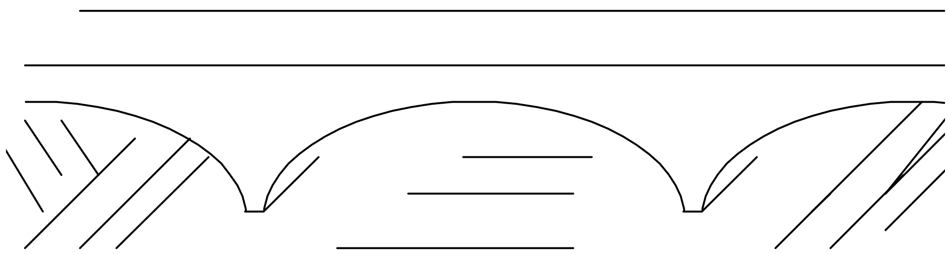
RISK ANALYSIS OF HYDROGEN INDUCED STRESS CORROSION CRACKING OF PRESTRESSED CONCRETE: IDENTIFICATION OF CRITICAL PARAMETERS



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ABSTRACT

The corrosion of the existing stock of reinforced concrete structures such as bridges and car park decks becomes more and more severe. This can be attributed to the prolonged exposure of these structures to a chloride-laden environment, i.e. marine structures or through the application of de-icing salts. Although carbonation of concrete also causes reinforcement corrosion, chloride is the most important factor. It penetrates the concrete cover and eventually reaches the reinforcement where corrosion starts once a critical threshold is exceeded. Corrosion is an electrochemical process and, thus, the most effective methods of rehabilitation are electrochemical in nature. These methods are cathodic protection, cathodic prevention or electrochemical chloride extraction. Additionally, the alkalinity of carbonated concrete can be restored using re-alkalisation.

Most of these structures contain prestressed elements such as slabs or beams and the application of electrochemical rehabilitation techniques to theses elements would lead to savings through the extension of the service life of these structures. Prestressed concrete contains high strength steel which is susceptible to hydrogen embrittlement that may cause the collapse of the entire structure. In this case, a special form of hydrogen embrittlement, hydrogen induced stress corrosion cracking (HISCC), occurred. Hydrogen is generated during electrochemical processes on the surface of the steel of the steel and, for this reason, the application rehabilitation techniques, such as electrochemical chloride extraction, have been ruled out. Hydrogen embrittlement can be regarded as insurmountable barrier which does not allow for the application of electrochemical rehabilitation or as a problem for which a solution can be found. The latter approach requires the identification of critical factors leading to the occurrence of HISCC and subsequent risk analysis. An economic and fast approach for risk analysis is numerical modelling.

This paper presents the results of a numerical investigation into the risk of HISCC of prestressed concrete due to the application of electrochemical chloride extraction. Fourteen parameters were incorporated into the numerical analysis and their contribution to HISCC was investigated. The numerical model (SIM_RISK) incorporated a continuous finite difference approximation for the diffusion of hydrogen into the steel and a Monte Carlo simulation for the stress in the steel. The hydrogen surface concentration was obtained from a finite difference approximation on ion migration in concrete (SIM_RISK). Critical parameters causing HISCC are identified and possible approaches to avoid its occurrence are discussed. The paper concludes that the application of electrochemical chloride extraction is unsuitable for prestressed concrete, but it suggests the use of cathodic protection as alternative long-term rehabilitation due to the low concentration of atomic hydrogen.

INTRODUCTION

When electrochemical rehabilitation methods such as ECE are applied to concrete structures, hydrogen is generated on the steel surface. It is known since 1864 (Bockris et al, 1998) that part of this hydrogen is incorporated into the steel matrix where it can cause damage and cause failure due to HISCC (Figure 1). One of the factors influencing stress corrosion cracking is stress and ECE has therefore not been applied to prestressed concrete where the steel is stressed to some degree. Moreover, it is widely believed that high strength steels are more susceptible to suffer hydrogen induced failure than ordinary reinforcement (Roberge, 2000).

Field data does not exist or is insufficient (Odden and Miller, 1994) and there are only two published laboratory studies on the phenomenon with contradictory results (Ashida and Ishibashi, 1993; Ihekwaba and Hope, 1998). The risk of a structure to suffer HISCC was simulated and critical factors were identified. Two problems have to be considered when stress corrosion cracking is simulated. First, the diffusion of hydrogen into the steel and second, the damage caused by hydrogen due to the condition of steel (loading, age, etc.). The diffusion process was simulated using a fully implicit central finite difference scheme and it is based on Fick's second law of diffusion.

The condition of the steel and its impact on structural performance during ECE contains an element of uncertainty and therefore the finite difference approximation was embedded into a Monte-Carlo simulation for probabilistic risk assessment.

RELIABILITY AND RISK ANALYSIS

Reliability can be defined as the probability of loss or injury to people and property due to the failure of systems. In 1940 Robert Lusser, a German mathematician, derived the product law of reliability for components in series, RE_s, where a series system is equal to the product of reliabilities of its components RE_n:

$$RE_s = \prod_{n=1}^{n} RE_n \qquad \text{(Equation 1)}$$

The reliability of structural components decreases with increasing age of the structure due to repetitive loading. Sometimes reliability is weighted with a factor to accommodate for the consequence of a risk (Shetty et al, 1997):

$$Risk = \mathrm{Pr}obability\ of\ \ failure \times Consequence\, of\ \ failure \qquad \text{(Equation 2)}$$

The reliability of a structural component will decrease with increasing age of the structure and the risk of failure will increase. The age of a structure is sometimes expressed not in years but through its load history. For structural design the load history is expressed in stress ranges from a stress spectrum and summarised using Miner's rule as follows:

$$\sum_{n=1}^{n} \frac{\overline{n}_n}{\overline{N}_n}, \qquad \text{(Equation 3)}$$

where $\overline{n}$ is the number of load cycles from a stress range n applied to the structure and $\overline{N}$ is the number of cycles of the stress range n to failure. Risk analysis in structural reliability models is a three-stage process. First, a preliminary hazard analysis is carried out where possible hazards, their extend and origin is identified. Then a sequence of hazards is put together in a fault tree and third, the consequences of the hazard are analysed (Andrews and Moss, 1993; Vose, 2000). In Monte-Carlo Analysis a statistical function is imposed on individual branches of the fault tree (Ross, 1997).

Fault trees used to assemble the different distributions in a Monte Carlo Analysis are heuristic and based on human judgement (Heneley and Kumamoto, 1991). The predictive qualities of Monte-Carlo analysis increases with increasing number of tests, not only in terms of Monte-Carlo cycles, but also for the amount of different statistical distributions imposed on the system. The model will only repeat the distribution and not give new knowledge if only one statistical distribution is used throughout the system (Nelson, 1995).

AIM OF THE RESEARCH

Aim of the risk assessment was to identify the critical parameters leading to HISCC in prestressed concrete and facilitate the investigation of a broad spectrum of parameters. The risk analysis constitutes a more sophisticated approach to the phenomenon of HE and HISCC of prestressed concrete compared to that of a "go/no-go" answer which had been employed previously (Ihekwaba and Hope, 1998; Isecke, 1993).

The program was based on the input of twenty variables and a parametric study of the risk of prestressed steel to suffer HISCC was conducted. The effects of individual parameters were revealed by first running a base case and then changing each parameter from the base case. The following questions were investigated:

- Do the amount of tendons and their properties give a degree of redundancy against HISCC?
- Do the initial strength and the initial load on the tendon influence HISCC?
- Does the age of the structure, in relation to its service life, influence the susceptibility of HISCC?
- What is the impact of different kinds of corrosion and the time passed since corrosion initiation on HISCC? Do exposure and concrete quality play a role?
- How does the hydrogen surface concentration influence the HISCC susceptibility?
- How does the speed of hydrogen diffusion into steel influence HISCC? Do stresses in the steel influence HISCC?
- Do treatment parameters of electrochemical chloride extraction influence HISCC?

