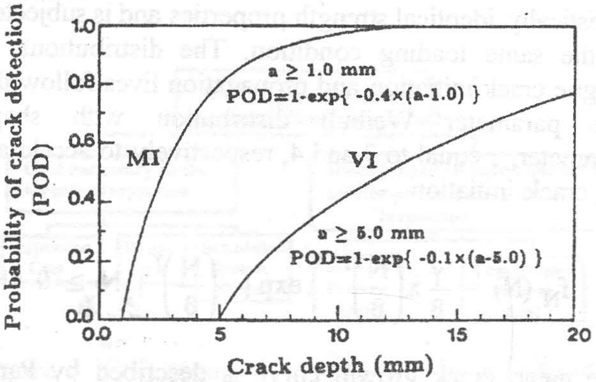

Figure 5. Probability of detection curves for visual and Mechanical inspections.

The number of members, fatigue property, the probability of existence of initial defect, the probability of catastrophic failure, the selected inspection years and quality for each member set for the platform structure are given in Table (1). From this table, it is clear that the first inspection timing becomes later when the initiation life of the member is longer. However, the inspection timing becomes early when the probability of existence of initial defects is high.

Results of the cumulative probability of failure for each member set and the whole system probability of failure calculated by the sequential cost minimization method for the given platform structure are presented in Figure (6). The figure depicts that, after 28 service years, the probability of system failure is equal $3.6x10^{-2}$ which is acceptable from the reliabili viewpoint. Each member set probability of failure also shown in the figure. As one can see, member se 3 and 4 are considered the most sets subjected deterioration, and consequently the most close membe sets to the system probability of failure. This is tru since studies of observed material failures in fixe offshore structures showed that most of the failure occurred in or near the tubular joints and bracin members.

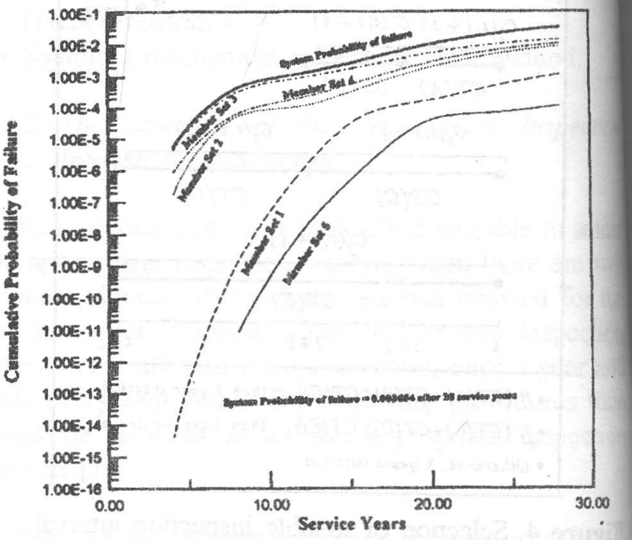

Figure 6. Cumulative probility of failure for platform structure.

5. CONCLUSIONS

A sequential cost minimization method and its consistent formulation have been used after modification for investigating the inspection planning problem of deteriorating platform structures. With the balance between minimum operating cost and optimum structural reliability incorporating the proposed model for system probability of failure, an optimum inspection and maintenance strategy for the whole structure has been obtained. Using such technique, a planning for maintenance based on the system probability of failure can be achieved rather than using the original form of the sequential cost minimization method [2] which is based on the member set failure probability.

Table 1. Platform fatigure property and selected inspection strategy.

Member set	No. of members	Nc years	Np years	PID	PCF $x10^{-5}$	4	8	12	16	20	24	28
1	100	25	20	0.0	5.0	-	-	-	M	M	M	M
2	50	20	15	0.002	1.5	-	M	M	M	M	M	M
3	60	15	15	0.500	4.0	M	M	M	M	M	M	M
4	40	18	15	0.010	5.0	M	M	M	M	M	M	M
5	50	25	30	0.0	1.0	-	-	-	-	M	M	M

M : Mechanical Inspection

Through the computational analysis of a fixed platform assuming a structural member set with fatigue deterioration and a perfect repair model, it can be concluded that:-

1- For the problem of structures for which the inspection interval is not fixed, the optimal interval to the next inspection and the optimal inspection qualities for each member set can be selected simultaneously so as to minimize the total expected operating cost. However, when a replacement of a member and/or imperfect repair by welding is employed as the usual practice that often happens in the offshore industry, because it is economically profitable, the reliability of the member after repair and its effect on the inspection planning should be considered.

2- Developing the whole system probability of failure is more informative as to depicting the behavior of system failure during its service life and giving an indication of the critical subsystems (member set) probability of failure relative to the whole system probability of failure in regard to the inspection and maintenance planning.

3- Although the specific example contained herein pertains to conventional steel template-type platforms, the concept of cost-based inspection is applicable to other marine structures.

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