# Improvement in Performance Prediction of Corroding Concrete Structures using Health Monitoring Systems

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***Abstract***
Predicting future condition and reliability of the deteriorating structures is vital for their effective management. Probabilistic models have been developed to estimate and predict the extent of deterioration in concrete structures but their input parameters are fraught with uncertainties, hence limiting the effective use of the models for long term predictions. On the other hand, continuous innovations in the sensing and measurement technology have lead to the development of monitoring instruments that can provide continuous (or almost continuous) real time information regarding structural performance. Thus, powerful decision-support tools may be developed by combining information obtained through structural health monitoring with probabilistic performance prediction models.
The potential benefits of improving performance prediction using health monitoring systems and their implications on the management of deterioration prone structures are presented in this paper. A typical structural element of a bridge (e.g. slab, beam or a cross beam etc) subjected to chloride induced deterioration is considered. It is shown that the confidence in predicted performance can be improved considerably through the use of health monitoring methods and hence, the management activities such as inspections, repair and maintenance etc can be adjusted whilst keeping consistent target performance levels. A comparison of various probabilistic models for the input parameters (e.g. exposure conditions, threshold chloride concentration etc) indicates that the effects of uncertainty can be minimised through the in-service health monitoring systems.

***Keywords*****:** Corrosion in concrete, Structural health monitoring, Performance updating.

***Introduction***
Reinforced concrete has been widely used as a construction material for civil infrastructure facilities around the globe in the last century. Among other high value asset structures, reinforced concrete has been widely used in the construction of highway bridges. In the UK, out of over 9000 trunk road and motorway bridges (valued at around £20 billion) administered by the UK's Highways Agency alone, more than 80% contains concrete as structural elements, and about 65% are either reinforced or prestressed concrete bridges [1]. These structures represent 2% of the national network length but 30% of its total asset value. It is worth mentioning here that over 50% of the total bridge and large culvert stock, estimated at over 150,000, were constructed between 1960 and 1980 [2]. The UK Department of Transport estimated a total cost of repair of over £600 million due to corrosion damage to motorway bridges in 1989 [3].
The main motivation for the use of reinforced concrete is its ability to be moulded into virtually any size and shape, and its perceived high durability. Understanding of the latter was very limited until the 70's; as a result, many structures comprised of concrete are deteriorating at rates higher than envisaged in the original design [3]. In general, deterioration of concrete structures is associated with the corrosion of reinforcement embedded in concrete [4]. This is caused mainly by either carbonation, or chloride attack. These mechanisms are unique in the

sense that the aggressive agents penetrate into the concrete without any visual signs of deterioration until they reach the reinforcement level and initiate corrosion. In addition to the loss of section in the steel bars, the expansive products of corrosion cause delamination and spalling of concrete, which ultimately may lead to failure of the structure.
In most developed countries with already established, but aging, infrastructure, the investment on maintenance of these structures is either approaching, or has already increased, the capital spent for new construction [5]. Hence, maintenance management is of increasing importance and significant research is directed towards this area.

***Performance Prediction and Health Monitoring***

Predicting future condition and reliability of deteriorating structures is vital for the effective management of deteriorating structures. Research in this area has lead to the development of predictive models to estimate and predict the extent of deterioration in concrete structures for a variety of material and environmental conditions. A typical model for the time to corrosion initiation based on Fick's second law of diffusion [6] is presented in Eq. 1.

$$T_I = \frac{E_{\mathrm{mod}} X^2}{4D\left[erfc^{-1}\left(\frac{C_{th}}{C_o}\right)\right]^2} \qquad \text{.....Eq. 1}$$

