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# Comparing efficiency of systematic and conditional maintenance for randomly ageing components

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Inspection based maintenance strategies can provide an efficient alternative for ageing civil engineering components subjected to ageing and degradation. The technical and/or economic efficiency of such strategies depends on many factors such as the availability, cost and efficiency of inspection techniques, the mechanisms involved in the loss of performance, the relation between what can be measured through inspections and the level of performance of the structure, the level of required serviceability of the structure, and the direct and indirect economic losses due to a reduction in the performance of a structure. On this basis, this paper studies, using Monte Carlo simulations, the benefits and limitations of an inspection based maintenance strategy. The quality of the inspection technique is analyzed in terms of its sensitivity to defects in their initial stage of development, and on its discriminant ability (detection of a real defect, while avoiding false alarms). The study is carried out in a general context, but is fed with data and models used in the MEDACHS Project, devoted to the analysis of maintenance and reliability of ageing structures in a marine environment. More specifically, the efficiency of inspection based maintenance and systematic maintenance is compared, under different conditions.

## 1 INTRODUCTION

Many of the structures that were built around the 1960's are coming to the end of their service lives and are showing significant signs of deterioration. Consequently, bridge maintenance costs are already very high and are increasing. Currently the biggest challenge that structure owners/managers face is finding the optimum balance between the increasing number of deteriorating structures, and the limited funds available for their upkeep. The demolition and replacement of large engineering structures results in high economic and environmental costs, further increasing the need for efficient management plans to maintain these structures.

As a result, a lot of research has been conducted in this area over the last decade to develop methods of maintenance management which optimize maintenance budgets (Estes and Frangopol 1999, Faber and Sorensen 2002, Kong and Frangopol 2003, Kong and Frangopol 2004, Kong and Frangopol 2005, Lauridsen et al 2006, Radojicic et al. 2001, Stewart 2001, Stewart et al. 2004, Stewart 2005, Stewart and Mullard 2006). The main objective is to find the optimal maintenance management plan, thereby optimizing the life-cycle cost of the structure. Many of these methods rely on quantitative data from inspec-

tions, rather than qualitative and subjective data. Therefore, monitoring and inspections are key aspects in this process. The information from these tests can be used to update deterioration models and to derive the optimal economic maintenance strategy for the remaining lifetime of the structure.

The main focus of this paper is on inspection based maintenance, and how the quality, cost and time between inspections, affects the ability to provide useful information. The maintenance strategy chosen depends on many factors such as the rate of deterioration, the mode of failure, the correlation between the measured parameters, the performance of the structure, and the consequence of failure. The aim of the paper is to use a cost-based analysis to determine whether inspection based maintenance or systematic maintenance is a more efficient strategy. Irrespective of the maintenance strategy, the safety of the structure is maintained above a specified certain target level.

Through both analytical analysis and Monte Carlo simulations, this paper studies the benefits and limitations of inspection based maintenance strategies. The study is based upon data and models developed and used in the European Union Funded MEDACHS research Project. MEDACHS is dedicated to the optimisation of the service life of structures in marine

environments. Both the analytical analysis and Monte Carlo simulations use deterioration models, and information supplied from inspections, to determine the most suitable inspection method along with the optimum inspection period, for different deterioration rates. The probability of detection (PoD) and probability of false alarm (PFA) are used in the study to quantify the quality of an NDT method.

In addition, the results of this analysis are then used to compare annual total cost of a structure using inspection based maintenance and systematic maintenance, for a given set of parameters, and hence, determine the optimum maintenance strategy.

## 2 THEORETICAL BACKGROUND OF PROBABILISTIC MODELLING OF INSPECTION RESULTS

The models that are used to determine the optimum maintenance management strategy are just estimations which predict how the structure will behave over time. Since these models include uncertainty, it can be useful to carry out regular inspections to ensure that the structure is behaving as predicted, or to detect possible problems. The information from the tests can be used to update these models and come up with a more economical maintenance strategy over the remaining lifetime of the structure (Faber and Sorensen, 2002).

Given the size of the defect, and the inspection method being used, there is a certain probability of detection (Faber and Sorensen 2002, Onoufriou and Frangopol 2002, Straub and Faber 2003). The probability of detection can be evaluated using Equation 1,

$$PoD(a) = P(a \geq a_d) \quad (1)$$

where  $a_d$  is the detection threshold, under which it is assumed no crack can be detected (for a particular method), and  $a$  is the measured crack length (Schoefs and Clement 2004). For example, Onoufriou and Frangopol (2002) developed Equation 2 to calculate the probability of detection, which corresponds to an NDT method which has a 90% probability of detecting a 40mm long crack.

$$PoD(2c > x) = 1 - \exp(-x/17.3) \quad (2)$$

The probability of detection (PoD) and probability of false alarm (PFA) can be used to quantify the quality of an NDT method. A variety of NDT methods each with different costs and quality can be used to assess the condition of a structure over its lifetime (Onoufriou and Frangopol 2002). For a given crack size, ROC curves (a plot of PoD versus PFA) of different NDT methods can be used to compare the quality of different methods (Schoefs and Clement 2004, Rouhan and Schoefs 2003).

