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MODELLING OF CORROSION PROTECTION AS STANDBY SYSTEM FOR COATED REINFORCED CONCRETE STRUCTURES

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Abstract. Various protective barriers are used in practice to protect reinforced concrete structures in severely aggressive environments. In this paper, we consider a multi-component corrosion protection system (CPS), taking into account the performance of protective surface barrier, concrete cover and steel reinforcement, which is modelled as a three-unit of non-identical components cold standby system. The system is non-maintained. This is the case when the system is not easily accessible for repair, repair; is time-consuming and costly. In this system it is assumed that degradation rates of all components are exponential and different. Under these assumptions, using the Markovian degradation process, some important reliability indices such as the system reliability and mean time to failure are defined. In addition, we present simulation results to substantiate the analytical model and to demonstrate the sensitivity analysis to estimate protection system reliability.

Keywords: reinforced concrete, anti-corrosion protection, non-repairable system, standby system, Markovian process, reliability, time to failure.

1. Introduction

Methods for improving the performance of reinforced concrete structures by surface corrosive resistant barriers have been used for many years. The type of protective barrier depends on the resistance of the barrier materials to the chemicals involved. Materials to be used for prevention of aggressive attack may be in the form of coatings, hot melts, resin mastics and mortars, ceramics, sheets. Various types of organic and non-organic coating systems are used to protect the structures in highly corrosive atmosphere or industrial environments (e.g., Barbucci *et al*. 1997; Kamaitis 2007b; Park 2008; Sanjuan, Olmo 2001). In recent years, bonding of external FRP is considered as an effective method of strengthening and protection of civil infrastructures subjected to severe environmental conditions (e.g., Benzaid *et al.* 2008; Debaiky *et al.* 2002; Valivonis, Skuturna 2007). There may be a need for protection of chemical attack on reinforced concrete structures in such places as chemical process plants, chemical storage tanks, cooling towers, silos, pipes, industrial chimneys, sewers or sometimes in such ordinary locations as floors, foundations, bridge structures or dams. It is necessary to stress that the condition of the anticorrosion protection has a great effect on the condition and safety of the structural component. Therefore, it is important to search for economic and efficient protective system planning and analysis that is possible only based on reliability methods.

Protective barriers as well as concrete and steel reinforcement in aggressive environments in general have limited service lives. The protection systems particularly organic coatings are continuously deteriorating by corrosion and ageing although the rate of their degradation is considerably slower than that of concrete or steel reinforcement. During service life of reinforced concrete structures recoating is frequently required. In some structures such as industrial chimneys, pipes, underground structures the protection systems are not easily accessible for inspection and repair. Coating stripping and renewal in large and not easily accessible areas is a major operational, safety, and cost challenge. In design of such structures it is desirable that the time to failure of protection system is not less than required design lifetime of the structure. In this situation the protection system is considered as non-repairable (without repair).

Numerous investigations reported in literature are conducted to evaluate experimentally the durability of coated concrete or steel reinforcement specimens by assessing chemical resistance or permeability of organic and inorganic coatings. To the best of the author's knowledge, very little information on the analytical modelling and design of protective coatings for reinforced concrete structures is available (e.g., Barbucci *et al.* 1997; Beilin, Figovsky 1995; Kamaitis 2007b; Sanjuan, Olmo 2001; Park 2008; Vipulanandan, Liu 2002). On the other hand, in some environments along with the protective barrier the protection capabilities of concrete cover and reinforcement (sometimes epoxy coated) can be exploited.

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Most of the literature on reinforced concrete deterioration models is due to the action of chlorides, atmospheric carbon dioxide, frost or alkali-aggregate reactions. Fewer studies are devoted to reinforced concrete deterioration in highly corrosive environments, where special protection is required. As a rule, the deterioration models deal with individual components only. To the author's opinion, in some cases it should be useful to evaluate the corrosion protection ability of protected reinforced concrete as reliability of a complex system. If we consider the multilevel structure as a system, the reliability analysis of a system is closely related to system's model and performance characteristics of its individual components.