Where $T_I$ is the time to corrosion initiation at any given depth X; D, $C_o$, $C_{th}$, and $E_{mod}$ represent the effective diffusion coefficient, surface chloride concentration, threshold chloride concentrations and model uncertainty factor respectively.
Uncertainties associated with the nature and rate of deterioration, the load (past, present and future) and the actual performance of these structures are considerable, and subject to change during the structures' service life. This realisation has led to a trend towards probabilistic deterioration modelling. Thoft-Christensen et al. [7] appear to be the first to use a probabilistic approach for the deterioration models. In this approach, the uncertain input parameters are modelled using random variables and hence, a distribution for the corrosion initiation time is obtained instead of a deterministic value.
The input parameters of the deterioration models are subject to uncertainty, both aleatory (physical) and epistemic (statistical and modelling), hence limiting their effectiveness in long term predictions, typically over 10 to 20 years [8]. On the other hand, continuous innovations in the sensing and measurement technology have lead to the development of monitoring instruments that can provide continuous (or almost continuous) real time information regarding the structural performance [9]. A very powerful tool can be developed by combining information obtained through structural health monitoring with the probabilistic predictive models. This would increase the confidence in the predicted performance by reducing associated areas of uncertainties in the predictive models. The uncertainties associated with the health monitoring instruments can also be incorporated within such a framework to obtain realistic performance predictions.

***Monitoring for Corrosion Initiation Phase***

The mechanism of corrosion may be split into two phases, 'initiation' and 'propagation'. From the point of view of the management of structures, the maintenance becomes very costly once the corrosion reaches the second phase, hence the focus of this paper will mainly be on the initiation phase of corrosion. The methodology developed can easily be extended to the propagation phase, where this is merited.
During the initiation phase, the corrosion risk of a reinforced concrete structure can be monitored through either chloride content measurements, or by measuring the penetration of the threshold chloride contents, in the cover concrete. Chloride measurement probes have

been developed though they appear to still be in the testing and validation stage. Corrosion risk probes have also been developed, and instruments available for this include;

- Ladder Arrangement (Fig. 1),
- Metallic Nail System,
- Expansion Ring System (Fig. 2).

