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Probability-based durability design software for concrete structures subjected to chloride exposed environments

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Abstract. Although concrete is believed to be a durable material, concrete structures have been degraded by severe environmental conditions such as the effects of chloride and chemical, abrasion, and other deterioration processes. Therefore, durability evaluation has been required to ensure the long term serviceability of structures located in chloride exposed environments. Recently, probability-based durability analysis and design have proven to be reliable for the service-life predictions of concrete structures. This approach has been successfully applied to durability estimation and design of concrete structures. However, currently it is difficult to find an appropriate method engineers can use to solve these probability-based diffusion problems. In this paper, computer software has been developed to facilitate probability-based durability analysis and design. This software predict the chloride diffusion using the Monte Carlo simulation method based on Fick's second law, and provides durability analysis and design solutions. A graphic user interface (GUI) is adapted for intuitive and easy use. The developed software is very useful not only for prediction of the service life but for the durability design of the concrete structures exposed to chloride environments.

Keywords: durability; corrosion; chloride penetration; service life; concrete structure.

1. Introduction

A large number of concrete structures have been constructed in many countries for the past several decades. However, these structures have suffered from safety and serviceability problems due to the deterioration of concrete. Therefore, concrete durability has received a great amount of attention. The penetration of water, chloride, and other aggressive ions into concrete are the most important factors in these deterioration processes (Mehta and Monteiro 2006). Among these ions, the chloride ion affects the most significant durability problem because it causes the corrosion of steel reinforcement embedded in concrete. Especially for concrete structures in marine environments, chloride-induced corrosion of steel reinforcements induces the spalling of concrete cover and the loss of steel cross-section. As a result, the service life of such concrete structures decreases due to the lack of safety and serviceability.

Thus, many studies have been carried out to obtain a more controlled durability and long-term performance of concrete structures in chloride-exposed environments. Also, several durability design methodologies which ensure the long term safety of concrete structures have been proposed (Sarja

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and Vesikari 1996, Chiu *et al.* 2008, Sancharoen *et al.* 2008). Traditionally, the durability design of concrete structures is based on implicit rules for individual materials, material compositions, working conditions, structural dimensions, etc. Examples of such 'deem-to-satisfy' rules are the requirements for a minimum concrete cover, maximum water/cement ratio, minimum cement contents, crack width limitations, air contents, cement type, coating of concrete surface, and so on. The purpose of all these rules has used to secure robustness for concrete structures, although no clear definition of "service life" has been presented (Sarja and Vesikari 1996, Edvardsen *et al*. 2006).

To overcome the limitations of the traditional durability design, the demand for new methods that can more accurately and reliably predict the durability of concrete structures has increased. Fortunately, extensive research on concrete durability has produced reliable information on deterioration processes and has made possible several new durability design methodologies. Accordingly, several types of new software also have been developed (Thomas and Bentz 2000, DuraCrete 2000, Ferreira *et al.* 2004, Schiessl 2005, Papadakis *et al.* 2007, Ramezanianpour *et al.* 2009, Teply *et al.* 2010).

Life-365 (Thomas and Bentz 2000) is one of the software which is commonly used in the durability analysis/design process. It calculates chloride diffusion in concrete using Fick's second law. The diffusion coefficient model proposed here considers ambient temperature and time effects. By using a deterministic approach, the program predicts the service life of concrete structures based on a finite difference method.

Recent studies (Schiessl 2005, Edvardsen *et al.* 2006) show that the probabilistic durability design method is the most advanced and reliable one for estimating performance- and reliability-based service life of concrete structures. This new approach has been used for to develop a corrosion-resistant durability design of new structures as well as for the redesign of existing structures and the estimate of their remaining service life. However, other studies (DuraCrete 2000, Schiessl 2005, Edvardsen *et al.* 2006) and software (Ferreira *et al.* 2004) have been based on a model which was oversimplified during the equation derivations (Luping and Gulikers 2007), so that the model could provide unreliable prediction of the concrete's chloride ingress under certain conditions (Luping and Gulikers 2007).

For many engineers, application of this advanced probabilistic methodology to practical design process is difficult without the appropriate software. Therefore, a durability analysis and design software, based on the adequate models and approaches, is very much needed.