In the author's paper (Kamaitis 2008) the concept of corrosive protection system (CPS) of reinforced concrete members taking into account the performance of protective surface barrier, concrete cover and steel reinforcement itself was proposed. Degradation of CPS as multicomponent protection system begins, in general, from the top layer. After degradation of topcoat, the concrete cover is put in operation allowing the protection system to continue its protection function until all components are deteriorated and the limit states of degrading structure are reached. When all components fail, does the protection system fail.

From a probabilistic point of view, multi-component protection system can be generated with the standby models. These models involve the use of redundant components that are in intact (not loaded) reserve and are activated when operating unit fails. Standby systems are widely used in telecommunication (De Almeda, De Souza 1993), electric power (Wang, Loman 2002), textile (Pandey *at al.* 1996), and urea (Kumar, R., Kumar, S. 1996) plants, alarm and satellite systems (Azaron *et al.* 2007), offshore platforms (Aven 1990). Reliability and availability of cold standby systems have been extensively studied for many different system structures, objective functions, and distribution assumptions. Most researchers have investigated the standby systems with different maintenance/repair strategies.

If the protection system is not easily accessible for repair, repair is costly and time-consuming or the time to failure of the system has to be no shorter than required design lifetime of the structure, the system should be designed as non-repairable (without repair). Relatively little research is found on the cold-standby systems with non-repairable components (Coit 2001; Finkelstein 2001; Utkin 2003; Azaron *et al.* 2007). However, this type of standby models is successfully used, for instance, in satellite systems (Azaron *et al.* 2007). In our previous publication (Kamaitis, Cirba 2007) the cold-standby model approach to model the performance of multi-layer corrosion protection system for civil infrastructures is presented. We found no studies that model combined anticorrosion protection barriers for reinforced concrete structures as standby redundancy.

This study was conducted to develop a framework for reliability evaluation and service life prediction of non-repairable three component anticorrosion protective system which can be used for durability analysis of reinforced concrete structures. The author did not attempt to investigate the real reinforced concrete structures exposed in given aggressive conditions, but merely to introduce the concept of multi-level anticorrosion protection as a cold standby system. In this paper we formulate a cold-standby model to describe the behaviour of the CPS in which the next component is switched in operation, when the primary component fails. The system is not maintainable/repairable. The Markov transition probability matrices were used for prediction of the deterioration process. For illustrative purposes, the sensitivity analysis of parameters involved on the systems reliability is presented.

2. System description and assumptions

Consider a three-unit standby redundant non-repairable parallel system with intact (not loaded) reserve, which comprises three independent non-identical parallel-connected elements (Fig. 1a). Let S_i for i = 0, 1, 2, 3 be the states of the system, where $\lambda_i > 0$ represents the rate of deterioration. State S_0 represents initial new state at $t = 0$. If the sequence of component 1 failure then component 2 then component 3 is considered then the system will successively reach the intermediate states S_1, S_2, and S_3 reflecting system's relative degree of deterioration (Fig. 1b). The reserve component is brought in operation, when the previous unit fails with final state S_3 corresponding to system failure. Only when all elements fail does the protection system fails. The states S_0, S_1, and S_2 are called the up states and state S_3 is the down state.

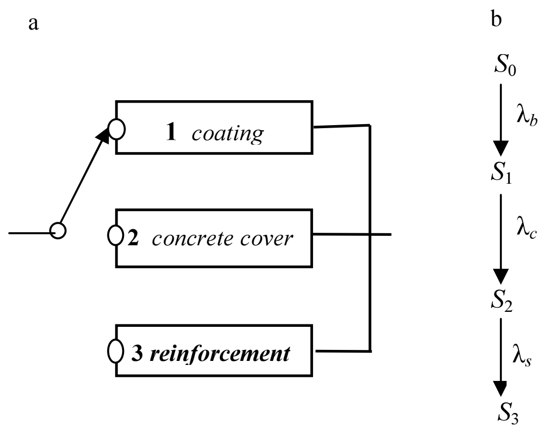

Fig. 1. Standby parallel system: a – structural system; b – state transition diagram