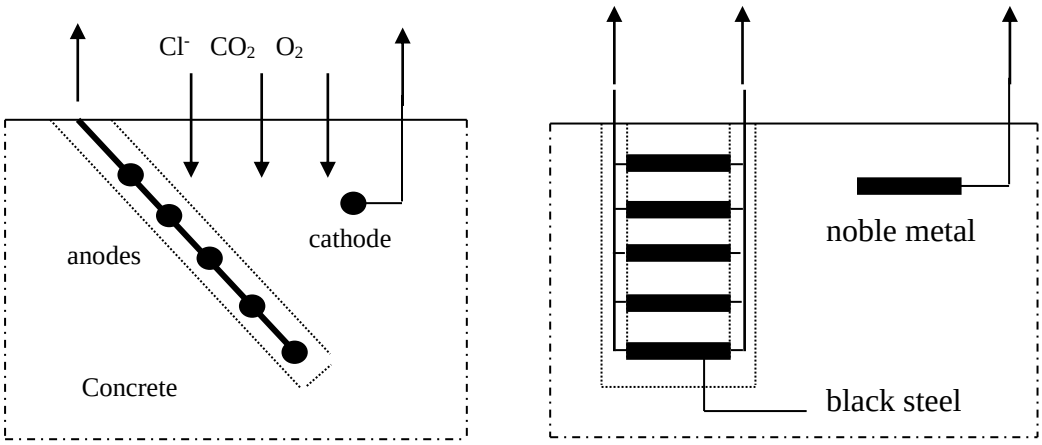


*Figure 1: Ladder arrangement [10]*

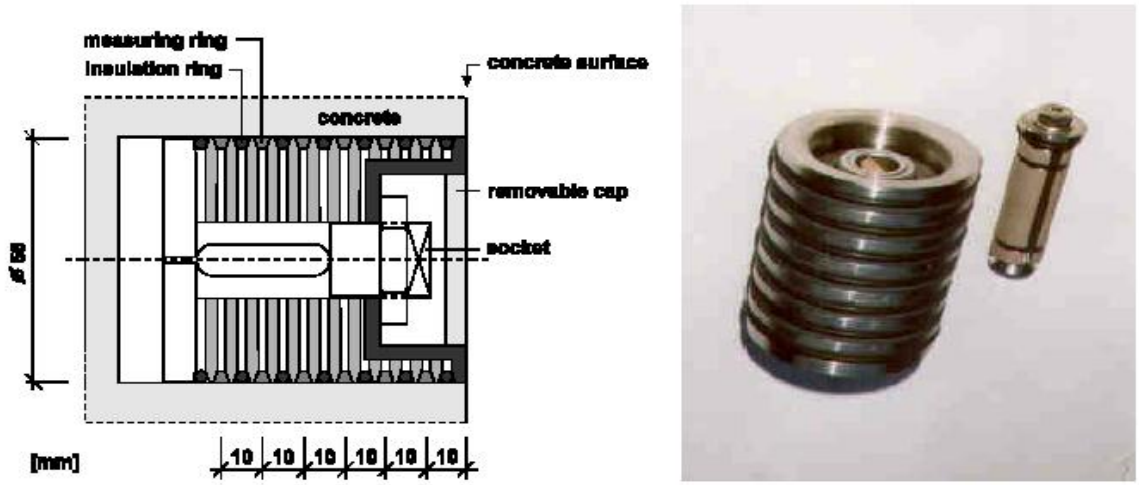


*Figure 2: Expansion Ring System [9]*

The ladder arrangement can be installed in new structures or during repair works in existing structures. Expansion ring and Metallic nail systems can also be installed into existing structures without damaging the existing concrete cover. The working principle for all three systems is identical. Small pieces of steel are installed at various known depths into the cover concrete and the corrosion activity of these pieces is monitored. The initiation of corrosion of these steel pieces gives an indication of the corrosion penetration depth into the cover concrete. A curve of the corrosion penetration depth is plotted against time, which is then extrapolated to predict the time to corrosion initiation at the rebar level.

***Issues and limitations of Health Monitoring Systems***

Despite all the advantages offered by health monitoring systems, there are several issues that should be addressed to facilitate the use of these sensors for the health monitoring of structures. With regard to the spatial variability of corrosion deterioration, a major concern in the use of the above systems is that they only provide information at a small number of

specific locations; careful thought has to be given as to how these results can be considered as representative (or not) for the entire member or structure.
Another vital issue with the use of such systems is that pertaining to results that are unexpected or might be misinterpreted. If, for example, several sensors (steel bars) are installed at various depths what should the conclusion be, if a sensor close to the surface still shows passivity, whereas another at a greater depth indicates corrosion activity? Alternatively, what if a sensor close to the surface returns to a passive state, whereas another at greater depth still confirms corrosion activity, etc. Other possibilities of cases that may need to be considered include no readings or clearly erroneous readings obtained from a particular sensor. But even when the sensors are free from obvious errors how confident should we be regarding their output, and to what extent can this information be used for performance prediction purposes?
The above arguments lead to the belief that, instead of relying entirely on the information obtained through location specific monitoring systems, this information should be combined with the prior information regarding the deterioration phenomenon and its prediction through empirical and/or semi-empirical models. This information is often diverse in quality and quantity and certainly contains uncertainty! Thus, a primary objective of combining prior information with monitoring data should be to reduce areas of uncertainties, whilst realising that there are different and diverse sources.

***Bayesian Updating***

The need for combining information obtained through health monitoring systems with probabilistic predictive models is highlighted earlier. A powerful and versatile approach dealing with performance evaluation and prediction of systems in the presence of uncertainty is the Bayesian approach. This approach has had a significant impact in nuclear plants assessment and in the health care systems. More recently, similar techniques have been used successfully in offshore installations and steel bridges, for the planning and optimization of inspection and maintenance schedules [11-14].
The Bayesian updating approach can be used to incorporate information obtained from different sources at different point-in-time during long service lives, e.g. either from detailed inspections and monitoring or even from the qualitative assessment methods, i.e. visual inspections or service records, etc. An application related to concrete structures is presented by Faber & Sorensen [15], where inspection results are used to evaluate the condition states of bridges at any given time.

***Performance Updating for Reinforced Concrete Structures***

In the present work, a methodology has been developed using Bayesian event updating framework that can integrate data obtained though health monitoring with prior information [16]. The application of this methodology for performance updating of concrete structures prone to reinforcement corrosion is highlighted here. The two possible outcomes considered for corrosion risk sensors are;

- Passivity confirmation at the sensor location at the time of monitoring, or
- Confirmation of corrosion activity at the sensor location at the time of monitoring.