For a given test, the PoD depends on the crack size, the detection threshold and noise. The PFA, however, depends only on the detection threshold and noise. Therefore, the PoD is the probability that the signal “noise+signal” is greater than the detection threshold, and the PFA is the probability that the signal “noise” is greater than the detection threshold (Rouhan and Schoefs 2003). Figure 1 outlines the effect that noise can have on the accuracy of inspection results, and how a false alarm can occur if the noise is greater than the detection threshold. Noise can depend on environmental conditions, human interference and the nature of what is being measured.

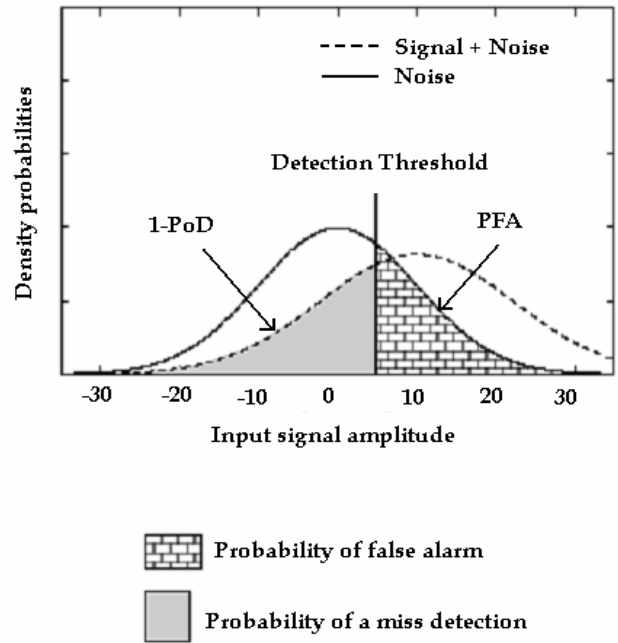


Figure 1. The effect of noise on inspection results (Rouhan and Schoefs 2003)

Rouhan and Schoefs (2003) further developed this methodology by focusing on the probability that a defect exists after an inspection has been carried out. The PoD is the probability that an existing defect is detected, whereas a more useful parameter is the probability that a defect exists, given the results of an inspection. A decision scheme is introduced which considers four inspection events, which are represented in Figure 2 and by Equations 3, 4, 5 and 6,

$$P(E_1) = P(X = 0 | D(X) = 0) \quad (3)$$

$$P(E_2) = P(X = 0 | D(X) = 1) \quad (4)$$

$$P(E_3) = P(X = 1 | D(X) = 0) \quad (5)$$

$$P(E_4) = P(X = 1 | D(X) = 1) \quad (6)$$

where  $X$  represents crack presence, and  $D(X)$  represents the detection of a crack.

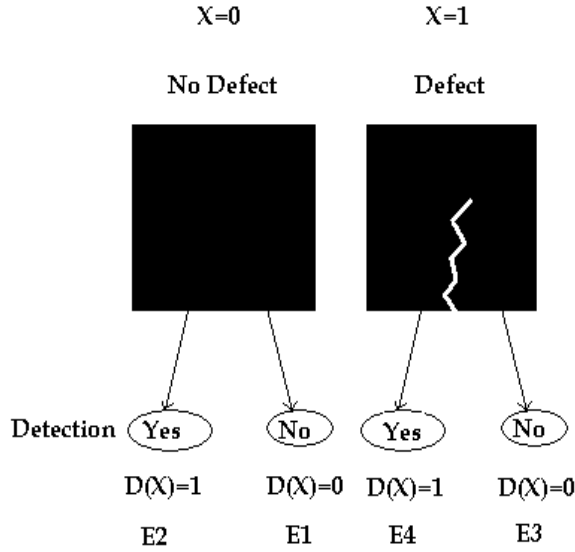


Figure 2. Four inspection events in the decision scheme

The occurrence of these events also depends on another parameter, the probability of presence of a crack at the inspection area,  $\gamma$ . The probability density function of  $\gamma$  is related to the natural size of existing cracks and their spatial variation (which comes from expert judgment or an historical data base). The probability of these events can then be evaluated using Bayes Theorem and are subsequently introduced as parameters into cost functions which are used to investigate the effect of cost over-run due to inaccurate inspection results.