The failure rates λ_i indicate the rates at which the transitions are made from one state to another. As yet there are not sufficient data available to predict the parameter λ_i for CPS components the system reliability estimates was based on constant failure rate assumptions. This, of course, is not fully realistic but it simplifies the analysis. By the way, the exponential distribution was found to be well fitted to the polymer coatings deterioration (Vipulandan, Liu 2002; Логанина *et al.* 2003; Kamaitis 2007a). This distribution is also used for modelling the concrete physical and chemical degradation (Leech *et al*. 2003; Huang *et al*. 2005; Schneider, Chen 2005) or structural deterioration of reinforced concrete flexural members in a marine environment (Li 2003). A need exists for experimental data on the model of component failure rates. The rate of deterioration depends on the mechanical, chemical and geometrical properties (thickness) of components and external aggressive environment.

The basic assumptions made to model the performance of the system are:

a – degradation function of CPS is independent of the load history of reinforced concrete member; only deterioration due to external aggressive attack is considered;

b – the system consists of 3 non-identical components in cold-standby configuration; all components are activated sequentially in order upon failure of an operative component;

c – the system is considered as non-repairable (without repair);

d – component failure rates $\lambda_i \geq 0$ are constants and time independent but different for components 1, 2 and 3; the most resistant component is coating, then $\lambda_c > \lambda_b < \lambda_s$;

e – each component has 3 possible modes: operating, idle, failed;

f – system fails when all the components are in failed state.

3. Assessing reliability of CPS

The durability of CPS depends on several factors:

- exposure conditions;
- surface protective measures (composition, thickness and properties of barriers);
- composition and properties of the concrete;
- cover to reinforcement;
- concrete cover cracking;
- type and diameter of reinforcement (steel, prestressing steel, coated steel, non-metallic);
- size, configuration and detailing of cross-section.

The performance of the CPS cannot be predicted with certainty. Thus, the behaviour of CPS with time is probabilistic in nature. The system reliability depends of its structure as well as on reliability of its components. Reliability of individual component is a function of a component service life on a system operating time.

Let t_i to be the time to failure of the *i*th component with i = 1, 2, 3. Then the system time to failure is determined as

$$T_{CPS} = \sum_{i=1}^{3} t_i. \quad (1)$$

Hence, system reliability is the sum of individual component reliability values, i.e. the sum of component failure times t_i. Probability distributions of component time to failure must be known with certainty.

The reliability of protection system can be modelled as union of componential reliability events. During the time interval T the reliability or the probability that the system will work for a prescribed period of time t_d, $P_{CPS}\{T \geq t_d\}$, as a 3 standby parallel system is the probability that either the protection barrier does not fail until T, $t_b > T$, or the protection barrier fails, but the concrete cover does not, $t_b < T \cap t_c > T - t_b$, or the first two components fail, but the reinforcement will not fail until a time greater than T, $(t_b < T) \cap (t_c < T - t_b) \cap (t_s > T - t_b - t_c)$ (Fig. 2). Since these three possibilities are mutually exclusive, we obtain:

$$P\{T_{CPS} \geq t_d\} = p\{t_b > T\} + p\{t_b < T \cap t_c > T - t_b\} + p\{(t_b < T) \cap (t_c < T - t_b) \cap (t_s > T - t_b - t_c)\}. \quad (2)$$