Performance (in this case, time to corrosion initiation at rebar level) updating is achieved assuming ‘n’ number of sensors along the depth of the cover concrete. The expression used for updating is shown in Eq. 2, details of which can be found in Rafiq et al. [17].

$$F_T^{"}(t) = P\left[\frac{\left[T_I(X = X_c) \le t\right]\bigcap_{i=1}^{n}\left[M_i \le 0\right]\bigcap_{i=1}^{n+1}\left[M(X_i) > 0\right]}{\bigcap_{i=1}^{n}\left[M_i \le 0\right]\bigcap_{i=1}^{n+1}\left[M(X_i) > 0\right]}\right] \qquad \text{……..Eq. 2}$$

Where $X_i$ = depth of sensor no. i from the concrete surface = $X_c$ (cover depth) for i = n+1
$T_I(X = X_i)$ = priori predicted initiation time at depth $X_i$.
$M(X_i)$ = safety margin for expected corrosion initiation time at depth $X_i$ from the surface of concrete at any time $t = t_a$.
= $T_I(X = X_i) - t_a$, when passivity is confirmed at depth $X_i$.
= $T_I(X = X_i) - (T_{Ii} - t_{int})$ when corrosion has initiated at depth $X_i$ and time to corrosion initiation of sensor i, $T_{Ii}$ becomes known.
$M_i$ = Safety margin between predicted and actual initiation time for corrosion, when the time to corrosion initiation of sensor i becomes known.
= $T_I(X = X_i) - T_{Ii}$ and
= 0 for passivity confirmation case.
$T_{Ii}$ = time at which initiation is detected by the sensor i.
$t_{int}$ = time interval between the two events i.e. 'corrosion initiation confirmation' and 'passivity confirmation' that reflects the inability of monitoring instruments to detect exact corrosion initiation time.

***Case Study***

In order to demonstrate the effectiveness of the proposed updating methodology in gaining confidence in performance prediction, a simple bridge element such as a beam, slab or cross-beam is considered here. The distribution characteristics for the input random variables in the model for corrosion initiation time (Eq. 1) are shown in Table 1. More advanced deterioration models can be incorporated easily once their distributions shape and parameters are established. The distribution for the time to corrosion initiation at rebar level (on average located at 40mm) based on these variables is shown in Fig. 3.

*Table 1: Distributions of input variables in the model for corrosion initiation time*

| Parameter | Mean | C.O.V. | Distribution |
|---|---|---|---|
| $C_o$ | 3.5 Kg/m$^3$ | 0.5 | Lognormal |
| D (Nominal) | 5x10$^{-5}$ m$^2$/Yr | | |
| *Model Error(D)* | 1.0 | 0.2 | Normal |
| $C_{th}$ | 0.9 Kg/m$^3$ | 0.19 | Uniform (0.6 – 1.2 Kg/m$^3$) |
| $E_{mod}$ | 1.0 | 0.25 | Lognormal |
| X | 40 mm | 0.1 | Normal |
| $X_i$ | 10, 20 & 30mm (Fully Correlated) | σ =1 mm | Normal |
| $t_{ini}$ | 0.1 Years | | Deterministic |

The results shown in Fig. 3 can be interpreted in two different ways. The ordinate gives the probability that corrosion initiation at rebar level is reached up to any particular point in time (absissa). If an acceptable (tolerable) target probability can be specified, the curve could be used to estimate the point in time at which certain management actions are to be taken (e.g. if a target probability of 0.3 is considered, actions would be taken after 10 years). On the other

hand, the ordinate may be interpreted as the fraction of the area of a member exhibiting corrosion activity normalised by the total area. In this case, the target (or threshold) would represent the maximum corrosion damage tolerated for any particular member or structure.