This study has developed an effective reliability-based durability analysis software for concrete structures exposed to chloride. First, an analysis model is established to overcome the above-mentioned over-simplified diffusion problems. Then, based on the proposed models, the software was developed and the models were verified using the Life-365 program. This software implements practical durability design processes. Two examples of this application are presented in order to explain the design concept and the software developed in this study.

2. Durability analysis of concrete structures

2.1 Serviceability limit states

The concrete failure induced by steel corrosion is highly complex phenomena consisting of several processes including chloride transport, loss of passivity on embedded steel, steel corrosion, and the subsequent damage of the surrounding concrete. Given that these processes have not been completely understood, it is necessary to simplify many of the complexities and to make assumptions where the knowledge is not sufficient.

Corrosion of steel embedded in concrete is not visually evident until the damage reaches to the external signs of deterioration as rust spots, cracking or spalling. Even it takes a much longer time for the structural capacity or integrity to significantly decrease. Therefore, the time for de-passivation to begin, when the chloride ion concentration around steel has reached a critical level, can be conservatively defined as the serviceability limit (Ferreira 2004, DuraCrete 2000). With this definition, the limit state function can be defined as

$$g(\mathbf{X},t) = R(t) - S(t) \tag{1}$$

where, $\mathbf{X}$ is the design variable vector defining the limit state function g, t is time, $R(t)$ and $S(t)$ are time-dependent variables representing resistance and load, respectively. In chloride penetration problems, the resistance is described as critical chloride ion concentration and the load is defined as penetrated chloride ion concentration at the reinforcing bar location.

2.2 Durability model

The rate of chloride penetration into concrete is normally modeled using Fick's second law of diffusion, which is expressed as follows.

$$\frac{\partial C(x,t)}{\partial t} = D_c \frac{\partial^2 C(x,t)}{\partial x^2} \tag{2}$$

where $C(x, t)$ is the chloride ion concentration at a distance x from the concrete surface after being exposed for a time t, and D_c is the chloride diffusion coefficient.

Probably Collepardi *et al.* (1972) wrote the first paper which applied Fick's second law of diffusion to the chloride ingress into concrete. Assuming a constant diffusion coefficient with surface chloride content as the boundary condition, and $C = 0$ for $x > 0$, $t = 0$ as the initial conditions, the solution of Eq. (2) yields

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D_a t}}\right)\right] \tag{3}$$

where, C_s is the chloride concentration at the surface, D_a is the apparent diffusion coefficient, and erf (.) is the error function.

Since the mid-1990s, many researchers have adopted equations, which let the diffusion coefficient decrease with time (Tang an Nilsson 1992, Mangat *et al.* 1995, Bamforth 1998, Thomas and Bentz 2001), as follows.

$$D(t) = D_0\left(\frac{t_0}{t}\right)^m \quad (t < t_c) \tag{4a}$$

$$D(t) = D_0\left(\frac{t_0}{t_c}\right)^m = const. \quad (t > t_c) \tag{4b}$$

where $D(t)$ is the diffusion coefficient at time t, and D_0 is the diffusion coefficient at the reference time t_0 that is usually 28 days. The coefficient m has been developed to account for the rate of reduction in the diffusivity with time. In order to prevent the indefinite decrease of the diffusion coefficient over time, the relationship shown in Eqs. (4a) and (4b) is expressed in terms of time limit t_c (= 30 years). Beyond this time limit t_c, the diffusion coefficient is assumed to be constant throughout the rest of the analysis period as shown in Eq. (4b).

It should be noted that the apparent diffusion coefficient D_a in Eq. (3) cannot be equal to $D(t)$ in Eq. (4) because the $D(t)$ is a function of time that cannot be directly put into the error function solution without time integration. The oversimplified model ignores this difference and consequently yields an under-estimation of long-term service life (Luping and Gulikers 2007).

When the chloride diffusion coefficient changes with the time t, Eq. (2) is expressed by Eq. (5) (Crank 1975)

$$\frac{\partial C(s,t)}{\partial T} = \frac{\partial^2 C(x,t)}{\partial x^2} \tag{5}$$

$$T = \int_0^t D(\tau)d\tau \tag{6}$$

By substituting Eq. (6) with Eq. (4), T is obtained as follows

$$T = D_m t = \frac{D_0}{1-m}\left(\frac{t_0}{t}\right)^m t \qquad (t < t_c) \tag{7a}$$

$$T = D_m t = D_0\left[1 + \frac{t_c}{t}\left(\frac{m}{1-m}\right)\right]\left(\frac{t_0}{t_c}\right)^m t \qquad (t > t_c) \tag{7b}$$

where D_m is the mean diffusion coefficient from the initial time 0 to the analysis time t. The substitution of Eq. (5) with Eqs. (7a) and (7b) using the appropriate initial and boundary conditions, results in an equation which permits the prediction of chloride levels based on the time-dependent diffusion coefficient