An alternative approach is to introduce a parameter known as the probability of indication (PoI), Equation 7,

$$PoI(d) = PoD(d) + (1 - PoD(d))PFI \quad (7)$$

where  $d$  is the defect size, and PFI is the Probability of False Indication (Schoefs and Clement 2003, Staub and Faber 2003). The parameter, probability of false indication (PFI) must be defined relative to a specific size of the inspected area (Staub and Faber 2003).

### 3 DESCRIPTION OF MODEL DEVELOPED

#### 3.1 Deterioration Model

Monte Carlo simulations were performed to modeling annual deterioration over a period of 2000 years, which is equivalent to about 25 service lives.

The simple model describing the random growth of a structural defect is of the form presented in Equation 8,

$$\frac{d(t + \Delta t)}{d_0} = \begin{cases} \frac{d(t)}{d_0} & \text{with a probability} \left(1 - \frac{1}{g}\right) \\ \frac{d(t)}{d_0}(1 + g\alpha) & \text{with a probability} \left(\frac{1}{g}\right) \end{cases} \quad (8)$$

where  $d$  is the size of the defect,  $d_0$  is a reference defect size,  $g$  is a parameter describing the kinetics of the deterioration,  $\Delta t$  is the time step and  $\alpha$  is a normally distributed random variable (with a mean  $\mu$  and a standard deviation  $\sigma$ ) which increases the size of the defect over time.

By varying  $g$ , the growth of the defect can be either gradual, Figure 3, or rather abrupt, Figure 4, depending on the nature of the material and the deterioration process being considered.

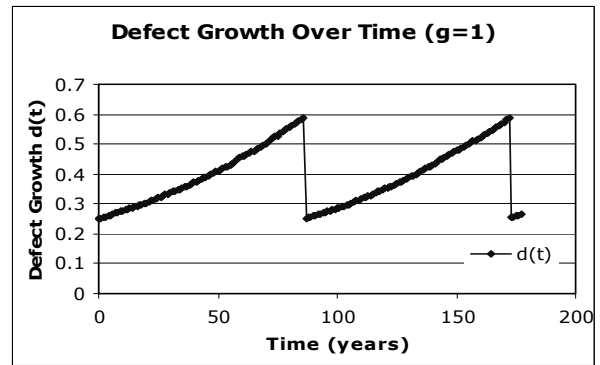


Figure 3. Gradual deterioration of structure

When a repair is carried out the size of the defect is assumed to return to the original size,  $d_0$ .

For each year of simulation, the annual probability of failure,  $p_F$ , is calculated using the Weibull cumulative distribution function, Equation 9,

$$p_F(d) = 1 - \left[ \exp - \left( \frac{d(t) - d_l}{d_0} \right)^m \right] \quad (9)$$

where the parameter  $m$  is the Weibull exponent, which determines the spread of the curve. The purpose of the limit defect size,  $d_l$ , is described by Equation 10 and Figure 5.

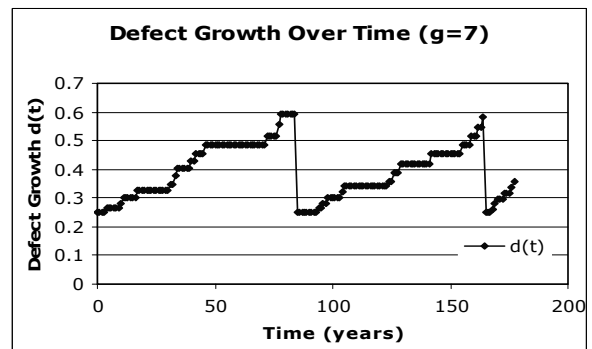


Figure 4. Abrupt deterioration of structure

$$p_F = \begin{cases} 0 & d \leq d_1 \\ p_F(d) & d > d_1 \end{cases} \quad (10)$$

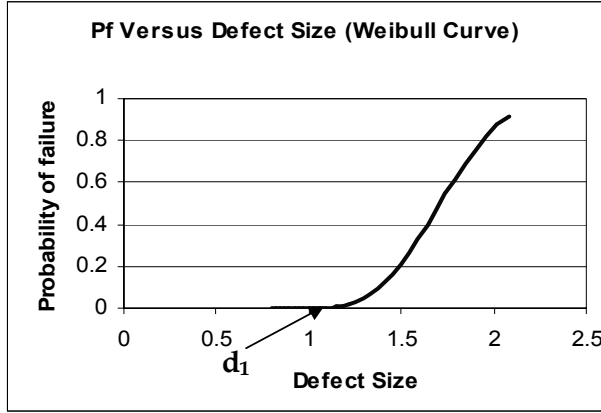


Figure 5. Effect of defect size on probability of failure

A repair is carried out if the size of the detected defect is above a critical defect size,  $d_c$ , Equation 11, which is calculated as a function of the allowable annual probability of failure,  $p_{FA}$ .