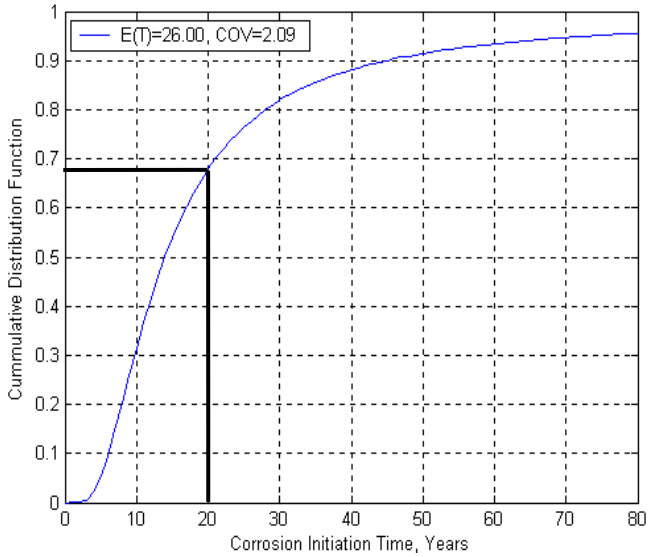


*Figure 3: Distribution for the corrosion initiation time.*

Consider now a case where a health monitoring system has been installed to the structure to monitor corrosion risk at various depths below the concrete surface. The results for the prior and posterior failure probabilities at 20 years versus time (where corrosion initiation at rebar level represents 'failure') are shown in Fig. 4a for one sensor at 10mm depth and Fig. 4b for two sensors at 10 and 20mm depths. The different colour lines represent different assumed times for corrosion initiation at sensor level; in a real case, the actual time would be obtained from the instrument. The different assumed times may be attributed to variation in exposure conditions and material properties, etc. It can be seen from these figures that:

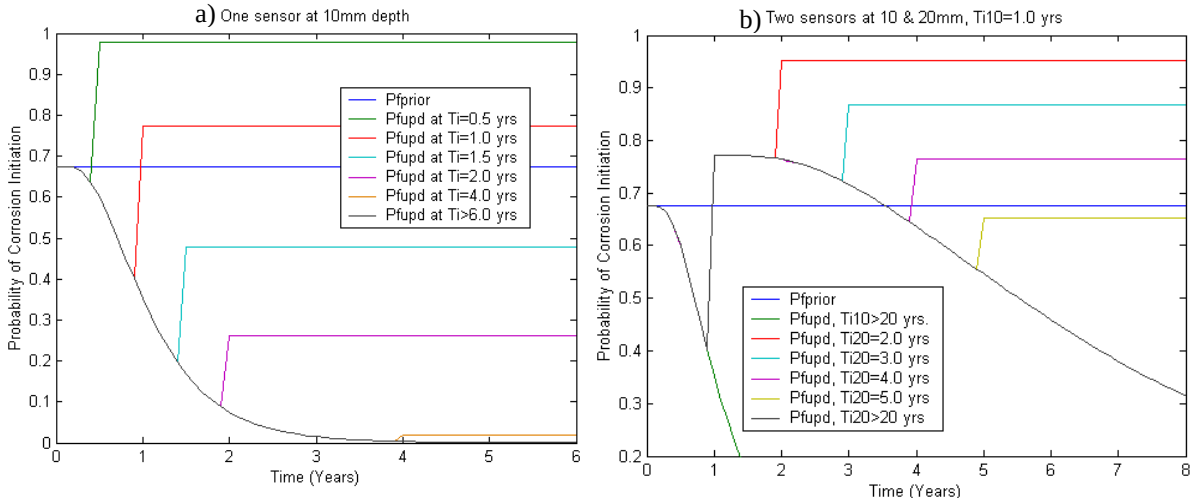


*Figure 4: Probability of corrosion initiation at rebar level in 20 years*
*a) One sensor at 10mm depth b) Two sensors at 10 & 20mm depth*

- Increase or decrease in the 'failure' probability (from the prior value) strongly depends on the time at which the sensors indicate that corrosion initiation is reached.
- If the first sensor (here assumed at 10mm depth) does not detect corrosion initiation in the first 3 years after the surface is exposed to chloride ions, the probability of

corrosion initiation at rebar level in 20 years time is negligible; of course, this assumes that the sensor is functioning properly and that exposure conditions and material properties will remain the same throughout this period. This result would suggest that a more detailed half-cell potential survey of the structure should be delayed beyond the value indicated above, as it is unlikely to yield any useful information about the condition of this particular structure.