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D_m t}}\right)\right] \tag{8}$$

The temperature effect can be incorporated using Arrhenius' law (Thomas and Bentz 2000). Eq. (9) is applied to allow for the temperature-dependent changes in the diffusion coefficient.

$$D(T) = D_0 \cdot \exp\left[\frac{U}{R}\cdot\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{9}$$

where $D(T)$ is the diffusion coefficient at time t and temperature T, D_0 is the diffusion coefficient at the reference time t_0, and the temperature T_{ref}, U is the activation energy of the diffusion process (35,000 J/mol), R is the gas constant, and T is the temperature in Kelvin.

2.3 Probabilistic analysis

In this study, the probabilistic analysis has been carried out using Monte Carlo Simulation (MCS). For specialized applications, the first-order reliability method (FORM) or second-order reliability method (SORM) can also be used to find solutions in probabilistic problems. However, MCS has been chosen since it has wide applicability to problems involving probability (Ang and Tang 1984) and can be easily implemented in computer software.

MCS is a numerical process that repeatedly calculates a mathematical or empirical operator where the variables are defined using probability density functions. At each simulation, the input variables are randomly generated using the pre-defined probabilistic distributions, and then the limit state function is calculated. The limit state function is defined by the difference between the chloride concentration at the reinforcing bar location and the pre-defined threshold concentration. If N_f is the number of simulation cycles when the limit state function g is less than zero, and N is the total number of simulation cycles, then the probability of failure is defined as follows

$$p_f = P[g<0] = \frac{N_f}{N} \tag{10}$$

The durability design based on the structural reliability theory requires the targeted reliability level be met. The reliability index can be calculated by the following equation

$$p_f = \int_{-\infty}^{-\beta} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{u^2}{2}\right) du = \Phi(-\beta) \tag{11}$$

where β is the reliability index, u is the random variable, and Φ is the cumulative distribution function of standard normal variables.

2.4 Durability design concept

The general concept behind durability design is the decrease of the transportation of chloride ions from the surface in order to delay the initiation of corrosion. When exposure and environmental conditions are given, the durability design for chloride penetration can be obtained by defining the minimum required performance of materials (Gelen and Schiessl 1999). When no special protection methods, such as stainless steel, coating, and cathodic prevention, are used, the primary approach for designing durable concrete incorporates two primary barriers against chloride ingress as follows: (i) high quality concrete with a low permeability, and (ii) adequate concrete cover depth (Edvardsen *et al.* 2005). In the designing stage, these two properties are set as main variables to ensure satisfactory performance over the intended service life of the structures. Then, the major objective of durability design is to propose the minimum requirements for the concrete to be used.

3. Durability design software

3.1 Scope

In order to facilitate the probability-based approach to the chloride diffusion problem, software has been developed using the models and simulation methods described above. The software is designed to evaluate remaining service life of concrete structures and optimized to their durability design.

The software mainly consists of 3 parts as follows: (i) the input module, (ii) the diffusion analysis module, and (iii) the design module, as shown in Fig. 1. The input module allows a user to name the project and to define the analysis conditions and models. The diffusion analysis module is used to predict the service life of concrete structures by either a deterministic or a probabilistic approach.

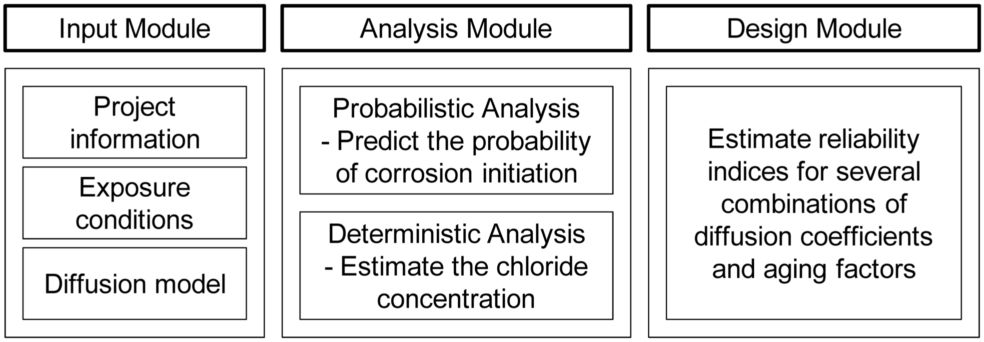

Fig. 1 Probability based durability design software schematic

In the design module, the software facilitates the practical durability design processes subjected to chloride attack conditions.