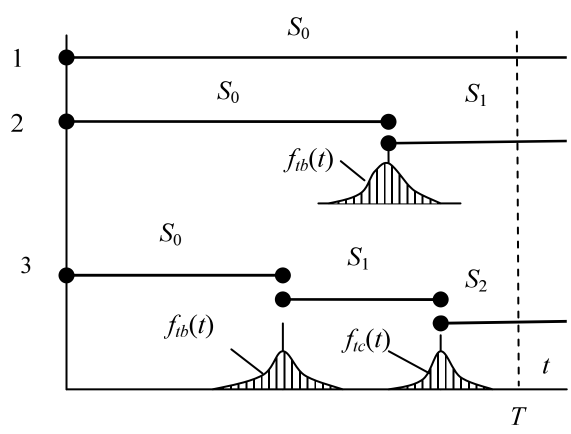

Fig. 2. States of safe operation of CPS

Suppose that the probability distribution function (pdf) of the time to failure for the component i is $f_{ti}(t_i)$. Then, the probability of component failing between t_i and $t_i + dt_i$ is $f_{ti}(t_i)dt_i$. Since after failure of component i the next component i + 1 is put into operation at time t_i, the probability that it will survive to time T is $p_{i+1}(T - t_i)$. Thus, the protective system reliability, given that the first failure takes place between t_i and $t_i + dt_i$, is $p_{i+1}(T - t_i) f_{ti}(t_i)dt_i$. Then, the CPS reliability can be expressed as

$$P\{T_{CPS} \geq t_d\} = p_b\{t_b > T\} + \int_0^T p_c(T - t_b) f_{tb}(t_b)dt_b + \int_0^T f_{tb}(t_b) \int_0^{T-t_b} f_{tc}(t_c) p_s(T - t_b - t_c)dt_c dt_b, \quad (3)$$

where $f_{tb}(t)$ and $f_{tc}(t)$ is the pdf for protective barrier and concrete cover, respectively.

The first term in Eq. (3) is just the reliability of the protective barrier which is the most important and extremely loaded component of protective system. To estimate conservatively the reliability of protection system in extreme severe environment for reinforced concrete, it could be assumed that

$$P\{T_{CPS} \geq t_d\} = p_b\{t_b \geq T\}. \tag{4}$$

The service life of CPS is described as the time when the reliability falls below an acceptable level

$$P\{T_{CPS} \geq t_d\} \geq P_{t\arg}. \tag{5}$$

If depassivation of steel in concrete is accepted as limit state of CPS, then reliability of two-component system is expressed as

$$P\{T_{CPS} \geq t_d\} = p_b\{t_b > T\} + \int_0^T p_c(T - t_b) f_{tb}(t_b) dt_b \geq P_{t\arg}. \tag{6}$$

As it can be seen, the equations of system reliability are obtained by integration of the appropriate probability density functions. According to model assumptions (see Section 2), the life times of components are presumed to be exponentially distributed. Assuming an exponential distribution given by the parameter λ_i, the probability density function is $f_{ti}(t_i) = \lambda_i e^{-\lambda_i t_i}$. In this situation the system behaviour can be represented by Markov model which is probably the most used to simulate the different stochastic processes of complex systems. Although it is possible to predict deterioration of CPS with other forms of models, including also deterministic models (Kamaitis 2008), the Markovian model is particularly suitable for condition state assessments based on inspection cycles. It requires only limited inspection data before model estimation becomes possible.

4. State transition probabilities

So, the deterioration process of protection system can be modelled as the Markov process (Lewis 1996). Then the reliability of component *i* will be expressed in the form of $R_i(t_i) = \exp(-\lambda_i t)$. From the state transition diagram (Fig. 1) we may construct the Markov equations for 4 states. According to state transition diagram (given that $\lambda_b < \lambda_c < \lambda_s > 0$), the probability that the system will be in state S_0 is

$$\frac{d}{dt} p_0(t) = -\lambda_b p_0(t). \tag{7}$$

For states S_1, S_2 and S_3 we have

$$\frac{d}{dt} p_1(t) = \lambda_b p_0(t) - \lambda_c p_1(t); \tag{8}$$

$$\frac{d}{dt} p_2(t) = \lambda_c p_1(t) - \lambda_s p_2(t); \tag{9}$$

$$\frac{d}{dt} p_3(t) = \lambda_s p_2(t), \tag{10}$$

where $p_i(t)$ is probability that the system is in state *i* at time *t*, for *i* = 0, 1, 2, 3.

Thus, for the system, consisting of 3 components, there are 4 possible states.