Conversely if the first sensor detects corrosion initiation at 0.5 years, then the corrosion initiation at rebar level by year 20 is practically certain. This can be used to bring forward the time for a half-cell potential survey and would also emphasise the need for preventative actions to be taken (e.g. cathodic protection).

- The figure also shows the evolution of posterior probability profiles for the case of two sensors assuming different scenarios. In these cases, it is the combined information from the sensors that becomes relevant for drawing the appropriate conclusions regarding the inspection and maintenance regime for the structure.

The reduction in uncertainty can be quantified by comparing prior and posterior distributions for the time to corrosion initiation for the sensor initiation (Fig. 5a) or simply confirmation of passivity at sensor locations (Fig. 5b). It can be seen from these figures that;

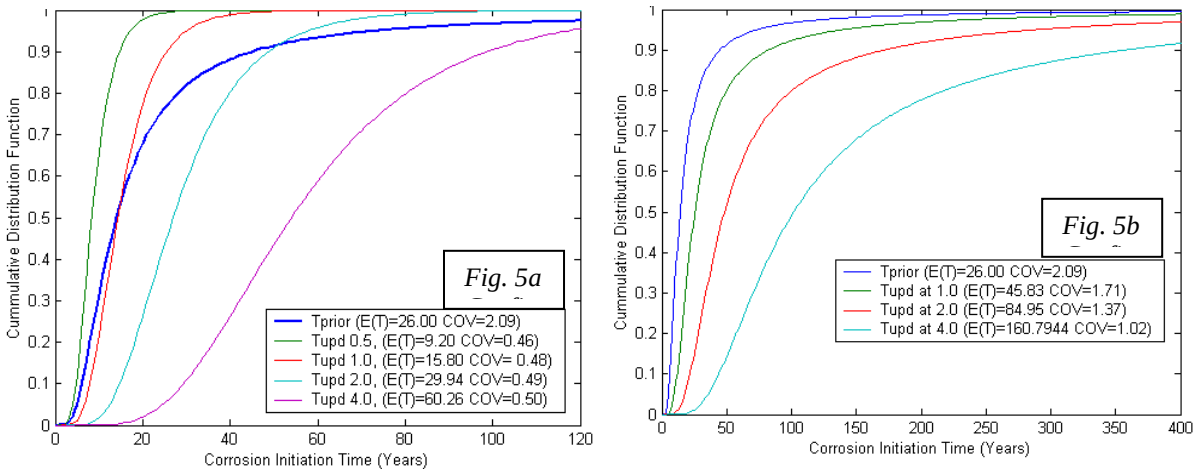


*Figure 5: Posterior corrosion initiation time at rebar level*
*a) Initiation confirmation case b) Passivity confirmation case*

- Uncertainty is reduced continuously as more information becomes available, be it in the form of confirmation of passivity or in detecting initiation at sensor locations. The reduction in uncertainty (in terms of the COV) is more pronounced when the actual time to initiation at sensor location becomes available rather than when only passivity is confirmed at any specific point in time.

- The percentage reduction in COV, with one sensor in position, is around 76 % and is practically constant regardless of the time to corrosion initiation at the sensor level (see Fig. 5a). In the case of confirmation of passivity, the COV reduces continuously with time and approaches 50% after about 4 years (Fig. 5b).

- The change in updated corrosion initiation time at the rebar level (from its prior value) depends upon the early or delayed sensor initiation time from its prior expected value e.g. the mean value of the updated time to corrosion initiation at rebar level reduces (from the prior value of 26.0 years) to 15.8 years if sensor detects initiation at 1 year time, or increases to 29.94 years for sensor initiation time of 2.0 years (Fig. 5a).