3.2 Input module

The input module is composed of 3 windows, which have been setup to input the project information, the exposure conditions, and the analysis models. In the project information window, the basic project information, such as title, date and brief project description, can be input. In the

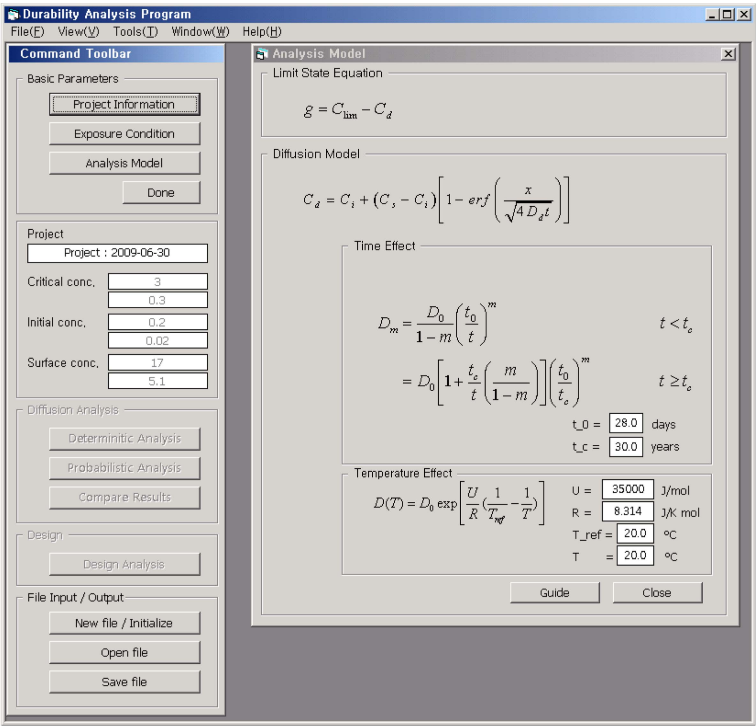

Fig. 2 Model input window

exposure condition window, the parameters related to the initial and boundary conditions, such as critical, initial, and surface chloride concentration, can be set. The parameters determining the diffusion properties can be set in the analysis model window, as shown in Fig. 2.

3.3 Analysis module

The analysis module has been developed according to the durability analysis procedures described in Sec. 2. In this module, diffusion analysis can be conducted using the probabilistic as well as the deterministic approach in order to estimate the probability of corrosion initiation over the service life of concrete structures. The probabilistic approach can be used for the quantitative estimation of service life, whereas the deterministic approach can be used to predict chloride concentration and penetration depth for the specific parameters and to understand the probabilistic results more comprehensively. The deterministic prediction can also be used to estimate the sensitivity of each durability variable. Fig. 3 shows an example of the windows as they appear in the software. The results are shown in graphic form for both failure probabilities and reliability indices. In this module, a user can carry out several analyses with changing parameters, and the analysis results are stored and can be compared each other in one graph as shown in Fig. 4.

3.4 Design module

The design module is intended to help engineers reduce time and efforts in conducting parametric analyses by implementing practical durability design processes into the software. As seen in Figs. 5 and 6, this design analysis module has been designed and developed according to the durability design procedures substantially based on the probabilistic analysis approach. After determining the service life of the concrete structure, the sample size for simulations, and the cover depth, a user can easily calculate the reliability index for the maximum 16 combinations of the diffusion