Typical arrangements of tendons in prestressed and post-tensioned concrete are depicted in Figure 2. A parametric study was conducted to identify and weight the impact of different parameters on system performance. The base case of parameters and their variation for the study are shown in Table 1. It became obvious during the simulation that the amount of tendons did not significantly alter the system performance; therefore the simulation was carried out for a set of 10 tendons thereby keeping the computational work to a minimum.

MODEL ASSUMPTIONS

Aim of the model was to investigate the risk of hydrogen induced failure of a bridge beam during ECE. The critical failure mode was assumed to be hydrogen induced stress corrosion cracking. The beam model was kept simple with the tendons of the structure considered to be in a parallel system. The initial load ratio, the design and service life, and the deterioration of steel due to ageing were treated as random variables and wherever possible, probabilistic elements of the model were replaced with deterministic elements.

The load in a structural element, such as a prestressed concrete beam, is distributed over several tendons. Therefore, a degree of redundancy against failure may be given by the amount of tendons and failure of one tendon will not necessarily cause the failure of the entire structural element. The position of the tendon, leading to different kind of stresses in case of failure of adjacent tendons, is neglected. An equal distribution of load between the tendons is assumed and load on an individual tendon is distributed equally amongst other tendons when failure occurs.

Prestressed steel in concrete is stressed to initially between 70% and 80% of its proof strength. The stress in the steel is reduced to a lower value by short term elastic shortening of the steel and long term losses such as concrete creep (Hurst, 1998). Engineering calculations of the remaining prestressing force contain a degree uncertainty of approximately $\pm$ 5%. Therefore, only the mean of the initial load ratio is specified and subsequently was varied by $\pm$ 5% for each Monte-Carlo-repetition.

Bridge structures containing prestressed steel are usually designed for a service live of 120 years (BS 5400 Part 10, 1990). This design process is based on fatigue data of steels (s/n – curves). The cycles of different stress ranges are added using Miner's rule to obtain the design values for bridge elements (BS 5400 Part 10, 1990). The fatigue process consists of crystal deformation, formation of a crack and opening of a crack leading to failure (Almen and Black, 1963). Crystal deformation results in a reduced strength of the steel (Bockris and Reddy, 1998), which determines the load ratio on the tendon. It is assumed that a structure will not collapse after the service life has elapsed and the second stage of the fatigue life will not be reached throughout the service life. The strength of the steel was randomly reduced with increasing age of the structure thereby increasing the load ratio.

Service life and design life are used interchangeably throughout this thesis although BS 5400 Part 10 (1990) specifies the service life of bridge structures to be 120 years. The design life depends on design and its practical implementation and it tends to be higher than the service life. Therefore, Wagner (1985) treated design life as random variable and this approach was adopted in this study.

The speed of corrosion in concrete depends on the exposure condition and the quality of the surrounding concrete and Roefstra (2001) derived a corrosion speed matrix, where the propagation of the corrosion front is given for pitting corrosion and for general corrosion. The loss of load bearing diameter was determined using this corrosion speed matrix and the time of corrosion initiation was specified separately for general and pitting corrosion. The effect of general corrosion is twofold: first, to reduce the load bearing cross section uniformly around the reinforcement bar (Roelfstra, 2001) and second, to decrease the hydrogen diffusion coefficient (Lillard and Scully, 1996). Pitting corrosion is faster than general corrosion, but the pit occurs only from one side and its corrosion products are different compared to that of general corrosion and do not reduce hydrogen uptake.

Hydrogen uptake of steel is stress related and stressed steel incorporates larger amounts of hydrogen compared to unstressed steel (Bockris et al, 1998). Stress related diffusion models have been developed in the past (Yokobori et al, 1996). Under a certain stress threshold level or stress intensity factor, no failure occurs (Toribio, 1998), although cracks develop in the steel (Parkins, 2000). It was assumed that a crack develops when a certain hydrogen concentration was exceeded thereby reducing the load bearing cross section and increasing the stress on the tendon. This threshold varies largely for different types of steel and it can be as low as 1 ppm (Cottis, 1994).

The maximum stress range is 20 N/mm^2 for fully prestressed elements where the concrete is never tensioned. Allowable stress ranges for other structural elements are specified in BS 5400 Part 10 (1990), but do not exceed 73 N/mm^2. Therefore, the load ratio was kept constant during the simulation, assuming only marginal changes due to traffic, which were neglected. Alternatively, the load would have to be varied every time step thus leading to a very complex and computationally intensive program with no clear benefit over the constant load model.

Hydrogen can penetrate the steel only in its atomic form H^+ (Ihekwaba and Hope, 1998) and the recombination atomic hydrogen to molecular hydrogen H_2 takes place rapidly so that only a very small fraction of atomic hydrogen enters the steel matrix. The hydrogen concentration is taken from the ECE model (SIM_ECE) according to the hydrogen evolution reaction in alkaline environments (Bockris et al, 1998):

$$H_2O \xrightarrow{e^-} H^+ + OH^- , \qquad \text{(Equation 4)}$$

where the production of one unit of hydroxide equals the generation one unit of hydrogen.

Certain substances such as cyanides and sulphides (Rehm et al, 1981) are known to poison the recombination reaction of hydrogen and their presence significantly increases hydrogen uptake into the steel matrix and the associated risk of brittle fracture (Mietz and Isecke, 1995). These substances, also known as promoters, carry a negative charge and are hence carried away from vicinity of the negatively charged steel in a short period of time during ECE. The surface hydrogen concentration was adjusted to a lower value than given by the finite difference approximation (SIM_ECE) to accommodate for the recombination and, if promoters were present, increased again to the maximum concentration obtained from SIM_ECE. The effect of negatively charged promoters, i.e. the full uptake of the surface hydrogen as generated by SIM_ECE, is reduced when its concentration decreases due to electrochemical chloride extraction. The fault tree of HISCC of prestressed concrete is shown in Figure 3. Safe treatment is possible for the condition “no failure” and might be acceptable for the condition “partial failure” or “collapse with prior warning”.

MODEL FORMULATION

The hydrogen concentration, C_H, was obtained from Fick's 2nd law of diffusion as follows:

$$\frac{\partial C_H}{\partial t} = D_H \frac{\partial^2 C_H}{\partial x^2} , \qquad \text{(Equation 5)}$$

where D_H is the hydrogen diffusion coefficient in steel. At the boundary, the hydrogen concentration, C_{Hb}, was given (Dirichlet boundary condition) as follows:

$$C_{Hb} = \nu \overline{C}_{Hb} , \qquad \text{(Equation 6)}$$

where $\overline{C}_{Hb}$ is the hydrogen concentration at the steel surface from the electrochemical chloride extraction (SIM_ECE) and ν is a reduction factor to account for the recombination of hydrogen ($0 \leq \nu \leq 1$). The maximum hydrogen concentration, C_{Hmax}, is stress dependent and can be calculated as:

$$C_{H\max} = C_{H0} e^{\frac{\sigma_H \overline{V_H}}{R_G T}} , \qquad \text{(Equation 7)}$$

where C_{H0} is the hydrogen concentration at stress σ_H = 0, T is the absolute temperature, R_G the gas constant and V_H is a stress factor with a value of 2.6 cm^2/mol (Bockris and Reddy, 1998). The critical amount of hydrogen, H_{crit} (parts), when crack propagation occurs in each layer d is calculated from the threshold concentration C_{Hthres} (ppm)

$$H_{crit,d} = C_{Hthres} N_A \frac{V_d \delta_{Fe}}{M_{Fe}} , \qquad \text{(Equation 8)}$$

where N_A is Avogadro's' number, δ_{Fe} the density of iron, M_{Fe} the molar mass of iron and V_d the volume of each finite layer d. The maximum amount of hydrogen, $H_{max,d}$ that the steel can incorporate into each layer is obtained as follows:

$$H_{\max,d} = C_{H\max} V_d N_A \qquad \text{(Equation 9)}$$

And similarly, the amount of hydrogen in each layer, $H_{H,d}$, from the finite difference approximation is:

$$H_{H,d} = C_H V_d N_A \qquad \text{(Equation 10)}$$

The upper bound for the amount of hydrogen that can be incorporated into the steel matrix depends on the stress in the slice, therefore:

$$H_{\max,d} \geq H_{H,d} \qquad \text{(Equation 11)}$$

The amount of hydrogen in the layer is corrected as follows, if the condition in equation 8 is not satisfied:

$$H_{H,d} = H_{\max,d} \qquad \text{(Equation 12)}$$

From condition shown in equation 9 it follows that the concentration of hydrogen in the layer, $C_{H,d}$, has to be corrected as follows:

$$C_{H,d} = \frac{H_{\max,d}}{V_d N_A} \qquad \text{(Equation 13)}$$

Finally, crack propagation occurs if:

$$H_{crit,d} \leq H_{H,d} \leq H_{\max,d} \qquad \text{(Equation 14)}$$

General corrosion does not only reduce the load bearing area of the steel, but also hinders the diffusion of hydrogen, therefore the hydrogen diffusion coefficient, DH, is reduced in the layer, d, where general corrosion stops as follows:

$$D_{H,d} = \nu D_{H,d} \quad (\nu = 0.1) \qquad \text{(Equation 15)}$$

The corrosion products of pitting corrosion are different from the corrosion products of general corrosion and do not hinder hydrogen uptake and, therefore, the hydrogen diffusion coefficient does not change. However, cracks formed due to any form of corrosion allow the hydrogen from the surface to enter the steel and advance unhindered to the crack tip. Therefore, the hydrogen concentration in the crack tip is equal to the surface hydrogen concentration and was obtained from a finite difference approximation on ion migration. The geometric properties of a prestressed bar undergoing cracking are depicted in Figure 4.

COMPUTATIONAL IMPLEMENTATION

The code of SIM_RISK was written in JAVA 1.3.1. The resulting trigonal matrix equation from equation 5 was solved using the DoubleMatrix.multiply([B][b]) and DoubleMatrix.solve([A][c]) classes by Visual Numerics™. Random numbers were generated using the Java random number generator which gives uniformly distributed numbers between 0 and 1. The time steps of the model had to be consistent with the time steps used in SIM_ECE, because this program gave the hydrogen surface concentration for each time interval. Therefore, the finite difference scheme was made fully implicit. The simulation was carried out 200 times for each set of parameters and required between 2 minutes and 4 hours on a PC with a Intel PIII processor with 450 MHz dependent on the amount of survivors and the time to failure.

RESULTS AND DISSCUSSION

To facilitate optimum use of computational resources each set of parameters was computed 200 times. This was possible because most of the HISCC failures occurred initially, followed by an almost failure free performance. Therefore, the risk of HISCC is governed by an extreme value distribution. Comparative studies using common random numbers CRN to achieve faster convergence (Nelson, 1995) showed good agreement between single random and common random number approach. Moreover, a check of extreme values by replacing each random number generator by either 0 or 1 did not yield different results compared to those of the random number generator.

With increasing number of Monte-Carlo Cycles, the total number of failures decreased and when the simulation was repeated 10 000 times the probability of HISCC failure dropped below 1%. However, the public accepts risks only if the probability of occurrence is below 10^{-6} % (Henley and Kumamoto, 1991) and it would take approximately 4 months to accomplish one simulation with 10^{6} on a PIII processor. Regardless of the true extent of HISCC failure indicated by the model, the author weights human life infinitely greater than limited economic benefits. Therefore, the HISCC failure is weighted according to equation 2 with a factor in the order of ∞ and the risk of no failure as insignificant with the “consequence of failure” being equal to 0. For this reason further analysis is concerned with the probability of HISCC failure only and the influence of parameters on changes of this probability.

Sensitivity Analysis of Parameters influencing HISCC Failure Probability

The sensitivity analysis was focused on the relative change of HISCC failure through the variation of model parameters. The influence of 14 parameters and that of corrosion on the susceptibility of prestressed concrete was investigated. The results of the sensitivity analysis are displayed in Figure 5. The three most important parameters with first order effects on HISCC failure probability were the diffusion coefficient, the load ratio and the hydrogen uptake ratio.

Second order effects occurred due to pitting and general corrosion at progressive stage, which led to increasing number of failures, but these failures occurred as consequence of overloading due to corrosion induced reduced load bearing area and not due to hydrogen uptake of the steel.

The model was less sensitive with regard to the presence of promoters and only marginally sensitive to other parameters, age of the structure and strength of the steel being amongst these. This appeared surprising as one of the most commonly repeated arguments against ECE on high strength steels is that the high strength of the steels would lead to increased risk of HISCC failure (Roberge, 2000). The simulation suggests that the susceptibility of steel to HISCC failure is better expressed in terms of other parameters than its strength. The load ratio (non dimensional form of stress) is the most important factor.

First Order Effects of Parameters on the Probability of HISCC Failure

Three parameters showed first order effects in the sensitivity analysis. These were the hydrogen diffusion coefficient, the load ratio (non-dimensional form of stress) and the hydrogen uptake ratio into the steel. The influence of the hydrogen uptake ratio is depicted in Figure 6. The maximum hydrogen surface concentration for an uptake ratio of 1.0 is not reached in practice, because of the fast recombination of atomic hydrogen to molecular hydrogen. Another reason for reduced atomic hydrogen concentration on the steel surface is the presence of oxygen that will react with atomic hydrogen to water or hydroxide. The model suggests a significant reduction of HISCC failures if the hydrogen surface concentration is reduced by a factor of the order of 10^{-5}. Two strategies could be pursued to achieve this:

- Application of Inhibitors
- Enrichment of electrolyte with oxygen.

Inhibitors will reduce the contact time of hydrogen with the steel surface. The atomic hydrogen (H^+) will have recombined to molecular hydrogen (H_2) before it reaches the vicinity of the steel. Molecular hydrogen, in contrast to atomic hydrogen, does not penetrate the steel and does, therefore, not constitute a risk to HISCC failure. The second strategy is the enrichment of the electrolyte with oxygen to stimulate the reaction of atomic hydrogen to water or hydroxide. However, this process will only work if the diffusion of oxygen through saturated concrete is sufficiently fast to reduce the oxygen that is consumed at the cathode. The oxygen consumption in turn depends on the applied current. The application of ECE, being a short-term treatment, is based on high applied currents, therefore, oxygen will be used up after a short period of time (Mietz, 1998) and the oxygen enrichment strategy may not be suitable for the application with ECE.

The sensitivity of the model to applied current density was low and a current density of the order of $10mA/m^2$, which is similar to the current density employed for CP, did not change the susceptibility of the structure to suffer from HISCC failure. This can be explained by the fact that hydrogen uptake ratio and current density were not coupled in the model, because no relationship is known for the rate of this reaction. Therefore, the susceptibility of steels to suffer HISCC does not depend on ECE treatment parameters.

The presence of oxygen has never been considered in the past (Isecke and Mietz, 1993) despite its importance for the occurrence of HISCC failure. The reaction of oxygen with atomic hydrogen has been excluded by using de-aerated solutions in order to achieve experimental success, i.e. HISCC failure. In doing so, however, a worst-case scenario has been created, which does not necessarily represent processes in concrete. Cathodic protection is a long-term treatment with low currents being applied to the structure, for this reason, the oxygen consumption at the cathode is low compared to that of ECE. Moreover, the application of CP is carried out without having a permanent electrolyte reservoir allowing the concrete to undergo wetting and drying cycles. The diffusion of oxygen into concrete is therefore much faster compared to permanently water saturated concrete, such as during ECE. The long-term effects of CP are currently being investigated at the University of Ulster, using parts of a 30-year old prestressed concrete structure. The influence of load ratio, the non-dimensional form of stress, on the probability of HISCC failure is depicted in Figure 7. The model suggests that only without stress (load ratio = 0) the probability of HISCC failure is reduced to 0. The probability of HISCC failure is higher than that of failure free treatment at stresses above 17%. Townsend (1972) reported on a stress intensity factor of the order of 15%.