$$d_c = d_1 + d_0 [ -(\ln(1 - p_{FA})) ]^{1/m} \quad (11)$$

Scheduled inspections are simulated every  $T_i$  years, where the PoD, Equation 12, and PFA, Equation 13, are determined based on the defect size and the inspection method chosen. For the purpose of this paper it was chosen to estimate the profile of the PoD using a Weibull distribution function.

$$PoD(d) = 1 - \left[ \exp - \left( \frac{d - d_{min}}{d_0} \right)^\beta \right] \quad (12)$$

where  $\beta$  is the Weibull exponent and  $d_{min}$  is the detection threshold, which depends on the NDT method chosen. The quality of the method, which is defined by the parameter  $Q$ , Figure 6, relates the PoD to the PFA,

$$PFA(d) = PoD(d)^Q \quad (13)$$

where  $Q$  depends on the quality of inspection carried out. The higher  $Q$ , the more expensive the inspection technique, and the more accurate the results (for the same PFA, the technique with a higher  $Q$  gives the higher value of PoD). A  $Q$  value of 8 describes well experimental results obtained during the MEDACHS project.

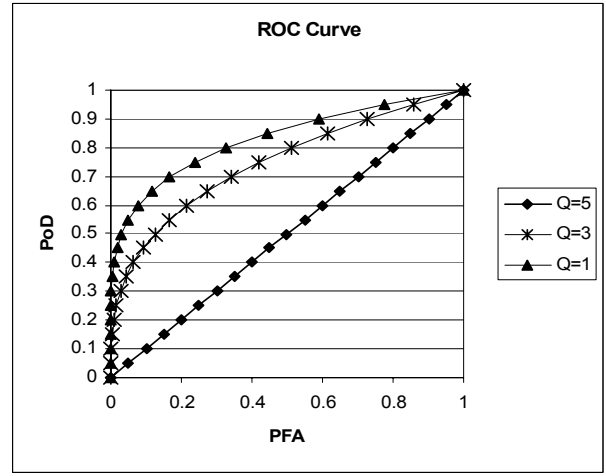


Figure 6. ROC curve for different quality of inspections

### 3.2 Inspection Results

When a scheduled inspection is carried out, every  $T_i$  years, there are various costs involved. As well as the cost of inspection there may also be an associated repair cost, or failure cost, both of which depend on the results from the inspection. For each inspection, there can be 5 possible outcomes with varying associated costs.

In the following derivation it is assumed that the NDT tool is sufficiently accurate, i.e. that  $d_{min} < d_c$ . The sizing capability of the NDT tool is not discussed. In the case of false alarm it is assumed that the detected virtual defect is systematically large enough to lead to a repair ( $d(\text{detected virtual defect}) > d_c$ ). In the case of a successful detection, the size of the detecting defect is assumed to represent the size of the real defect.

### 3.3 Expected Costs Computation

#### 3.3.1 $d < d_{min}$ : expected cost $E(C_{01})$

Due to the limitations of the test, the defect cannot be detected. Resulting costs are (i) Cost of inspection and (ii) Cost of failure (if  $d > d_1$ ).

$$E(C_{01}(t)) =$$

$$\sum_{j=1}^N C_I P_{jT_i}(d < d_{min}) + \sum_{j=1}^N C_F \frac{T_i}{\Delta t} P_{f,jT_i}(d(jT_i) | d(jT_i) < d_{min}) P_{jT_i}(d < d_{min}) \quad (14)$$

where  $N$  is the number of inspection and  $T_i$  the inspection time ( $T_0=0$ ),  $C_f = k_f C_0$ . By knowing  $P_f = 0$  when  $d < d_1$  two cases must be distinguished:  $d_1 < d_{min}$  or  $d_{min} < d_1$ . Of course, for this outcome, the cost of failure exists if and only if  $d_1 < d_{min}$  then the expected cost becomes:

$$E(C_{o1}(t))=$$

$$\sum_{j=1}^N C_I P_{jT_i}(d(jT_i) < d_{\min}) + \sum_{j=1}^N C_F \frac{T_i}{\Delta t} P_{f,jT_i}(d(jT_i) | d_1 < d(jT_i) < d_{\min}) \cdot P_{jT_i}(d_1 < d(jT_i) < d_{\min}) \quad (15)$$

$(P_{f,T_{i+1}}(d(T_{i+1}) | d(T_{i+1}) < d_{\min} - P_{f,T_i}(d(T_i) | d(T_i) < d_{\min}))$  can also be considered (Faber 2002). Where, in this case the relative increase of failure between two consecutive inspections is introduced and only the instantaneous probability of failure is present without multiplying by the duration between two inspections.