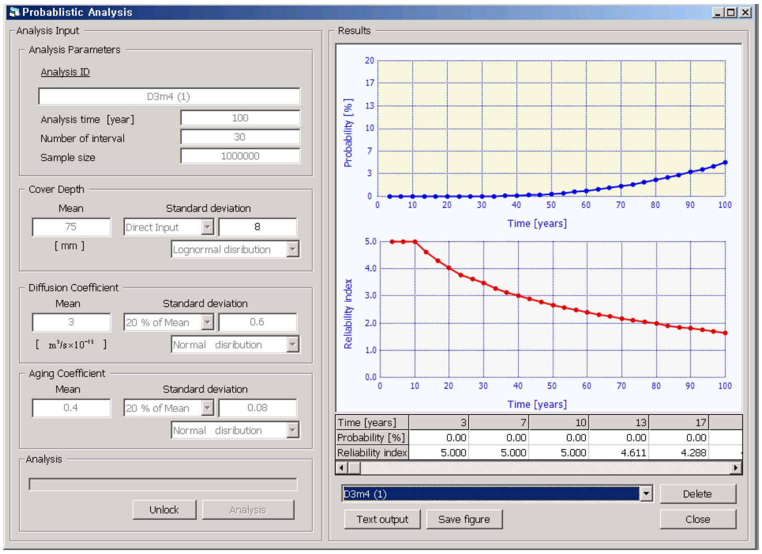

Fig. 3 Probabilistic analysis window

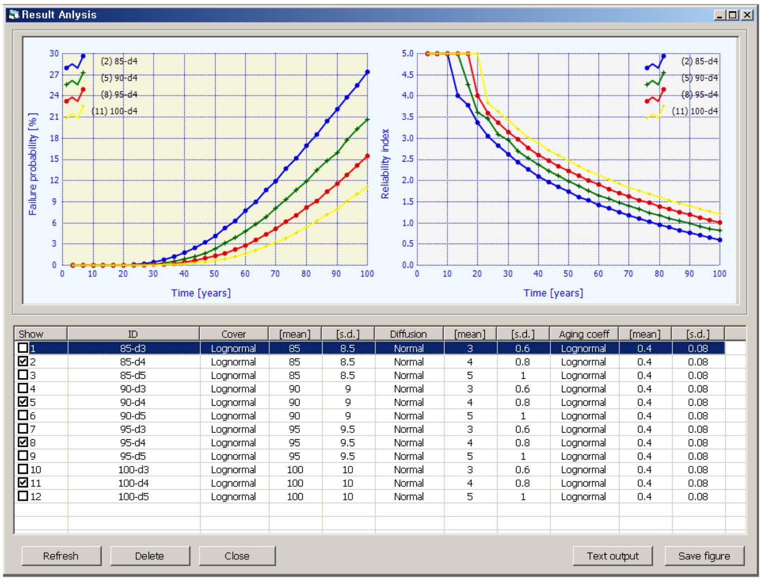

Fig. 4 Result comparison window

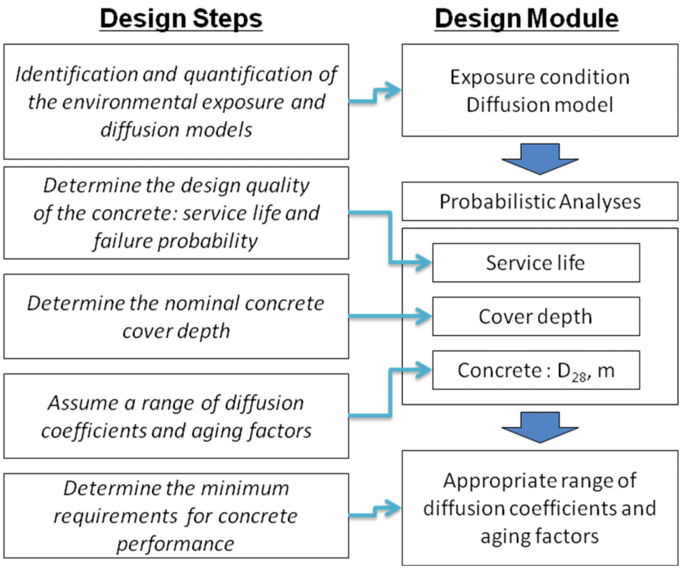

Fig. 5 Design module procedures

coefficients and aging factors. The table and graph in Fig. 6 show the spectrum of the obtainable reliability indices β depending on the chloride diffusion coefficients and the aging factors for the concrete structures with the specific concrete cover.

