ICOSSAR 2005, G. Augusti, G.I. Schuëller, M. Ciampoli (eds)
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Risk assessment for damage tolerant structures

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Keywords: Damage Tolerant Design, Risk Assessment, Inspection Scheduling, Life cycle simulation

ABSTRACT: Aging structures and life extension programs in civil and mechanical engineering are defining new challenges for design and maintenance management engineers. Damage tolerant structures rely on safety of damage detection during scheduled inspections and follow-up repairs. Accepting a certain maximum risk level demands the definition of an inspection and maintenance program. Fewer inspections increase the probability of failure while over-inspection will lead to an increase in life-cycle costs and reduced operation times. All governing variables describing aging structures, such as crack initiation, crack growth, damage detection and damage tolerance are of probabilistic nature. This paper presents a simulation framework, based on Monte-Carlo techniques, which assesses the failure risk of generic engineering structures taking into account scheduled inspection and repair programs.

1 INTRODUCTION

Assuring usability, integrity and reliability of a structure over its entire lifetime is a primary engineering challenge. Today it is widely accepted, at least in the engineering community, that despite all recent advances in structural science and technology, it is impossible to assure one hundred percent safety, even in brand new structures. The operational requirement for most engineering structures is that, over the expected service life span, the risk level is maintained below an acceptable value from socio-political considerations. Therewith the design philosophy for new structures has shifted over the last one-hundred years from static-strength design over safe-life and fail-safe design to damage tolerant design or *safety by inspection*. At the same time the economic constraints are pushing operators to exploit their structures (e.g. aircraft or traffic infrastructure) beyond initial design life. The necessary life extension programs of these aging structures are depending more and more on damage detection and repair, irrespective of the original safe design criterion.

Life extension programs based on damage tolerant design concepts are combining mechanical models for nonlinear structural response, putting special emphasis on predicting the damage evolution, together with inspection technologies and with probabilistic methods to account for the stochastic scatter of all process input variables. Over the next few decades, *safety by inspection* is likely to be the philosophy for high performance expensive engineering structures, where premature retirement is financially not acceptable to the system managers.

The deterioration of a structure is associated with both the initial manufacturing quality and the service usage. A slight variation in the manufacturing quality of new structures can lead to substantial differences in their life spans. In service, the hostile environment, operational as well as overloading and careless usage are responsible for degradation. Prediction of the exact limit state in terms of capacity and life is improbable. On the other side, the damage detection is subjective to the inspection program, i.e., inspection scheduling, detection technique and the inspector quality. Whatever the inspection tool may be, there is a *Probability of Detection (POD)* associated with damage type, size, location, orientation, and so on. There is a need to synthesize these seemingly deterministic probability distributions. Figures 1 and 2 qualitatively demonstrate the difference between the deterministic and the probabilistic nature and damage tolerance concept.

The deterministic concept in figure 1 shows sharp lines for the damage evolution as well as for the ultimate limit state of the structure, governed by the maximum tolerable damage, and for the minimum damage detection size. If at least one scheduled inspection is performed after the minimum detectable damage size is reached and before the maximum tolerable damage is reached, a critical structural damage will be found and maintenance action, e.g. repair actions, can be planned.

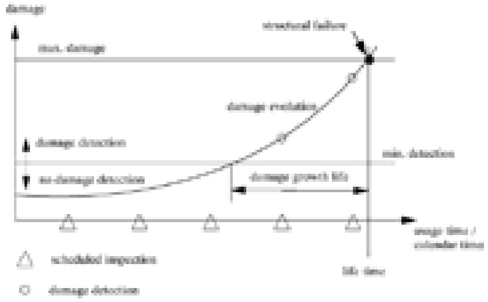

Figure 1: Deterministic damage tolerant design

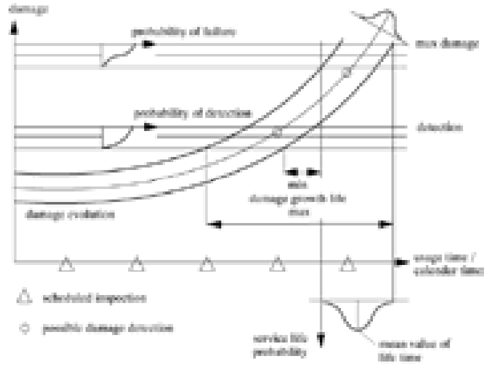

Figure 2: Damage tolerant design based on probabilistic input variables

As soon as the stochastic scatter of the input variables is accounted for, the sharp lines in Figure 1 are becoming bands with probabilistic variations across them. The intersection points of figure 1 therewith become intersection areas with complex probabilistic distributions.