### 3.3.2 $d_{\min} < d < dc$ : expected cost $E(C_{o23})$

The defect is large enough to be detected, but below the critical defect size so should the structure does not need to be repaired. However, there is a probability of a false alarm, i.e. the defect may be repaired even if there is no need to repair it. If there is no false alarm (probability = 1-PFA) the defect is not repaired. Therefore, there is a probability of failure. Resulting costs are (i) Cost of inspection and (ii) Cost of failure.

For this outcome, detection or non-detection of an existing defect leads to no action. By knowing  $P_f = 0$  when  $d < d_1$ , two cases must be distinguished:  $d_1 < d_c$  or  $d_c < d_1$ . For this outcome, the cost of failure exists if and only if  $d_1 < d_c$  then the expected cost becomes:

$$E(C_{o23}(t))=$$

$$\sum_{j=1}^N C_I P_{jT_i}(d_{\min} < d(jT_i) < d_c) + \sum_{j=1}^N C_R PFA(d(jT_i) | d_{\min} < d(jT_i) < d_c) \cdot P_{jT_i}(d_{\min} < d(jT_i) < d_c) + \sum_{j=1}^N C_F \frac{T_i}{\Delta t} \left[ (1 - PFA(d(jT_i) | d_{\min} < d(jT_i) < d_c)) \cdot P_{jT_i}(d_{\min} < d(jT_i) < d_c) \right] \cdot P_{f,jT_i}(d(jT_i) | d_1 < d(jT_i) < d_c) \cdot P_{jT_i}(d_1 < d(jT_i) < d_c) \quad (16)$$

It is important to note that the probability of false alarm cannot theoretically be considered as a function of the defect as this would be of no sense. This expression is used if and only if the inspector adjusts the NDT tool to try to detect small defects. Otherwise the PFA represents global information on the NDT tool and must be added to the expected costs determined from the 5 outcomes.

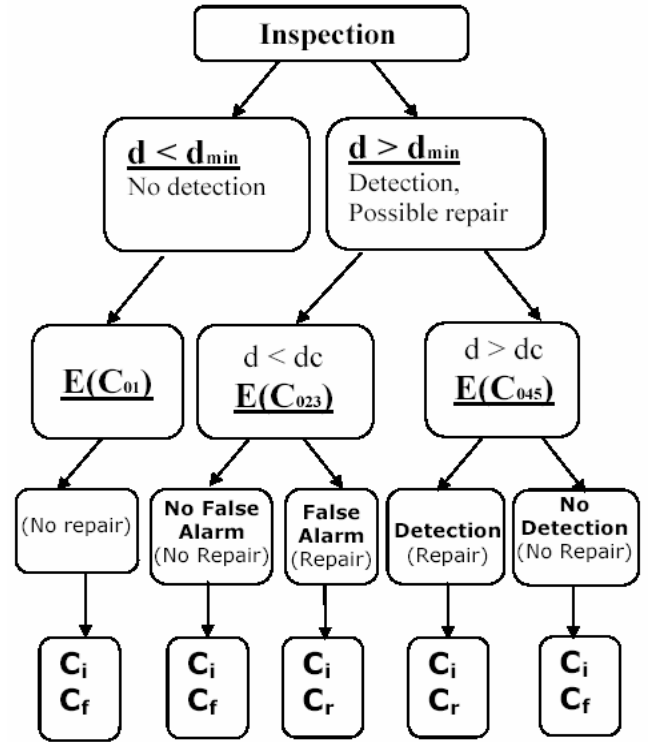


Figure 7. Event tree for outcome of inspections

### 3.3.3 $d_{\min} < dc < d$ : expected cost $E(C_{o45})$

The defect is large enough to be detected, and is higher than the critical defect size so should be detected and repaired. If the defect is detected by the inspection, it will therefore be repaired. If the defect is not detected by the inspection (probability = 1-PoD), it will not be repaired, and the probability of failure will remain. Resulting costs are (i) Cost of inspection and (ii) Cost of failure (if  $d > d_1$ ).