The critical threshold stress below which a certain type of failure will not occur is well established in corrosion engineering (Roberge, 2000). HISCC failure is a form of stress corrosion cracking and belongs to this type of failures and total failure will not occur below a critical stress although cracks develop (Parkins, 2000). This phenomenon has been observed during ECE experiments (Figure 8), although the stress of the tendon was at least 60% of its proof strength (and 90% in an additional study) HISCC did not occur. The findings are supported by ECE experiments of Ashida and Ishibashi (1993) where no failure was reported under similar conditions. These authors however attributed the absence of HISCC failure to the stress of the steel being too low for the initiation of stress corrosion. Indeed, the critical threshold stress may vary within wide margins and depend on the material. Material properties of steel may change over time due to ageing (Bockris and Reddy, 1998). Therefore, different probabilities of HISCC failure exist not only for each type of steel, but also for different locations at the structure where load history and subsequent load ratio may have been more severe.

The application of ECE is unsafe in combination with stress and the individual threshold stresses may vary within wide margins. The risk of HISCC can only be ruled out when the steel is untensioned. However, this cannot be achieved for prestressed or post-tensioned structures with grouted ducts as the tendons are embedded in the concrete/mortar and stresses cannot be reduced. The hydrogen diffusion coefficient, D_H, determines the speed of hydrogen permeation and this influences the probability of HISCC failure. The model suggests a significant reduction of HISCC failure for $D_H < 10^{-9}$ cm^2/s and the probability is equal to 0% if $D_H < 10^{-10}$ cm^2/s (Figure 9). The diffusion coefficient of hydrogen, however, is a material constant and of the order of 10^{-7} cm^2/s and, therefore, it has no practical influence on the reduction of HISCC failure.

Parameters with Second Order Effects on the Probability of HISCC Failure

Three parameters with second order effects were identified in the sensitivity analysis. These were general and pitting corrosion and the presence of promoters with regard to the change of magnitude of hydrogen uptake. Corrosion progression was simulated as function of the concrete cover quality and the exposure condition (Roelfstra, 2001). It was assumed that general corrosion would uniformly reduce the load bearing cross section of the steel and mitigate the hydrogen uptake. Pitting corrosion, in contrast, propagates much faster than general corrosion, but the cross-section is only reduced from one side. Moreover, the corrosion products (magnetite) would not reduce the hydrogen uptake through reduced diffusion coefficient.

The reduced hydrogen uptake of general corrosion, however, was important for progressive states of corrosion with increased film thickness. The steel would have failed under severe exposure conditions where for similar times of corrosion under less severe conditions a reduction of hydrogen uptake is achieved. Consequently, pitting corrosion led to a speed up of failure under severe exposure conditions and the structure failed due to corrosion after 16 years compared to 30 years of general corrosion for the same exposure condition. Moreover, pitting corrosion did not reduce the hydrogen uptake and had no beneficial effect at early stages.

Pitting corrosion occurs in chloride contaminated concrete (Raupach, 1996). The role of chloride induced corrosion on structural integrity of prestressed and post-tensioned bridges built in the 1950ies has been investigated by Göhler (1990). This author found only a 25% reduction in load carrying capacity of structures that had undergone some years of corrosion. Individual tendons had not failed although this would have to be expected from the findings of Roelfstra (2001). For this reason the model gives a conservative estimate of the effects of corrosion and the structural integrity may not suffer as much as suggested by the model. To avoid anodic dissolution through stray currents during ECE (Roberge, 2000) each individual wire and any other metal in the structure has to be connected to the impressed current system. Hence, it is not possible to treat wires separately and reduce thereby the risk of total failure of the structural element. It was therefore assumed that the hydrogen generation would take place at a similar rate on the individual steel surfaces.

The influence the treatment of several tendons on the degree of redundancy against HISCC failure is shown in Figure 10. Most structural elements contain between 10^1 – 10^2 individual wires (Figure 2), but the probability of HISCC failure is not reduced significantly for such a number of individual tendons. The treatment of structures consisting of many separate tendons is therefore not safer than of structures containing only a few prestressed bars.

Whilst the presence of promoters had a second order effect on the probability of HISCC failure, the exposure duration to promoters was of marginal importance only. Promoters are substances that poison the hydrogen recombination reaction and therefore increase the concentration of atomic hydrogen on the steel surface. Promoters are often negatively charged and for this reason migrate away from the cathode during ECE within a short period of time. SIM_ECE suggest that negatively charged ions are removed from the immediate vicinity of steel after already 60 hours of ECE treatment. However, the risk simulation suggested that 60 hours are sufficient time for HISCC failure to occur. Therefore, ECE should not be applied when the concrete contains promoters. Moreover, it should be investigated if the presence of a promoter, such as sulphate, will cause HISCC failure in mild steel reinforcement. Although the hydrogen uptake in untensioned steel and the hydrogen threshold concentration above which failure occurred were varied within wide margins (Table 1) they were only marginally important to the probability of HISCC failure. It can be assumed that the recombination of hydrogen is responsible for a major part of the reduction of the atomic hydrogen concentration. HISCC failure would otherwise have quickly occurred in experimental studies in de-aerated solutions, in particular as the critical hydrogen threshold has been reported to be of the order of 10^1 ppm (Cottis, 1994) and, therefore, would be exceeded almost immediately upon start of ECE treatment.

Although the mechanisms are still subject of the scientific research, it is known that ageing of steel causes degradation of strength (Bockris and Reddy, 1998) and a subsequent increase of load ratio. The model suggests that the probability of HISCC is reduced with increasing age of the structure. A more rigorous model would be necessary to investigate this phenomenon. The reaction speed increases with increasing temperature and the reactions at the cathode leading to increased hydrogen concentration take place faster at higher temperatures. Therefore, with increasing temperature the probability of HISCC failure increases marginally.

Influence of Parameters on Time to HISCC Failure

All HISCC failures occurred either below 280 hours or not at all, but with the variations of diameter, hydrogen diffusion coefficient and hydrogen uptake ratio the time of occurrence of HISCC failure changed. The time to failure increased with the increasing diameter of individual wires. However, wire thickness in excess of 3.0 cm is unusual for prestressed concrete applications, where strands consisting of several thin wires (0.3 – 0.9 cm) are the most commonly used material (Hurst, 1998, Wagner et al, 1993). With shorter ECE treatment duration the sensitivity of HISCC failure to wire thickness is increased, but even for short treatment duration (under 100 hours) a fraction of the 3cm bars suffered HISCC failure. The application of ECE is, therefore, not safe for short or intermitted ECE treatment. In contrast, intermitted treatment is used during cathodic protection on prestressed concrete to avoid HE (Doniguian et al, 1998). The hydrogen diffusion coefficient, D_H, determines the speed of diffusion and the saturation point after which failure occurs and HISCC failure did not occur for $D_H<10^{-10}$ cm^2/s. The diffusion coefficient of hydrogen in steel is of the order of 10^{-7} cm^2/s and a material constant. Therefore, HISCC failure may occur in steel.

The findings on hydrogen permeation described in Section 8.1 suggested that the hydrogen permeation increases during ECE and reaches steady state after approximately 1600 hours, whereas SIM_ECE suggests steady state after only 60 hours. Uncorrected hydrogen surface concentration (ν = 1.0), however, causes failure after only 11. This effect was not observed during the experimental study and the hydrogen surface concentration is therefore less than suggested by the Nernst-Plank migration model. As already discussed, the application of inhibitors was considered to reduce the hydrogen uptake ratio. Although inhibitors reduced the hydrogen uptake in artificial concrete pore solution, the concrete acted as barrier preventing migration of the inhibitors to the steel. The results of this experimental investigation were published elsewhere (Siegwart, 2002).