Based on the prior information, the time of first intervention on the bridge is 4.9, 6.0 and 8.0 years for the 5%, 10% and 20% distribution fractile respectively. These intervention times for different cases of passivity confirmation and sensor initiation times are summarised in Fig. 6. For example, it can be seen that the time to corrosion initiation at rebar level (using the 10 % distribution fractile) changes from 6.0 years (prior information) to about 8 years (if the corrosion initiation is detected at the sensor location, at 10mm cover depth, after 1 year) or 12 years (if passivity is confirmed by the 10mm sensor after 1 year). The results are clearly different for different distribution fractiles (i.e. 10%, 20% etc), and for different scenarios. As a result, the first intervention on the bridge (e.g. detailed inspection using half cell survey etc) can be brought forward or postponed accordingly.

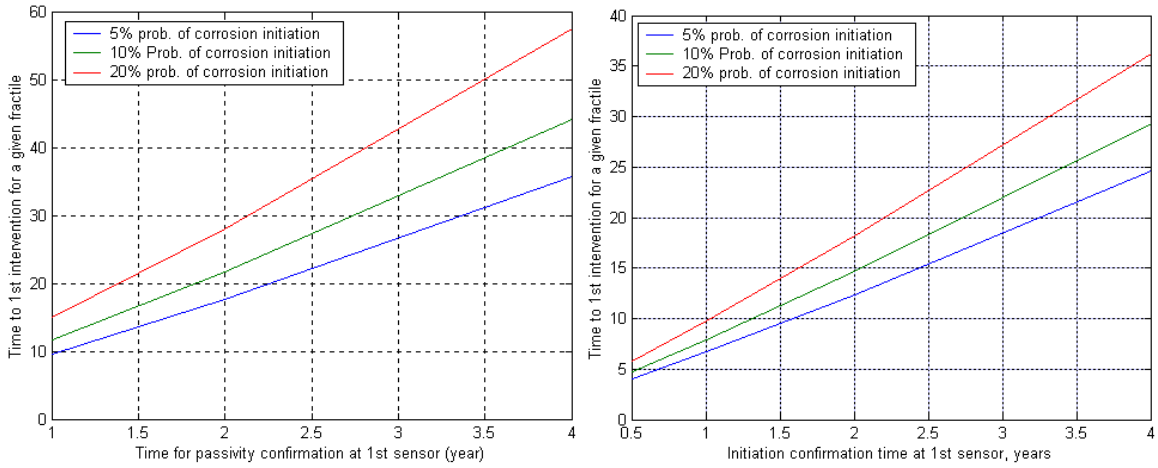


*Figure 6: Time to corrosion initiation (at rebar level) for different probability of corrosion initiation and initiation detection times (one sensor at 10mm depth)*

In order to establish the robustness of the methodology for different input models, sensitivity studies of different input parameters on the corrosion initiation times have been carried out. The results for the sensitivity study are presented in detail in Rafiq et al. [18].

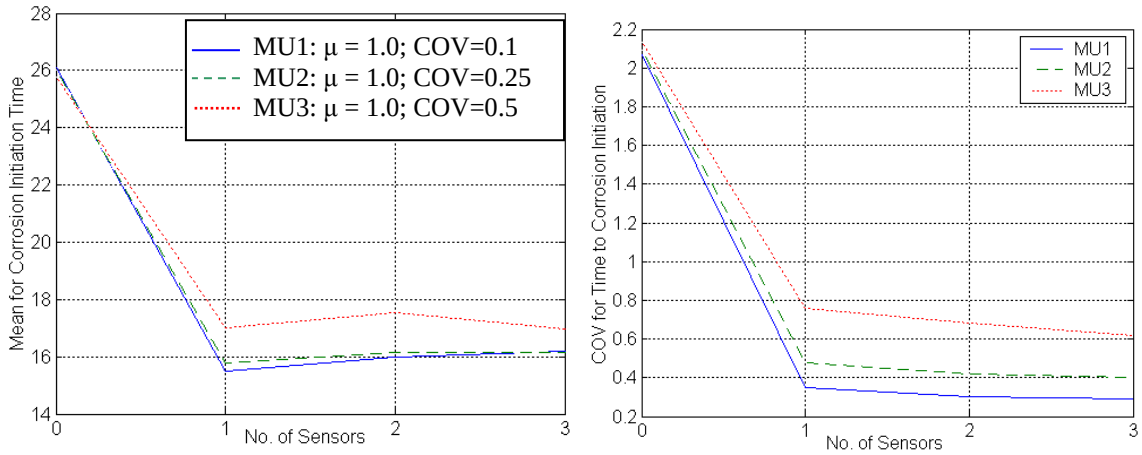


*Figure 7: Effect of number of sensors in reducing uncertainty for time to corrosion initiation.*