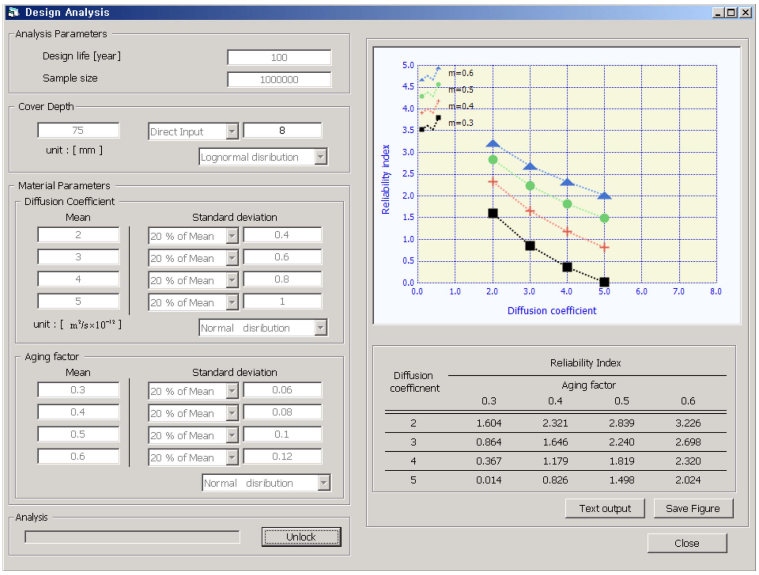

Fig. 6 Design analysis window

4. Verification and application examples

4.1 Verification of analysis results

The results of this analysis software are verified by comparing results from other programs. First, the deterministic analysis results based on the error function approach are verified with the results of the Life-365 software (Thomas and Bentz 2000) that calculates the chloride diffusion in concrete structures using the finite difference method (FDM). In the analysis, the surface chloride concentration is 13.00 kg/m^3, the critical chloride concentration is 1.6 kg/m^3, and the average temperature is 20^{o}C. The diffusion properties used for the verification are listed in Table 1. The cover thickness is 95 mm. Results of comparison between the softwares in Fig. 7 indicate that the deterministic analysis results correspond well with the results of Life-365. This also proves that the error function solution corresponds well with the FDM result.

Secondly, the probabilistic analysis results by MCS are verified with the FORM results calculated using MATLAB (2004). The Advanced First Order Second Moment (AFOSM) method is applied as a FORM (Ang and Tang 1984). For the verification, the average values in Table 1 are used.

Table 1 Diffusion properties used to verify the proposed software

Parameters	Diffusion coefficients ($\times 10^{-12}$ m^2/s)	Aging factors
Base case	Life-365 model (W/C=0.4, silica fume=5%, slag=20%)	
Case 1	4.0	0.4
Case 2	5.0	0.5
Case 3	6.0	0.6

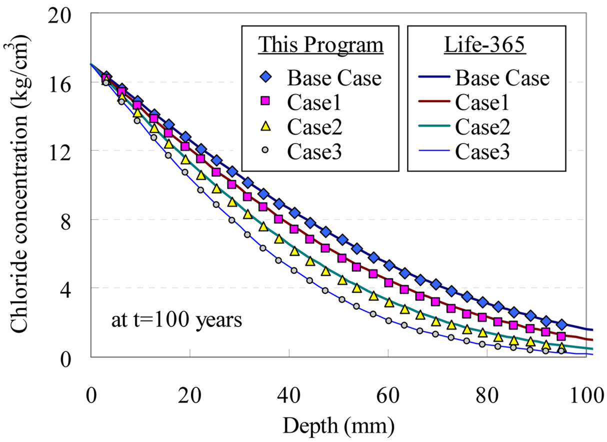

Fig. 7 Proposed software verification using Life-365

Table 2 Failure probabilities of analysis methods

	AFOSM method (%)	MCS method (%)	Difference (%)
Case 1	28.86	27.30	1.56
Case 2	16.59	15.67	0.92
Case 3	9.25	8.77	0.48

Additionally, the distributions of all the parameters except the cover depth are assumed to be a normal distribution with a 10% coefficient of variation. The cover depth is assumed to be log-normally distributed with a 10% coefficient of variation. The design life of the structure and the sample size of simulations are set to be 100 years and 10,000,000, respectively. Table 2 compares the probabilities obtained using the AFOSM and MCS methods. The failure probability differences between two methods are 0.48~1.56%. Even though the differences between the AFOSM and MSC results increase with an increase in the failure probability, the MCS results correspond well with the AFOSM results.