CONCLUSIONS

The risk of hydrogen induced stress corrosion cracking was investigated using a finite difference approximation combined with Monte-Carlo analysis. From the study the following conclusion can be drawn:

1. The probability of total collapse of a structural member due to HISCC failure is below 1% when it is treated with ECE.
2. In a sensitivity analysis the most critical parameters with first order effects on the HISCC failure phenomenon were as follows:
   - Load ratio (dimensionless form of stress)
   - Hydrogen diffusion coefficient
   - Hydrogen surface concentration (uptake ratio)
3. The probability of HISCC failure was zero when the load ratio was zero i.e. the steel was untensioned or compressed. In a structural member containing prestressed or grouted post-tensioned steel the load ratio cannot be reduced, as the stresses in the steel are distributed throughout the length of the structure through the concrete. Therefore, these structures are at risk to suffer HISCC failure when ECE treatment is conducted.
4. The probability of HISCC failure increased significantly at a load ratio of 17%, which is in agreement with previous research. In contrast, HISCC failure did not occur in experiments where the steel was at a load ratio of 60% and above. The critical load ratio is therefore subject to variation within wide margins and HISCC failure can only be excluded for untensioned steel.
5. The Probability of HISCC failure was equal to zero percent for a diffusion coefficient below 10^{-10} cm^2/s. However, the diffusion coefficient of hydrogen is a material constant and in the order of 10^{-7} cm^2/s and for this reason steel is susceptible to HISCC failure.
6. The sensitivity analysis revealed parameters with secondary order effects on the risk of HISCC. These were:
   - General corrosion
   - Pitting corrosion
   - Presence of promoters (magnitude of hydrogen concentration)

7. General corrosion reduces the risk of HISCC at an early stage of progress, but under severe exposure conditions and insufficient concrete cover quality the probability of stress corrosion cracking is equal to 100%. To reach this probability the period of exposure was equal to 16 years for pitting corrosion and 30 years for general corrosion.
8. Promoters increase the hydrogen uptake ratio, i.e. the hydrogen surface concentration through change of the hydrogen recombination. The magnitude of change in concentration had a more severe impact that the duration of the promoter exposure. Therefore, HISCC failure is a critical issue if concrete contains promoters, such as sulphates or thiocyanate at reinforcement level. It will occur in the first hours of ECE treatment before the concentration of promoters is reduced and, therefore, ECE treatment should not be applied.

The hydrogen surface concentration is crucial to the probability of HISCC failure. This concentration is influenced mainly by the speed of recombination of atomic hydrogen and it is further reduced by the presence of oxygen at the cathode. Recombination and reaction with oxygen have been simplified in the model using the uptake ratio (ν) described in Section 4.3. It is therefore recommended that further investigations are necessary into the influence of oxygen in the electrolyte to examine the probability of HISCC failure model and to corroborate the work from experimental investigations.

From experimental observations it was concluded that hydrogen recombination accounts for the major reduction in atomic hydrogen. The presence of promoters is, for this reason, very dangerous and ECE treatment should not be conducted when these substances are present in concrete. The author recommends investigating the impact of promoters on the probability of HISCC failure of ordinary reinforcement and, if necessary, the prohibition of the application of ECE treatment on concrete with mild steel reinforcement containing any promoters.

Recommended alternative strategies are investigated to avoid HISCC failure and mitigate the effects of corrosion. The application of cathodic protection could provide a safe alternative to ECE, because the rate of oxygen reaction is lower the concentration of atomic hydrogen might be sufficiently reduced to exclude HISCC failure. Cathodic prevention is not a rehabilitation technique, but a lifelong measure against corrosion; it is applied from the start of the service life. The current densities are ten times lower than that of cathodic protection and allow for oxygen to diffuse to the cathode in sufficient quantities to keep the hydrogen uptake into the steel low and it could be applied on prestressed concrete structures in chloride-laden environments.

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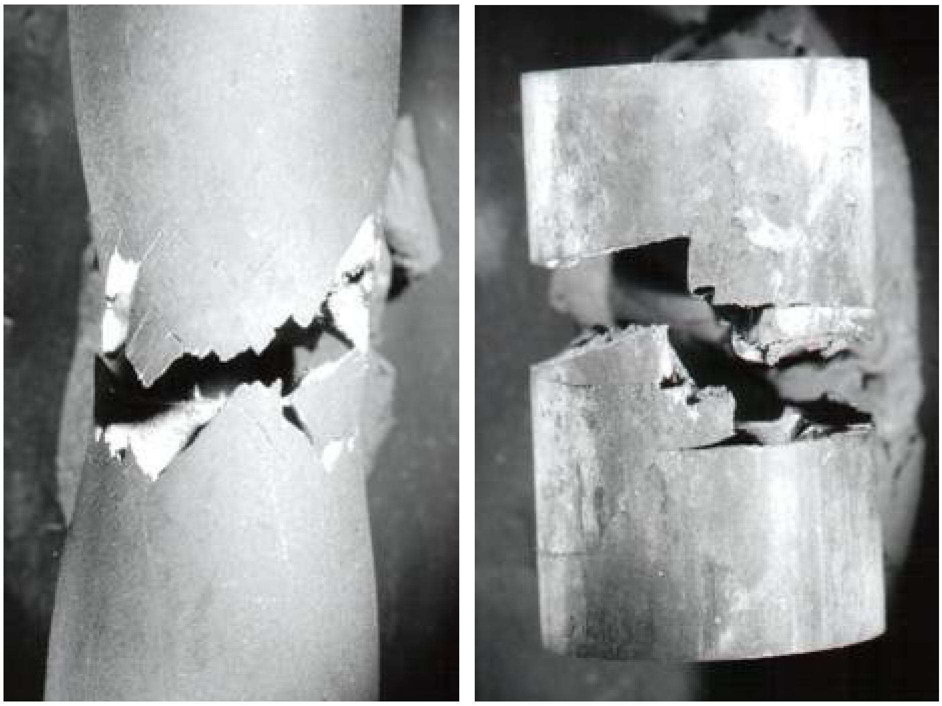

Figure 1 *Left: Rupture (ductile fracture) Right: Stress Corrosion Cracking (Hydrogen induced)*