Life cycle and damage tolerant design for engineering structures have been investigated over the last two decades with increasing effort in different areas of engineering science. Research programs in mechanical, aircraft and civil engineering have been attempting to develop new methodologies for damage tolerant design concepts. In non-aerospace structures the issue of structural integrity arises in the context of bridges, railways, roller coasters, surface vessels, automobiles. In aerospace industry which has been the forerunner on this subject, Lincoln (1990) reports a long drawn effort towards risk assessment associated with fatigue-induced cracking of aging fighter aircraft structural components. He discusses details of an approach that the USAF took to predict the onset of *Wide Spread Fatigue Damage (WFD)* which degrades aircraft safety. He mentions that risk assessment would require a category of information base which can be best obtained from *Tear Down Inspections (TDI)* which finally can be evaluated for the planning of management actions. Kaplan & Lincoln (1996) pointed out that the assumption of existing initial manufacturing defects or cracks that could go undetected have caused a major change in the design philosophy. Another set of efforts from USAF is on development of a software code called PROF, Berens et al. (1990), for performing risk analysis of aging air fleet. PROF feeds on crack growth data, probability of crack detection information, stress history, inspection schedules and population density of fatigue cracks. The primary objective is stochastic assessment of structural integrity in terms of safety and durability. A recent version of PROF (demonstrated during the ASIP conference in San Antonio, Dec. 1998) is a spreadsheet based tool, though very powerful, lacks in its ability to capture and project a life time portrait of structural response to a maintenance program. Ingraffea et al. (1990) and Ingraffea and Grigoriu (1992) have attempted application of probabilistic fracture mechanics to account for uncertainties during an extended life period, for establishing optimum inspection programs with reliability and economic constraints. The Monte Carlo simulation approach has been developed for components vulnerable to *Multi-Site Damage (MSD)*. Belytschko et al. (1992a, 1992b, 1992c) have developed and tested a technique to incorporate periodic in-service inspections using a First Order Reliability Method analysis of fatigue life. The attractive feature is that relatively few realizations in the random variable space need to be considered, which is especially important for complex components. The method was shown to be an effective tool for scheduling inspection times based on maximum POF. Grandt (2004) gives a comprehensive overview of damage tolerant design and non-destructive evaluation methods in mechanical engineering.

In civil structures, a recent research program supported by the European Union within the BRITE/EURAM program, which has been reported by Thoft-Christensen (1996), investigated the use of expert systems for optimal reliability based inspection and maintenance of reinforced concrete bridges. The reliability index of the bridge is estimated, based on two different failure modes, namely bending failure of the main bridge girder and compressive failure of the column. Concrete deterioration and reinforcement corrosion are taken into account for the compressive failure. The life-cycle reliability based optimal repair planning for a Colorado State Highway bridge is presented by Frangopol et al. (1997a, 1997b) by taking into account 16 possible failure modes and series/parallel system modelling. Environmental deterioration effects of steel reinforcement and girders are modelled by reducing the cross-sectional area with time (age). An optimum repair strategy is suggested taking into account realistic repair options and their associated costs. Both simulation systems estimate reliability indices of a structure based on a limited number of predefined failure modes. Ang and Leon (1997) propose a systematic approach for formulating risk based cost effective criteria for the design and upgrading of structures with special reference to earthquake hazard mitigation. Optimal target reliabilities, or acceptable risks, for damage control and life safety are determined on the basis of minimum expected life-cycle cost and from which risk consistent criteria for design and upgrading are developed. The approach is illustrated for a class of reinforced concrete buildings.

Our effort is somewhat similar in nature and also aims at `Cost-Risk-Life' tradeof-studies. The current approach suggests a numerical procedure that takes into account the scatter in structural usage, damage initiation, usage/time based damage growth, usage/time based inspections, probabilistic damage detection, maximum tolerable damage, and human factors is a possible way to combine these probabilistic distributions to arrive at a meaningful risk assessment. If a deterministic/probabilistic cost can be associated with each of the events in the simulation, then it would be possible to arrive at a cost-risk-life relationship over the life cycle of the structure. This can help evaluate the inspection program and life cycle costs in context of desired safety levels. There have been similar attempts earlier but with limited scope and success. The present framework, Singh and Könke (2000), goes a few steps beyond the current state of tools. It helps quantitative risk assessment, relate risk to maintenance management schedule and techniques, understand the economic impact of decisions, assess optimum maintenance infrastructural requirement. In summary, the novelty of this procedure is in its ability to estimate parameters of management interest over a life span of a fleet of structures.