For this outcome, detection or non-detection of an existing defect leads to no action. It is assumed here that:  $d_1 < dc$ .

$$E(C_{o45}(t))=$$

$$\sum_{j=1}^N C_I P_{jT_i}(d_c < d(jT_i)) + \sum_{j=1}^N C_R [PoD(d(jT_i) | d_c < d(jT_i))] P_{jT_i}(d_c < d(jT_i)) + \sum_{j=1}^N C_F \frac{T_i}{\Delta t} \left[ (1 - PoD(d(jT_i) | d_c < d(jT_i))) \cdot P_{jT_i}(d_c < d(jT_i)) \right] \cdot P_{f,jT_i}(d(jT_i) | d_c < d(jT_i)) \cdot P_{jT_i}(d_c < d(jT_i)) \quad (17)$$

## 3.4 Cost Analysis

The mean annual total cost of the structure is used to determine the optimum maintenance management plan. The total cost is the sum of the inspection cost, the repair cost and the failure cost.

### 3.4.1 Inspection cost

The cost of a single inspection is computed using Equation 18,

$$C_i = C_0 k_i \left( \frac{Q}{Q_{ref}} \right) \quad (18)$$

where  $C_0$  is the initial construction cost,  $Q$  is technique quality coefficient introduced in Equation 13 and  $k_i$  is the inspection coefficient.

### 3.4.2 Repair cost

The cost of repair depends on the size of the defect to be repaired (i.e. the cost is directly proportional to a dimensionless parameter related to the size of the defect, e.g.  $d(t)/d_{ref}$ ). Therefore, the cost of repair is calculated using Equation 19,

$$C_r = C_0 k_r \left( \frac{d(t)}{d_{ref}} \right) \quad (19)$$

where  $k_r$  is the repair coefficient,  $d(t)$  is the size of the defect at time  $t$ , and  $d_{ref}$  is a reference defect size.

When a repair has been carried out the size of the defect is assumed to be returned to the original size,  $d_0$ .

Repair may occur due to the detection of a defect, or due to a false alarm. The cost of repair is calculated separately for these two instances, so that the relative costs can be compared and the effect of false alarms can be analyzed.

### 3.4.3 Failure cost

The cost of failure of the system is also calculated as a multiple of the cost of construction. Analytically, the cost of failure is proportional to the probability of failure at the time of inspection. However, when using Monte Carlo to simulate the failure event, the cost of failure must be either zero or  $C_f$ . In this case, in Equation 20, the cost of failure is calculated as

$$C_f = C_0 k_f \quad (20)$$

where  $k_f$  is the failure impact coefficient.

## 4 RESULTS

A period of 2000 years (about 25 service lives) was simulated as part of the model, and was run 20 times. This is therefore equivalent to the simulation of the service life of 500 components. Table 1 shows the initial set of parameters used in the Monte Carlo simulation analysis. Using these parameters, the optimum time between inspections was determined on the basis of the minimum annual total cost of the structure. Figure 8 shows the results of the analysis. It is apparent that a period of approximately 4-years

represents the optimum inspection interval for the case considered.

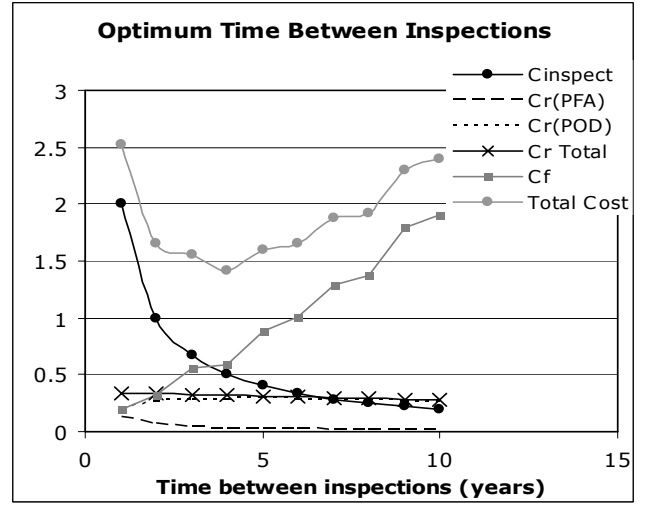


Figure 8. Costs versus time between inspections for parameters in Table 1.