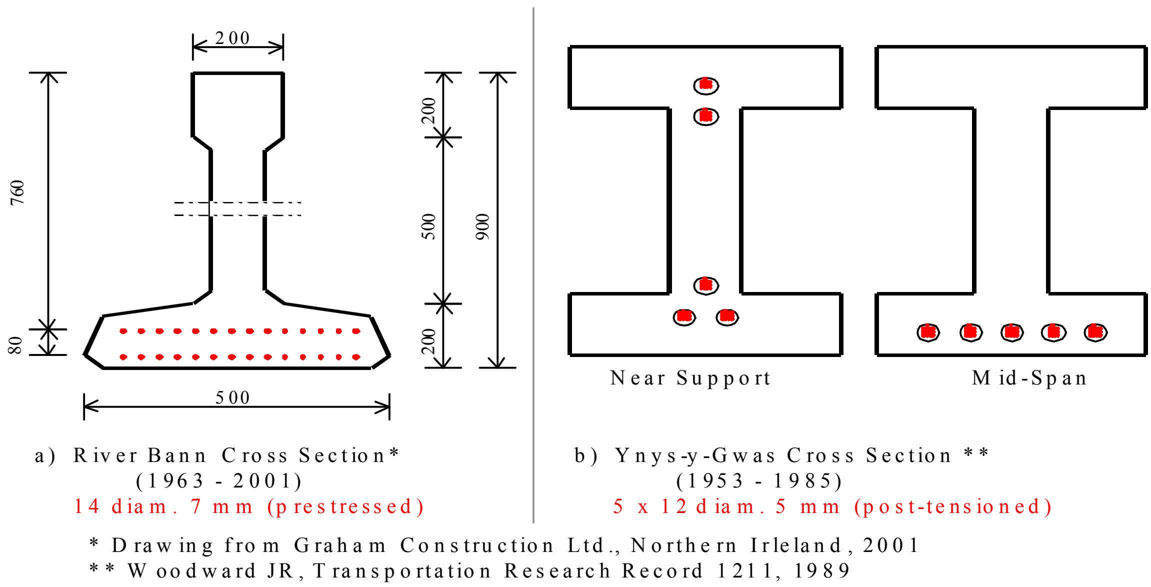

Figure 2 *Configuration of Strands in Prestressed/Post-tensioned Concrete Beams*

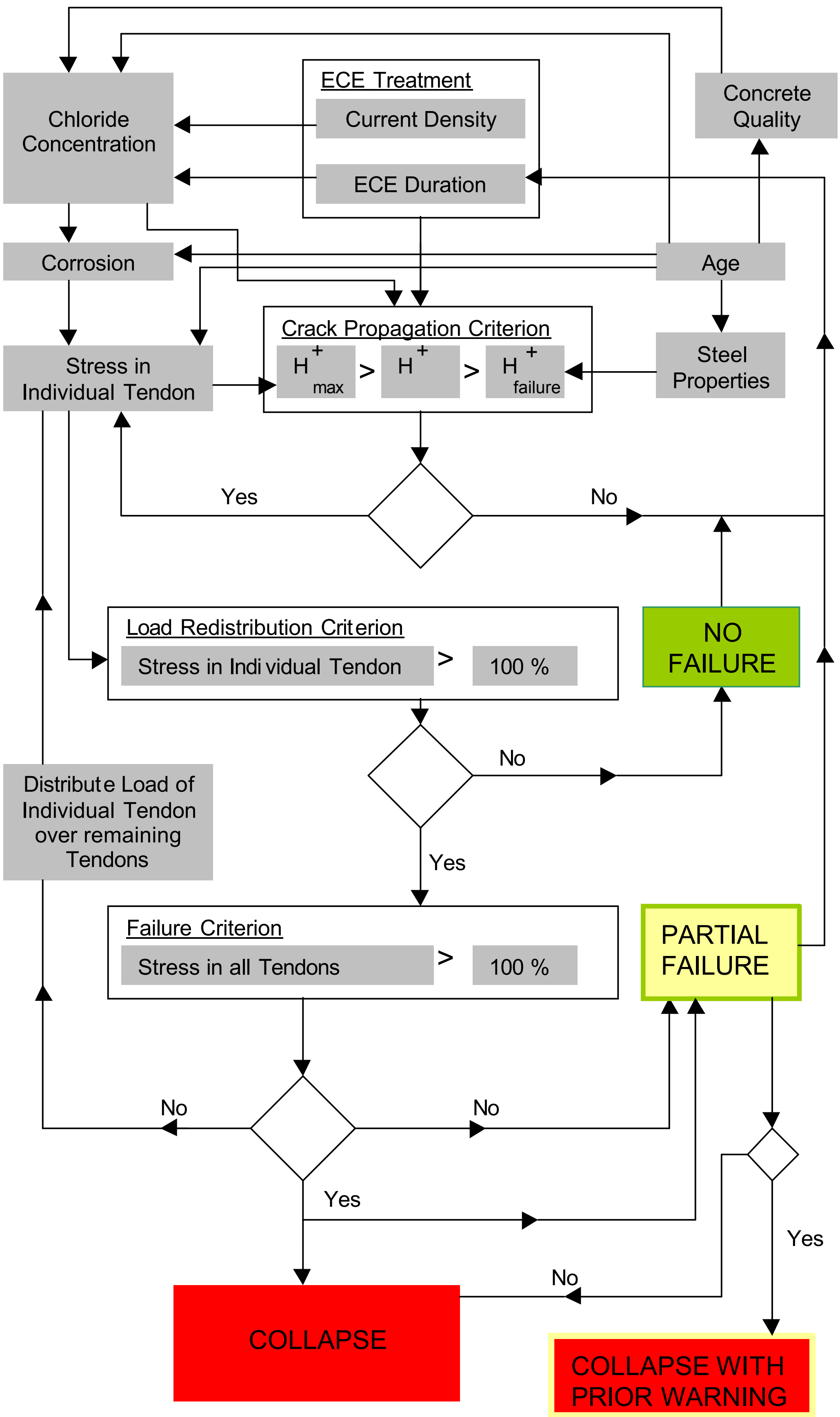

Figure 3 *Fault tree analysis of parameters leading to crack propagation and HISCC failure*