The state transition differential equations can be written in the matrix form

$$\frac{d}{dt} P(t) = MP(t), \tag{11}$$

where $P(t)$ is a column vector with components $p_0(t)$, $p_1(t)$, $p_2(t)$, and $p_3(t)$; M is the Markov transition matrix

$$M = \begin{bmatrix} -\lambda_b & 0 & 0 & 0 \\ \lambda_b & -\lambda_c & 0 & 0 \\ 0 & \lambda_c & -\lambda_s & 0 \\ 0 & 0 & \lambda_s & 0 \end{bmatrix}. \tag{12}$$

The objective is to calculate the probability $p_i(t)$ that the system is in state *i* at time *t*.

The state S_0 is the state at $t = 0$ for which all the components are safe. For CPS as a passive parallel system:

$$p_0(0) = 1, \quad p_1(0) = p_2(0) = p_3(0) = 0. \tag{13}$$

Since at any time the system can only be in one state, we have $\sum_{i=0}^{3} p_i(t) = 1$.

Then, by solving the differential equation (11) and using initial conditions (13), we obtain the following state probabilities:

$$p_0(t) = e^{-\lambda_b t}; \tag{14}$$

$$p_1(t) = \frac{\lambda_b}{\lambda_c - \lambda_b}(e^{-\lambda_b t} - e^{-\lambda_c t}); \tag{15}$$

$$p_2(t) = \frac{\lambda_b \lambda_c}{\lambda_c - \lambda_b} \times \left[\frac{e^{-\lambda_b t}}{\lambda_s - \lambda_b} - \frac{e^{-\lambda_c t}}{\lambda_s - \lambda_c} + \frac{(\lambda_c - \lambda_b) e^{-\lambda_s t}}{(\lambda_s - \lambda_c)(\lambda_s - \lambda_b)} \right]; \tag{16}$$

$$p_3(t) = \frac{\lambda_b \lambda_c \lambda_s}{\lambda_c - \lambda_b} \times \left[\frac{1 - e^{-\lambda_c t}}{(\lambda_s - \lambda_c)\lambda_c} - \frac{1 - e^{-\lambda_b t}}{(\lambda_s - \lambda_b)\lambda_b} - \frac{(\lambda_c - \lambda_b)(1 - e^{-\lambda_s t})}{(\lambda_s - \lambda_c)(\lambda_s - \lambda_b)\lambda_s} \right]. \tag{17}$$

The presented are the calculations for state transition probabilities of three-component system. Similar approach may be used to find the state probabilities of protection system composed of single barrier or barrier and concrete cover.

If corrosion of steel reinforcement is not allowed, we will have two-component corrosion protection system and 3 possible states, S_0, S_1, and S_2, where the state S_2 corresponds to system failure. The values, $p_0(t)$ and $p_1(t)$, are computed by using Eqs (14) and (15), when $p_2(t)$ is given by

$$p_2(t) = \frac{\lambda_b \lambda_c}{\lambda_c - \lambda_b} \left(\frac{e^{-\lambda_c t}}{\lambda_c} - \frac{e^{-\lambda_b t}}{\lambda_b} + \frac{\lambda_c - \lambda_b}{\lambda_c \lambda_b} \right). \tag{18}$$

Simultaneously, if only protective barrier is considered, the value $p_0(t)$ is computed from Eq (14), and $p_2(t)$ as state of system failure is given by

$$p_2(t) = 1 - e^{-\lambda_b t}. \quad (19)$$

Let's illustrate the state transition probabilities by assuming arbitrary the values of degradation rates λ_i. The values of λ_b approximately correspond to real values of polymer coatings presented in our previous publication (Kamaitis 2007b). For instance, it was found that in some liquid solutions the rate of deterioration of IKA polymer coatings varies approximately from 0.043 to 0.183 1/year. There were no available data about λ_c and λ_s. These values were accepted arbitrary (based on some literature data) with realistic assumption that $\lambda_b < \lambda_c < \lambda_s > 0$.