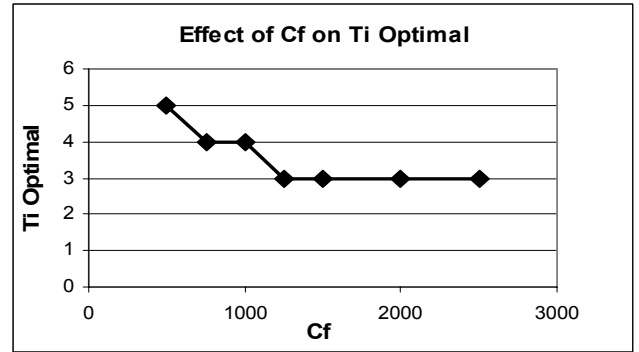


Figure 9. The effect of the cost of failure on the optimal time between inspections

Table 1. Properties assumed in model

Model Properties	
<i>Growth of defect</i>	
Growth rate, mean $\alpha(\mu)$	0.01
Growth rate, standard deviation $\alpha(\sigma)$	0.002
Initial defect size, $d_0$	0.25
Deterioration kinetics parameter, $g$	1
Reference defect size, $d_{ref}$	1
<i>Probability of failure</i>	
Probability of failure exponent, $m$	4
Limit defect size, $d_l$	0.5
Allowable annual probability of failure, $p_{FY}$	0.01
<i>NDT</i>	
Detection threshold, $d_{min}$	0.3
Quality of inspection, $Q$	8
Reference quality, $Q_{ref}$	20
<i>Cost Analysis</i>	
Initial construction cost, $C_0$	1000
Inspection coefficient, $k_i$	0.005
Repair coefficient, $k_r$	0.05
Failure impact coefficient, $k_f$	1

The cost of failure has a significant effect on the optimal inspection interval. As expected, as the cost of failure increases it becomes more economical to carry out more regular inspections to avoid failure, Figure 9. By varying the cost of failure from 500 to 2500, the optimum time between inspections is demonstrated to reduce from 5 years to 3 years.

The kinetics of the deterioration can also have a significant influence on the mean annual costs, with the cost failure steadily increasing as the defect growth becomes more abrupt, Figure 10. Consequently, the optimum time between inspections is also affected, with an inverse relationship between the optimum time between inspections and the deterioration kinetics parameter  $g$ , Figure 11.

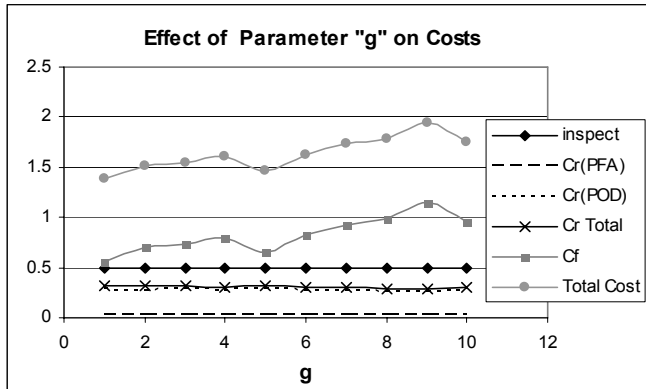


Figure 10. The effect of defect growth kinetics on annual costs

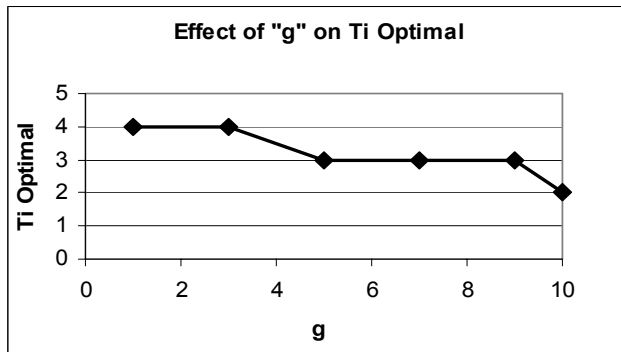


Figure 11. The effect of defect growth kinetics on the optimum time between inspections

The mean growth rate of the defect has quite a significant influence on the optimum time between inspections. A similar trend can be seen, with the optimum time between inspections reducing as the rate of deterioration increases, Figure 12.

Regarding the inspection cost, a change in the inspection coefficient has the opposite effect, with the optimum time between inspections steadily increasing with an increase in the inspection cost coefficient, Figure 13.