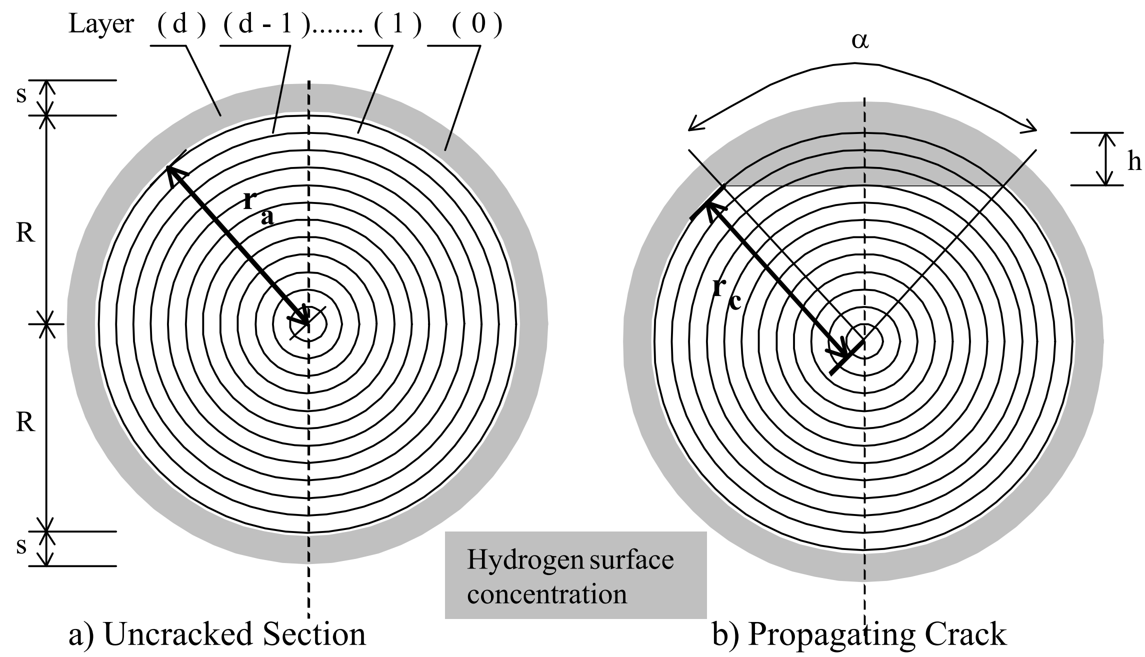

Figure 4 *Geometry of Prestressed Bar with Crack Propagation*

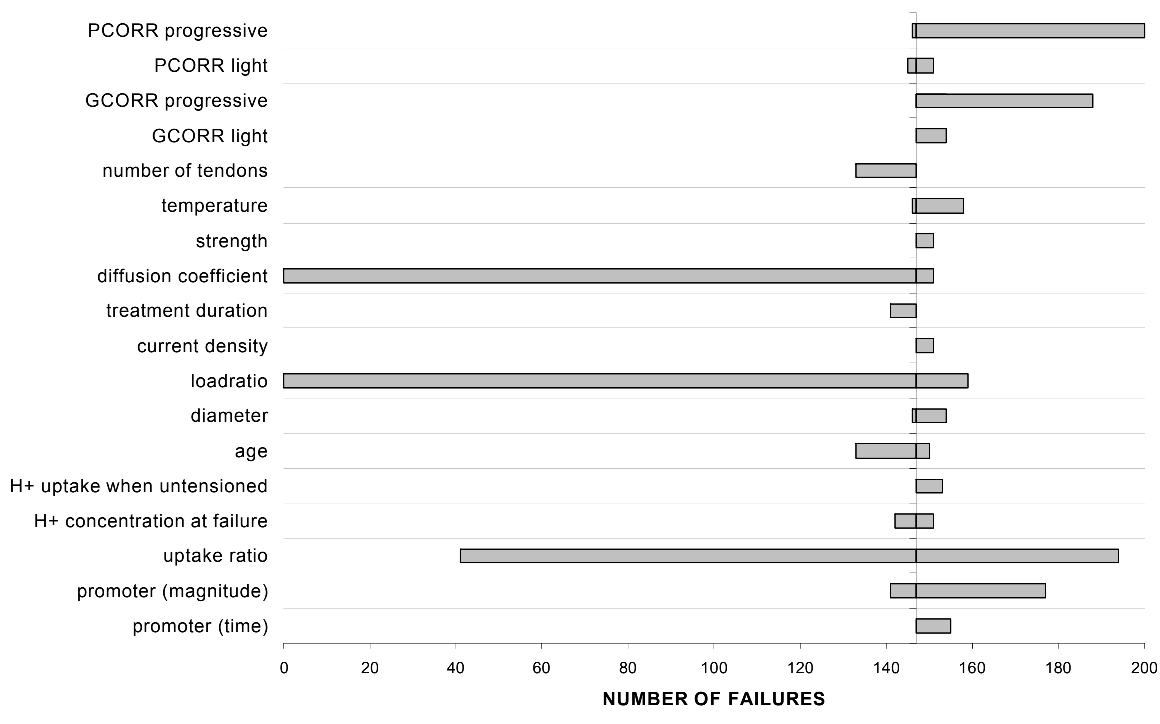

Figure 5 *Sensitivity of HISCC-Failure to Different Parameters*

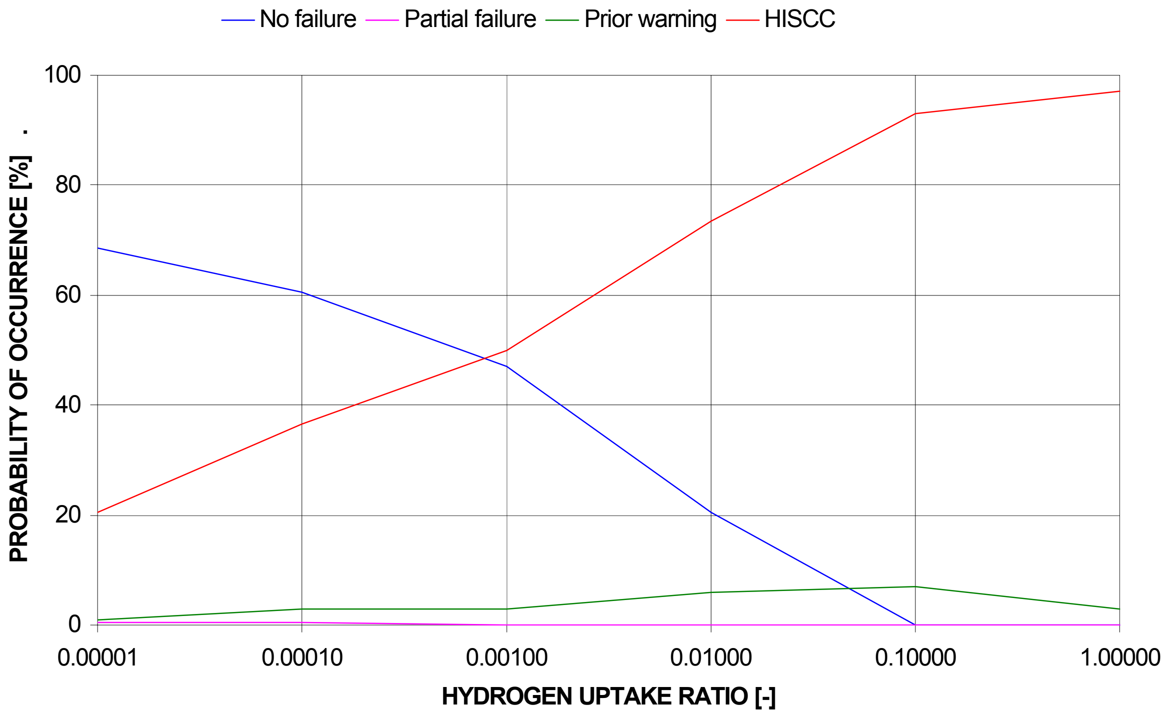

Figure 6 *Influence of Hydrogen Uptake Ratio on Probability of HISCC - Failure*

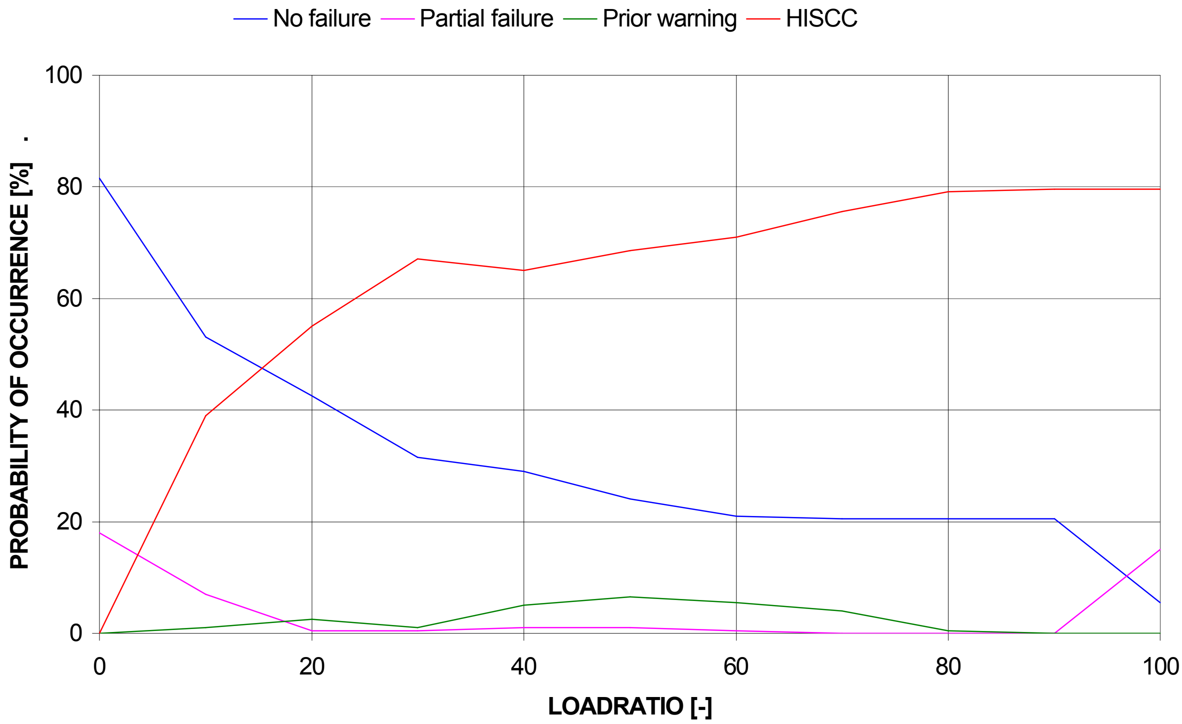

Figure 7 *Influence of Load Ratio on the Probability of HISCC - Failure*

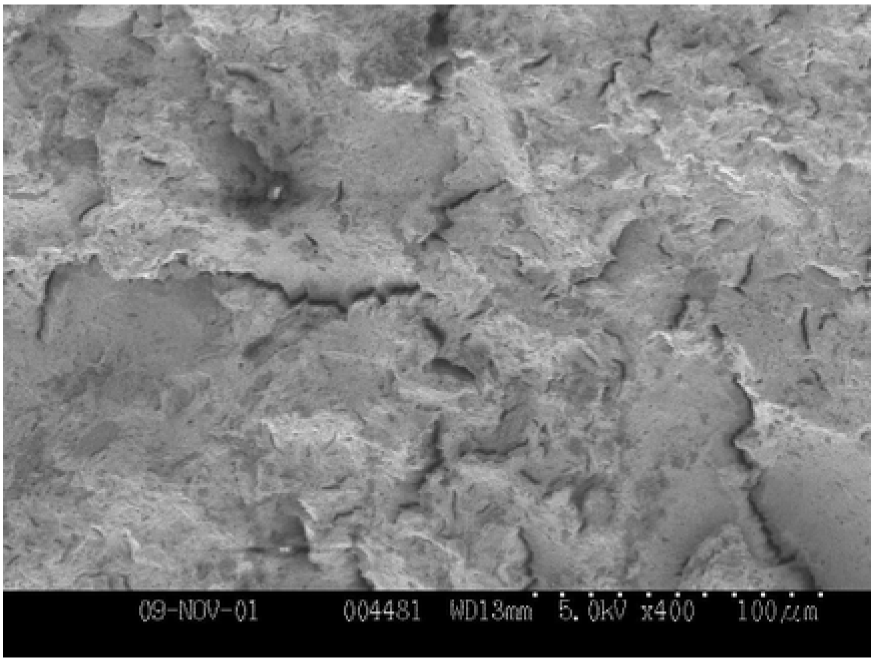

Figure 8 *Hydrogen induced Cracks in Steel*

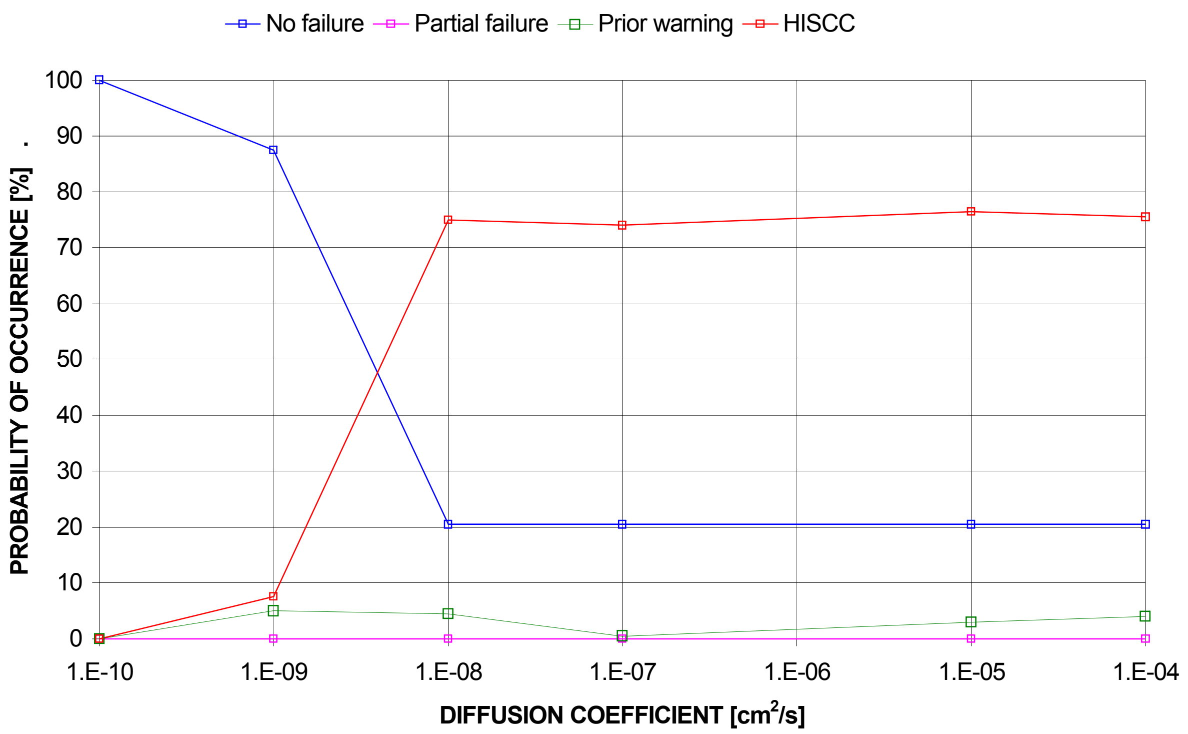

Figure 9 *Influence of Hydrogen Diffusion Coefficient on Probability of HISCC - Failure*

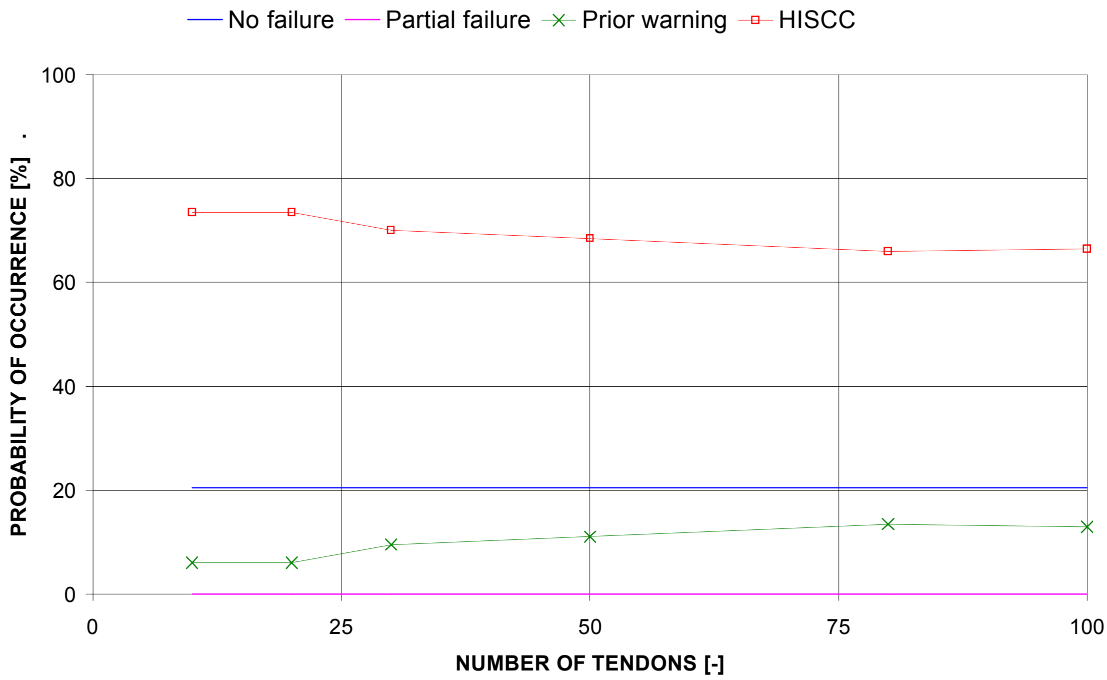

Figure 10 *Degree of Redundancy against HISCC - Failure by Number of Individual Tendons/Wires*

Table 1 *Parameters of "SIM_RISK" and check on system performance*

Parameter [Unit]	Base Case	Range (Number of Simulations)
	Without corrosion	
Amount of tendons [ ]	10	10, 20, 30, 50, 80, 100 (six)
Age [years]	30	0, 10, 20, 30, 50, 75, 100, 120 (eight)
Environment [ ]	S	S, L, D (three)
Concrete Quality[ ]	A	A, B, C (three)
Load ratio [%]	60	0 – 100 (eleven)