4.2 Probabilistic durability design examples

4.2.1 Submerged concrete tunnel

The developed software is applied to the durability design of the concrete tunnel submerged under seawater. As explained in Sec. 2.4, concrete diffusion properties and cover depth are the primary variables for this durability design. The input variables are determined based on the data used for the actual durability design of the concrete structure, but the standard deviation and distribution types are reasonably assumed, as shown in Table 3 (Kim *et al.* 2006, Edvardsen *et al.* 2006, Park *et al.* 2005). The analyses are performed by varying the design parameters over a relevant range of values while the other environmental parameters are fixed. In this example, the diffusion coefficient and aging factor are the design parameters.

Fig. 8 shows the probability of failure, which was defined as the initiation of corrosion with respect to the diffusion coefficients. The maximum allowable diffusion coefficient, which can ensure that the probability of failure is kept below 10% at the age of 100 years, is 3.78×10^{-12} m^2/s. Table 4

Table 3 Durability design parameters: Example 1

Parameters	Mean	Standard deviation	Distribution type
Surface chloride concentration	2.0% by wt. of binder	0.6	normal
Cover thickness (mm)	75	8	log normal
Critical chloride concentration	0.7% by wt. of binder	0.07	normal
Initial chloride concentration	0.1% by wt. of binder	0.01	normal
Diffusion Coefficients ($\times 10^{-12} m^2/s$)	3.0~6.0	0.2 × mean	normal
Aging factors, *m*	0.3~0.6	0.2 × mean	log normal
Target service life	100 years		

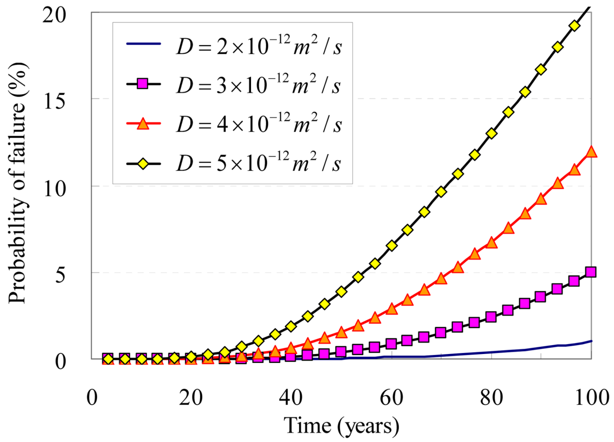

Fig. 8 Probability of failure based on diffusion coefficients

Table 4 Design results based on cover depth and diffusion properties

Cover depth	Aging factor	Reliability index: Diffusion coefficient ($\times 10^{-12}$ m²/s) 2	3	4	5	Maximum required diffusion coefficient ($\times 10^{-12}$ m²/s)
75 mm	0.3	1.604	0.860	0.368	0.013	2.44
	0.4	2.323	1.645	1.178	0.826	3.78
	0.5	2.835	2.248	1.823	1.500	> 5
	0.6	3.248	2.687	2.313	2.024	> 5

shows the design table of the obtainable reliability indices (β) depending on the combinations of the chloride diffusion coefficients and aging factors when the nominal concrete cover is 75 mm. In the design module of the software, a user can evaluate this table easily, as shown in Fig. 6.

From the results, the required concrete quality can be proposed in terms of the maximum diffusion coefficient as follows

- Max. $D_{28} = 2.44 \times 10^{-12}$ m²/s, m=0.3 for cover = 75 mm
- Max. $D_{28} = 3.78 \times 10^{-12}$ m²/s, m=0.4 for cover = 75 mm

During the material selection and construction processes, the quality of concrete should be verified to make sure that it satisfies the minimum requirements proposed.

4.2.2 Onshore structure

The concrete structure considered in this example is a tide embankment located on shoreline. The input parameters used in the design are summarized in Table 5. In this example, the design is performed using the probability-based method with a 10% probability of failure. The cover thickness and diffusion coefficient are the primary design variables in this example.

Fig. 9 shows the failure probabilities in regards to the diffusion coefficients and cover depth over time. In the figure, '85-D3' means that the cover depth and the diffusion coefficient are 85 mm and 3×10^{-12} m^2/s, respectively. From the figure, it can be observed that the diffusion coefficient is more sensitive parameter, affecting the failure probability, than the cover depth when the diffusion coefficient changes from 3×10^{-12} m^2/s to 5×10^{-12} m^2/s as well as when the cover depth changes from 85 mm to 95 mm.