2 DAMAGE TOLERANT DESIGN AND RISK ASSESSMENT

A simple measure of risk assessment is *the Probability of Failure (POF)* of a structure. It represents the ``instantaneous" odds of a structure breaking down while in use. When this number is integrated over a full structural fleet usage and over a period of time, it provides the number of catastrophic failures expected during that time. For example, in aviation a single flight POF value of 10^{-5} for a fleet size of 40 aircraft flying an average of 250 flights per aircraft and per year would mean one catastrophic accident every ten years. A fundamental disadvantage of the POF is, that it shows no relation to failure consequences. Neither casualties nor financial losses in case of a catastrophic structural failure are considered in this number.

In order to incorporate this information into the risk assessment the *Fatal Accident Rate (FAR)*, which is the number of deaths per 100 million manhours of exposure to the activity, can be applied. Menzies (1996) lists various FAR values, such as travel by motorcycle (FAR=300), by car (FAR=20), by bus (FAR=1), building collapse (FAR=0.002), UK bridge (FAR=0.1), background FAR at home (FAR=1). In general, the acceptable risk levels must take account of societal values. However, he goes on to say that the risk of 1 in 106 per year may be considered as acceptable. With these quantities, POF or FAR, a qualitative judging about the initial design of a structure and the influence of an inspection program can be conducted.

Damage in structural systems can be caused by human error, accidents and system malfunction. While the probability for the first two reasons can be assumed to be constant over the structure life-time, the third source is usage dependent. Periodic inspections can play a significant role in identifying structural damage in time and assuring prompt repair. The objective of the maintenance management plan for a damage tolerant structure is to ensure that a damage that is not detected during one of the scheduled inspections of the structure should not grow to critical levels before the next scheduled inspection. The risk assessment of a damage tolerant structure thus involves understanding of critical damage size, damage growth rate, and POD for a sub-critical damage (see Fig. 3), which contains the variations of POD with damage size and deterministic damage size and growth with usage plotted back to back so as to match the 'damage axis'. If we were to perform an inspection today, and discover 'no damage' then the probability of failure at a time T from today is equal to probability of non-detection (1-POD) of a damage that would grow to critical size in time T.

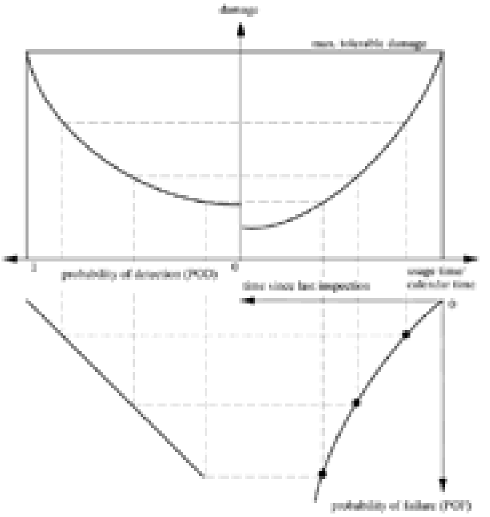

Figure 3: Deterministic model for Probability of Failure estimation

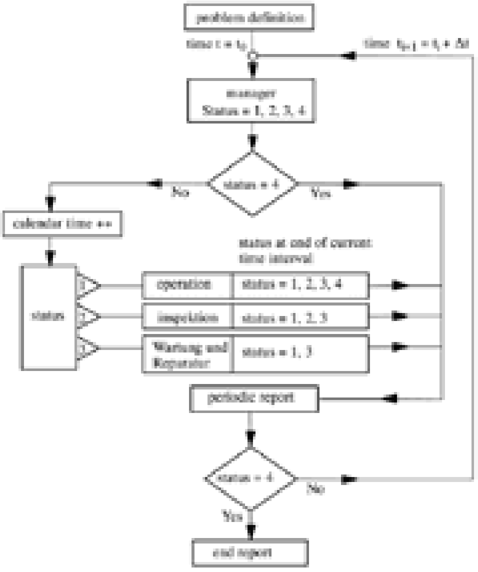

Figure 4: Flow chart CORAL

This value is shown in graphical form in the fourth quadrant of Fig. 3. This was analytically modelled by Sinha (1996). A similar approach has been parallely presented by Bailey et al. (1996) with a mathematical model to determine POF.