Graphical interpretation of Eqs (14)–(17) for the specified values of system parameters is shown in Fig. 3. As expected, as the time increases, the probability of three-component system being in state p_0 decreases, but increases the probability of being in states p_1, p_2, and p_3.

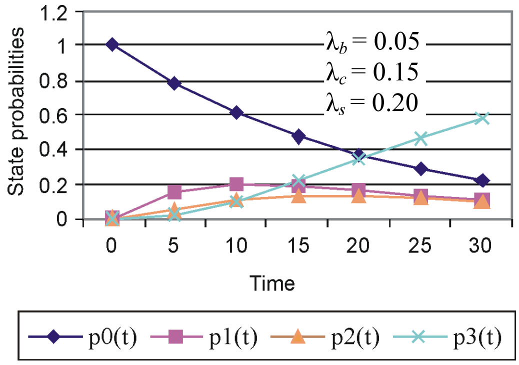

Fig. 3. Time dependent state probabilities for CPS

5. Performance indices

Once the probability $p_i(t)$ that the system is in state i at time t is known, the system reliability can be calculated as the sum of state probabilities taken over all the operating states. From Eqs (14), (15), and (16) the reliability for one, two or three-component protection system is expressed as

$$R(t) = \sum_{i=0}^{n-1} p_i(t). \quad (20)$$

The unreability of the system can be calculated from Eqs (17), (18), (19) or directly from Eq (20) as

$$1 - R(t) = 1 - \sum_{i=0}^{n-1} p_i(t), \quad (21)$$

where n is number of units in the system.

The plots of Eqs (20) and (21) for the specified varying values of system parameters λ_b, λ_c, and λ_s are shown in Fig. 4. We can see that when the values of time t become large, the probability of the system working in unsafe mode increases. This is typically observed for deteriorating non-maintainable systems.

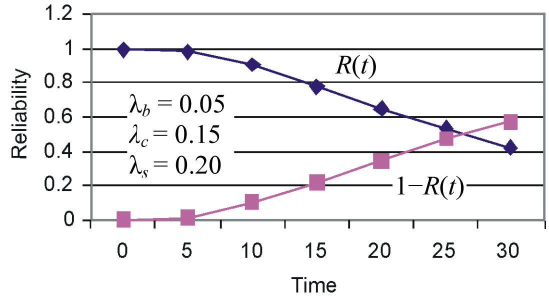

Fig. 4. Reliability and failure probability of the three-component system

Fig. 5 shows simulation results for the reliability of the system consisting of a single protective barrier, protective barrier and concrete cover (two-component system) as well as three component system at different protective barrier failure rates ($\lambda_b = 0.01$ and $\lambda_b = 0.1$) for the specified values of member parameters.

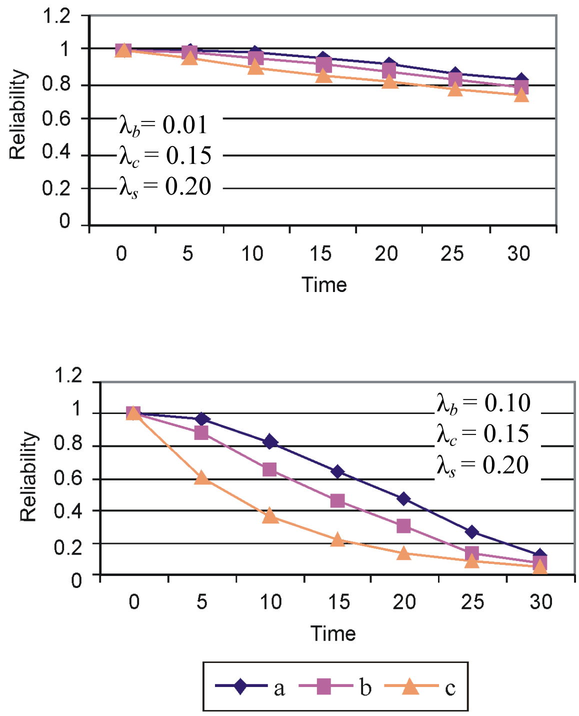

Fig. 5. Influence of component numbers on the systems reliability: a – three-component system; b – two-component system; c – single-component system

The results in Fig. 5 show that CPS has its system reliability higher than the reliability of its most resistant component. Two other components improve, in general, the reliability compared to the single protective barrier. In that case, the reliability and MTTF of the system will be increased. However, it can be seen that failure rate of protective barrier is a main factor. The higher the protective barrier reliability, the less sensitive the protection is to the number of components.