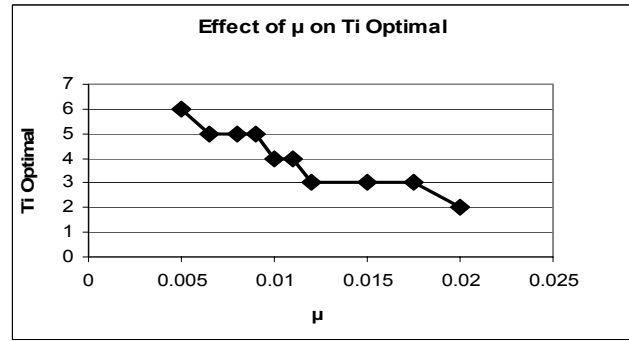


Figure 12. The effect of the growth rate on the optimum time between inspections

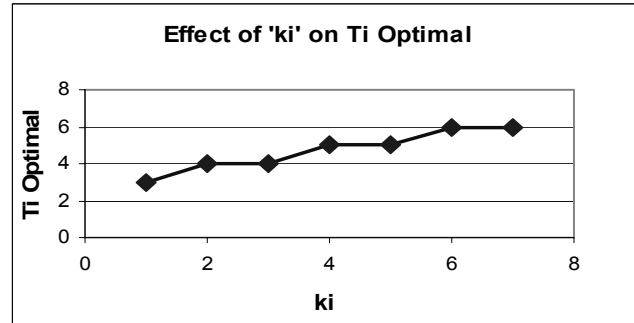


Figure 13. The effect of the inspection cost on the optimum time between inspections

When considering systematic repair, it is assumed that repairs are carried out at regular intervals. We define systematic repair, as repairs carried out at regular time intervals without any inspection taking place. The cost of repair depends on the extent of the repair being carried out. In this case, we consider three scenarios, where the cost of systematic repair is 10%, 50% and 75% of the original construction cost, Figure 14. The total cost, therefore, is comprised of the cost of repair and the cost of failure.

By comparing the mean annual total cost of the structure using systematic based maintenance and inspection based maintenance, it is possible to draw conclusions on the relative merits of both methods. Figure 14, shows that, the extent of repair for systematic repair has a huge effect on the mean annual total cost. In this case, for the set of parameters in Table 1, Figure 14 shows that inspection based maintenance is undoubtedly more cost efficient when the cost of systematic repair is 50% or 75% of the construction cost. However, when the cost of systematic repair is just 10% of the construction cost, then the mean annual total cost approaches the mean annual total cost of inspection based maintenance. For systematic repair, at time intervals between 70 years and 80 years, the cost due to systematic maintenance is less than the cost due to inspection based maintenance (at the optimum time between inspection = 4 years). At a time interval



greater than 80 years the cost of systematic repair increases due to a higher probability of failure and a corresponding higher cost of failure.

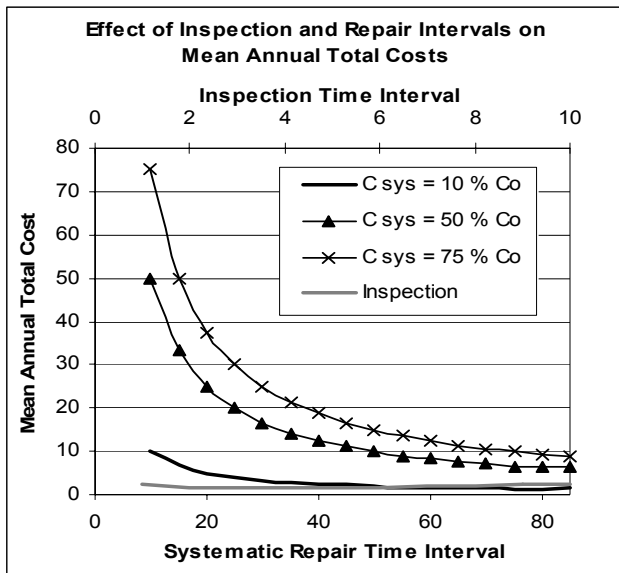


Figure 14. Comparison of mean annual total costs due to inspection based maintenance and systematic maintenance

## 5 CONCLUSIONS

The study performed demonstrates that the cost and quality of inspections has a significant influence on the optimum time between inspections, and hence the minimum annual total cost of the structure over its lifetime. The introduction of the deterioration kinetics parameter illustrates that it is not only the rate of the growth of a defect that influences the optimum time between inspections, and that the mode of deterioration of the material can have a significant effect on the results of the analysis.

In general, inspection based maintenance provides a more economical alternative to systematic maintenance, as repairs are only carried out based on the results obtained from inspections. Also, the extent of a repair is based on the size of the defect that was detected by the inspection. However, in some cases, systematic maintenance can be a beneficial maintenance management strategy, depending on the extent of the repair carried out, the time interval between systematic repairs and the properties of the deteriorating system.

Therefore, to find the optimum maintenance management plan, it is necessary to have accurate models for deterioration, inspections, and repair, and to have a good understanding of the influencing parameters involved in each of these stages. Further work is being carried out as part of the MEDACHS project to investigate these different aspects of maintenance management and to quantify the uncertain-

ties associated with these models and the influencing parameters.

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