Into this POF variation, if we introduce the probabilistic aspect of damage initiation and growth, we reach a situation where it is no longer possible to get a graphical or mathematical risk model. We then need some form of a numerical simulation procedure, which models damage growth and detection as explicit probabilistic events. Actually, such a simulation model can include all conceivable events in a service life environment, such as procurement, sub-detectable damage initiation, design usage, probabilistic damage growth with time and technical usage for each sub-component, scheduled inspections and maintenance program, damage detection based on POD information, subcomponent replacement/repair, damage non-detection and growth to sub-component functional failure or system catastrophic failure, probabilistic accident modelling, service time/usage based retirement, downtime, service delays, accumulated expense and earnings, and so on. Thus for a given structural system, predefined NDI technique, maximum risk level (POF or FAR) and inspection interval can be correlated. The outcome of simulation can be summarized in the form of cost risk-life plots and it can be used to optimize the maintenance management plans.

Estimating single component POF depends upon definition of component failure, which is rather simple as compared to defining a system failure. Due to built-in redundancy and fail safety the definition of system failure is much more complicated and would require a methodology to assess the residual strength of the structure with multiple minor damages to precisely predict failure. This has not been currently modelled. The scope of this paper is limited to a single damaged component but forms the basis for multi-element damage issues in aging structures risk assessment.

3 NUMERICAL SIMULATION OF LIFE-CYCLE

The main program flow of the numerical framework named CORAL is presented in Fig. 4. The primary independent simulation variable is time, which is incremented in time steps, e.g. day, week, month. During each time step, the manager module decides on fresh commission (induction into service) and the event destiny for each of the in-service structures by comparing their usage with scheduled retirement and maintenance management plan (maintain, inspect, overhaul) (see Fig. 5).

For a structure, usage and life are represented by two constituents, calendar and technical time. Calendar usage/life is the elapsed clock time since commission. Technical usage/life is the actual usage of the structure in terms of number of times (units) and/or actual time (hours) in service. For example, the life of a bridge could be thought of as 50 years and 100 million truck crossings. POF measure of risk is estimated from technical usage units and FAR estimations would be extracted from the actual usage time of the structure in hours.

The flow of the simulation (Figs. 4 and 5) is steered by a status flag attached to all the structures. The status for various events is Operation = status 1, Maintenance = status 2, Inspection = status 3, Repair = status 4, Overhaul = status 5, Out of Service = status 10. At every time step, based on the current status, all the structures in service get routed through one of the events, such as operation, maintenance, inspection, repair or overhaul. These events may or may not reset the status at the end of each time step, depending on the outcome during the event. Non-failure of the structure up to design service life (calendar or technical time) leads to scheduled retirement. A sub-detectable damage can be initiated in the structure at the time of commission or after a certain period termed as damage initiation life. Once initiated, the damage grows in service life. Primarily, the environmental damage grows with calendar usage and fatigue damage grows with technical usage. The growth rates and couplings, if any, can be modelled as analytical expressions or numerical lookup tables obtained from numerical simulations and/or experimental observations. Accidental damage is modelled as a random event based on probability of occurrence and quantum. Experimental damage growth assessments or computational damage growth analysis software can be applied to predict damage evolution. Probabilistic variation can be defined to create a deviation from the average damage initiation life/size and predicted growth rates.

Damage growth to critical values leads to one of the failure categories (minor, major, fatal) needing Maintenance (status 2), Repair (status 4) or Decommission (status 10), depending upon the user-defined significance of the structural component and critical damage levels. Catastrophic failures can lead to loss of life. If an accident is reported, the structure gets marked for Inspection (status 3). The simulation framework is designed to accommodate the entire maintenance management plan in three tiers. Maintenance includes scheduled periodic activity to maintain the expected damage growth rates. Inspections include scheduled search for damage, based on calendar time and technical usage. Overhauls include aperiodic maintenance, inspection, repair, and sub-component replacement for the structure, with schedules based on calendar time and technical usage. POD correlation with damage size and inspection tools can be input in analytical or numerical form. Damage detection during scheduled Inspection (status 3) or Overhaul (status 5) leads to Repair (status 4) event. Completion of maintenance management actions puts the structure back into service.