The design results are summarized in Fig. 10, which shows the reliability indices in terms of the diffusion coefficient and the cover depth. From this figure, the required diffusion coefficients that keep the reliability index below 1.28 over the design period can be obtained easily. The required concrete qualities are proposed in relation to their cover depths as follows

Table 5 Durability design parameters: Example 2

Parameters	Mean	Standard deviation	Distribution
Surface chloride concentration (kg/m^3)	17	5.1	normal
Cover thickness (mm)	85~100	0.1 × mean	log normal
Critical chloride concentration (kg/m^3)	3.0	0.3	normal
Initial chloride concentration (kg/m^3)	0.2	0.02	normal
Diffusion Coefficient ($\times10^{-12}m^2/s$)	3.0~6.0	0.2 × mean	normal
Aging factor, m	0.4	0.2 × mean	log normal
Target service life	100 years (10% failure probability)		

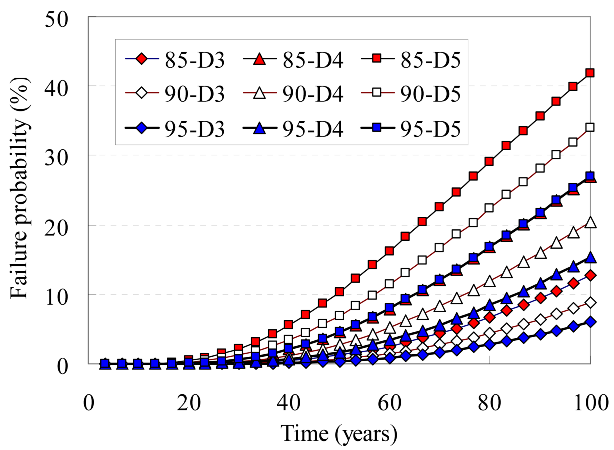

Fig. 9 Probability of failure based on diffusion coefficients and cover depths

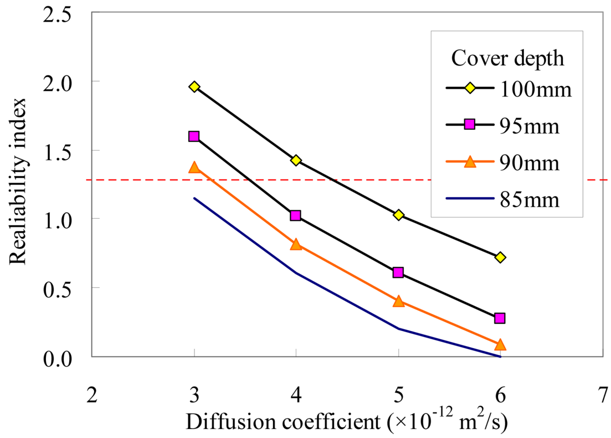

Fig. 10 Reliability indices based on diffusion coefficients and cover depths

- Max. D_0 = 3.2 × 10^{-12} m^2/s, m = 0.4 for cover = 90 mm
- Max. D_0 = 3.5 × 10^{-12} m^2/s, m = 0.4 for cover = 95 mm
- Max. D_0 = 4.4 × 10^{-12} m^2/s, m = 0.4 for cover = 100 mm

5. Conclusions

This study has developed a durability analysis software based on reliability for the service-life prediction and durability design of concrete structures exposed to chloride.

(1) Durability analysis methods were established using both deterministic and probabilistic approaches. The deterministic solution for chloride diffusion has been mathematically derived including the time integration process for the diffusion coefficient. The probability of corrosion initiation is calculated using the Monte Carlo simulation method in order to evaluate the service life of concrete structures.

(2) Probability-based durability design software has been developed for concrete structures subjected to chloride exposed environments. This software includes diffusion analysis and durability design modules. In the diffusion analysis module, the service life of concrete structure can be estimated by either the deterministic or the probabilistic approach. In the design module, the software provides optimized features for effective durability design.

(3) The developed software has been shown to work as an effective tool for the durability design of chloride-attacked concrete structures. The design examples show that the minimum required material resistance in conjunction with the corresponding concrete cover can be identified in order to insure the service life of concrete structures.

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