Strength [N/mm^2]	1860	250, 460, 900, 1230, 1560 (six)
Hydrogen uptake ratio [n]	10^{-2}	10^{0} – 10^{-5} (six)
H_{crit} [ppm]	10^{4}	10^{7}-10^{2} (six)
C_{HO} [ppm]	10^{2}	10^{0} - 10^{5} (six)
Hydrogen diffusion coefficient	10^{-7}	10^{-4} – 10^{-10} (six)
Temperature [K]	300	273, 300, 313, 333 (four)
Diameter [cm]	1.0	0.3, 0.5, 0.7, 0.9, 1.0, 2.0, 3.0 (seven)
	Combination of environment S, L and D and concrete quality A,B and C with corrosion	
General Corrosion [years]	Yes, for	0.5, 2.0, 8.0, 16.0, 30.0 (five x nine)
Pitting Corrosion [years]	Yes, for	0.1, 0.5, 1.0, 4.0, 16.0 (five x nine)
	With promoters, without corrosion	
Time of availability with full impact [hrs]		10, 50, 100, 500, 700 (five)
Magnitude of impact (full impact equals 1.00)		1.00, 0.90, 0.50, 0.20, 0.10, 0.05 (six)
	From electrochemical chloride extraction SIM_ECE	
Duration [hrs]	1000	1000, 10 000 (two)
Temperature [K]	300	as above
Current density [A/m^2]	1.000	10.000, 1.000, 0.100, 0.010, 0.001 (five)
	System Performance	
Common Random Number Generator CRN		200, 1000 cycles
Monte-Carlo Cycles	200	100, 200, 300, 1000, 10 000, 100 000
Extreme Value Distribution for Uniform random numbers		0, 1 (sixteen)