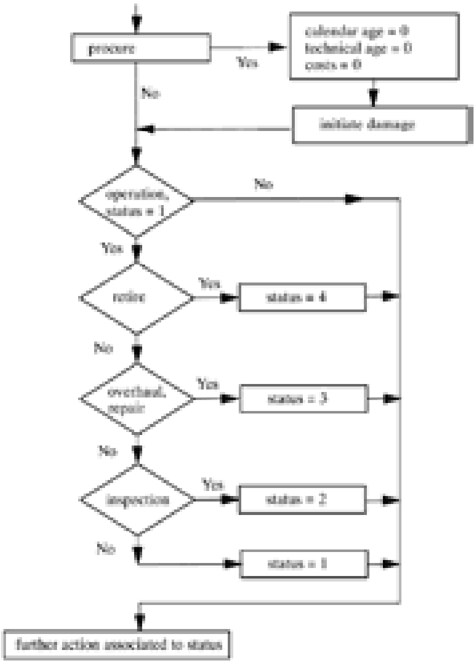

Figure 5: manager module

Costs are associated with procurement, time, operation, maintenance, inspection, overhaul, repair, downtime and disposal events. Failure and inservicability are associated with losses. Revenue may be generated during operation and post-decommission salvation. All these money-matters can be defined and life cycle cost can be easily estimated as a numerical integration over all events for individual structures as well as fleets.

Normal, lognormal, or 2- or 3-parameter Weibull distributions are available to be added on to induce scatter in usage, damage initiation, damage growth rates and so on. The governing variables for such distributions should be an engineering estimate from analytical and experimental information and experience. However, it is possible to evaluate the sensitivity of risk to accuracy in these estimates. The variations in usage and damage characteristics are randomly placed within the user-defined range and user-defined distribution pattern. The random number subroutine returns a variable between 0 and 1 with uniform deviate, Schrage (1979). This feeds on an initial seed value that can be linked to a system clock to get a different simulation every time. Since the model works for identical structures considering probabilistic deviations, the entire fleet can be modelled in a single simulation. For risk assessment of a single structure or too few structures, one can either run the simulation many times or simply upscale the simulation size.

4 EXAMPLE

As an example a single-span reinforced concrete slab bridge is studied (Fig. 6). The geometry of the structure, the problem boundary conditions, the applied load model and the reinforcement are shown in Fig. 7 according to Petryna et al. (1997), Könke (2000). This example is intending to investigate the impact of a hostile environment, leading to corrosion in the concrete reinforcement, and of influence of the manufacturing quality on the lifetime. Therefore damage effects due to fatigue loading of the bridge are neglected here.

In a first step the bridge has been discretized by 96 shell elements, each with 10 concrete and 4 reinforcement layers over the height. A nonlinear finite element simulation has been performed applying a constant dead load and incrementing proportionally the traffic load with a scalar factor λ. For a load factor of λ = 1.80 the first reinforcement bars at the free edge (Point A, Fig. 7) start yielding and at λ = 3.7 the ultimate limit state of the structure has been achieved. The nonlinear force-displacement diagram for Point A, determined from these nonlinear computations, is shown in Figure 8. In addition, the stress state of the slab at λ = 3.5 (shortly before the slab fails) is presented in Fig. 9. In this state, the bottom surface of the slab is almost completely cracked.

Additional deterministic sensitivity studies have been performed to obtain the dependency between the ultimate limit load and the compressive concrete strength and the reinforcement diameters, Petryna et al. (1997). Results of these sensitivity studies are shown in Figure 8.

Figure 6. Reinforced concrete slab bridge

The following life-cycle risk assessment of the bridge structure considers a stochastic scatter of load, concrete compressive strength and diameters of the reinforcement bars. These probabilistic input values are assumed to have Gaussian normal distributions with mean values and standard deviations as listed in table 1.