Two distinct types of behaviour have been identified. In both cases, the COV of the corrosion initiation time is reduced with the increase in the number of sensors, indicating increase in confidence. However, for the results shown in Fig. 7, which refer to different assumptions for the model uncertainty distribution, the posterior COV takes different values for various input models whereas for the results shown in Fig. 8, which refer to different assumptions regarding

exposure conditions, the posterior COV for various input models converges to a single value. It has also been concluded from this study that the posterior performance prediction is considerably less sensitive to variations in the input parameters.

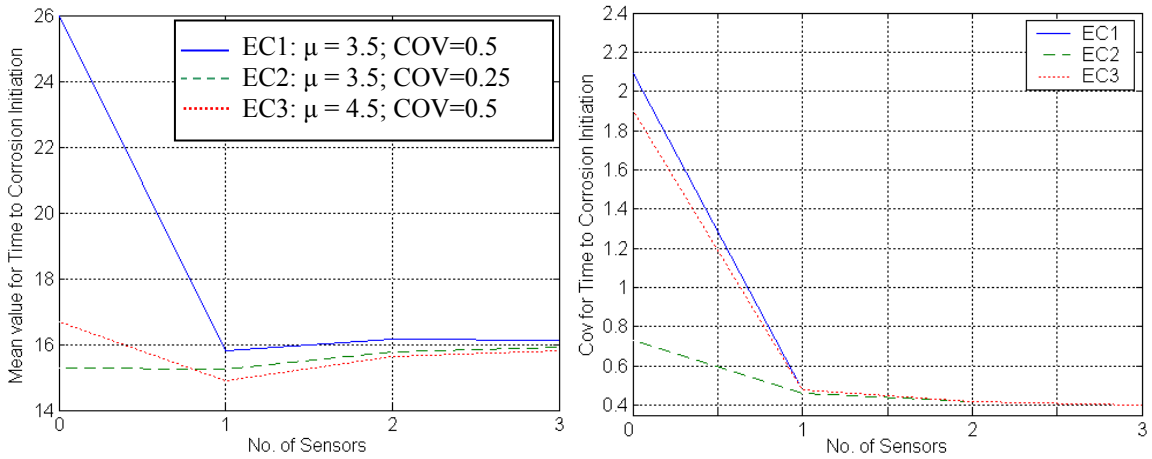


*Figure 8: Effects of no. of sensors on uncertainty associated with exposure conditions.*

***Conclusions***

Predicting future condition and reliability of the deteriorating structures is vital for their effective management. As the input parameters of the deterioration models developed to serve the purpose are uncertain, this limits the use of these models for long range predictions. On the other hand, state-of-the-art health monitoring systems have been developed to obtain structure specific information regarding deterioration characteristics and loading etc. The limitations of these instruments are that these provide information only at specific locations of the structures, and the uncertainty within the information gained. Combining the two can provide us with a powerful tool that can be used by bridge managers and owners to optimise the decisions regarding inspection and maintenance activities. A methodology based on Bayesian event updating framework is presented in this paper. The application of this methodology in the context of reinforced concrete structures prone to chloride induced deterioration is presented, and the gain in confidence in the performance prediction is quantified by comparing the coefficient of variations of the prior and posterior performance predictions. The result of the case study highlights the benefits that can be acquired through the introduction of 'smart' technology in managing bridges subject to deterioration. There are still many unanswered issues that, if addressed, would help assess the effectiveness of management activities, e.g. inspection, maintenance and repair, thus allowing an optimisation of available resources. For example, issues related to 'best' sensor locations, methods of dealing with the reliability of sensors, and of the information thus obtained, etc, are being developed and will be presented in the near future.

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