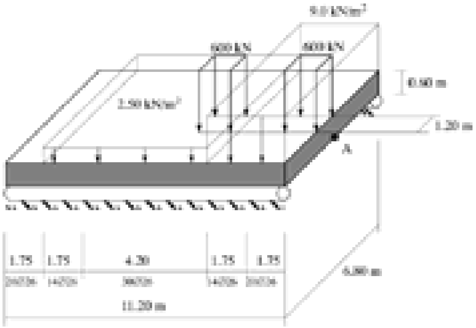

Figure 7: Geometry, loads, structural system and reinforcement

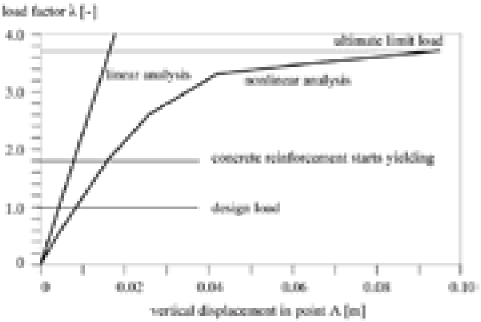

Figure 8: Nonlinear force-displacement curve for deterministic simulation

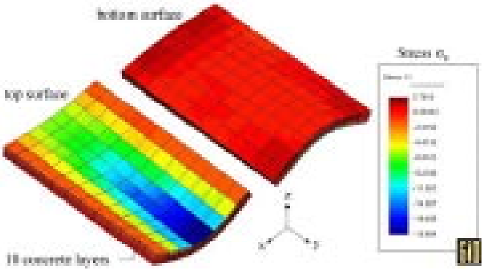

Figure 9. Stress state of the bridge at λ = 3.5

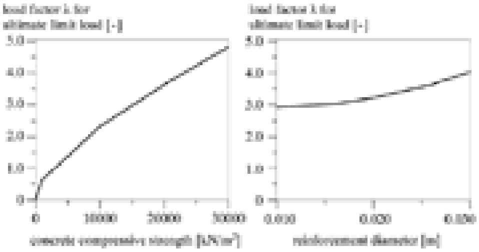

Figure 10. Sensitivity of ultimate limit load due to changes in compressive concrete strength and diameter of reinforcement bars

The major damage effect to be accounted for in this example is due to global reinforcement corrosion, governed by eq. (1)

$$D(t) = D_0 - 0.0232 \cdot t \cdot i_{corr} \qquad (1)$$

For the simulation we assume that the bridge is inspected in different service intervals, starting from 10 years up to 100 years, and that a decrease of the reinforcement diameter by 10 mm will be detected with 98.7 % probability. The simulation life-time is covering a 200 years period. In case of a catastrophic failure and a following structural collapse of the bridge it is assumed that just one car with two passengers will be on the bridge and that one casualty has to be accounted for. All following traffic is assumed to be stopped safely. The accepted FAR for this bridge in this example is set to FAR = 0.01.

The initially undamaged structure shows a probability of failure of POF = 10^{-9}. For different inspection intervals the POF and the FAR are listed in table 2.

It can be seen, that the effect of global corrosion of reinforcement is showing only small effects on the POF as well as on the FAR, as long as moderate large inspection intervals are assured. Only for very large inspection intervals of more than 50 years the corrosive effect is happening fast enough to substantially reduce the POF and increase the FAR. The required FAR of 0.01 can be obtained with an inspection interval of approx. 30 years.

5 CONCLUSIONS

The presented approach of a software framework for the risk-assessment of engineering structures allows design and maintenance management engineers to quantitatively judge on inspection and maintenance programs for their structures. Damage initiation and evolution can be included in the framework in a very flexible manner, by external special purpose software packages or by experimental results. Costs associated with downtime and repair as well as earnings associated with operation of investigated structures can be taken into account. The proposed framework can be conveniently applied to predict the outcome of maintenance management plans in terms of probability of failure, fatal accident rate, monetary expense, downtime periods and costs, availability, reliability and so on. The ability to correlate the cost and estimate impact of maintenance management plan has not been attempted before. When coupled with an optimization algorithm, CORAL can help managers arrive at the most economic maintenance management plan for a desired safety level.

Table 1: Stochastic values for input parameters

	mean value	standard deviation	distribution function
load factor λ [-]	1.0	0.3	Gauss normal distribution
Concrete compressive strength [kN/m2]	27000.0	4200.0	Gauss normal distribution
Initial diameter of reinforcement bars D_0 [mm]	26.0	4.0	Gauss normal distribution
corrosion rate i_{corr} [µA/cm^2]	2.0	1.0	Gauss normal distribution

Table 2: POF and FAR with respect to different inspection intervalls

inspection intervall	POF	FAR
10	0.596 □ 10^{-7}	0.000233
15	0.358 □ 10^{-6}	0.001397
20	0.775 □ 10^{-6}	0.00186
25	0.107 □ 10^{-5}	0.00349
50	0.224 □ 10^{-4}	0.09360
75	0.114 □ 10^{-3}	0.4536
100	0.283 □ 10^{-3}	1.09600

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