Fig. 6 shows the plots of Eq (20) for the varying values λ_b, λ_c, and λ_s.

As expected, the increase in the values of the member's rate of degradation decreases the systems reliability.

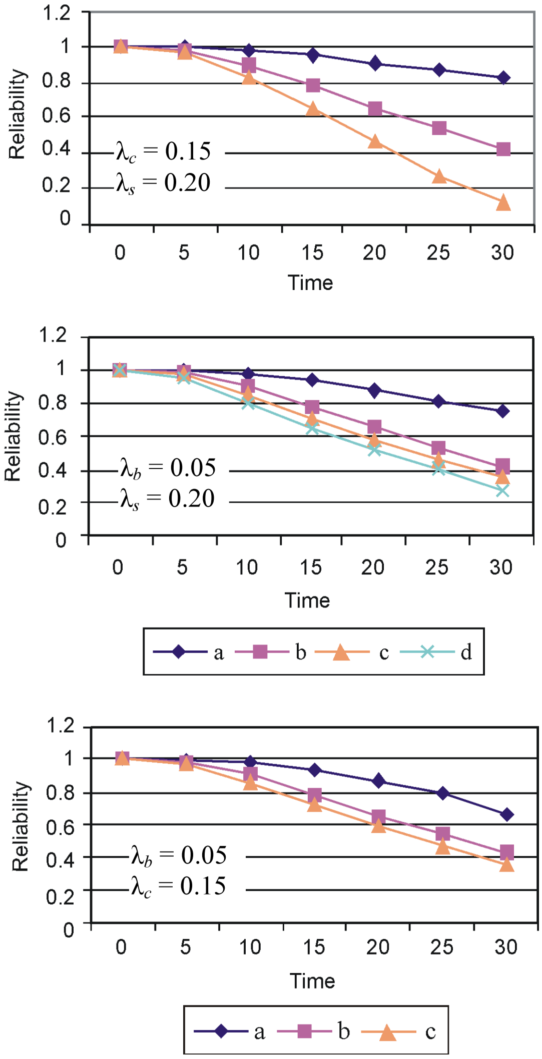

Fig. 6. Effect of varying λ_b: a – λ_b = 0.01; b – λ_b = 0.05; c – λ_b = 0.10 (top), λ_c: a – λ_c = 0.03; b – λ_c = 0.15; c – λ_c = 0.30; d – λ_c = 0.75 (midle), λ_s: a – λ_s = 0.04; b – λ_s = 0.20; c – λ_s = 0.40 (bottom) on the reliability of protection system

It is obvious that protective barrier's reliability has the most influence on overall system reliability. Note that much larger possibilities for varying of λ_b with different barrier systems exist in practice. Protective barriers, including also polymer coatings, are, in general, the multi-component systems and relatively expensive materials. To optimize protective system properties and costs, coating design should be one of the main focuses. Two other components may increase the overall reliability and decrease the costs of protection, if the resistances of these components are compatible with the exposure conditions.

The system mean time to failure (MTTF) is given by

$$MTTF = \int_0^{\infty} R(t)dt = \int_0^{\infty} \left[\sum_{i=0}^{n-1} p_i(t) \right] dt. \quad (22)$$

Inserting Eqs (14), (15), (16) in Eq (22), the following expression is obtained:

$$MTTF = \sum_{i=1}^{n} \frac{1}{\lambda_i}. \quad (23)$$

Eq (23) is shown graphically in Fig. 7 for the specified values of model parameters. As can be seen, the system's MTTF decreases for the increasing values of λ_b, as it should be.

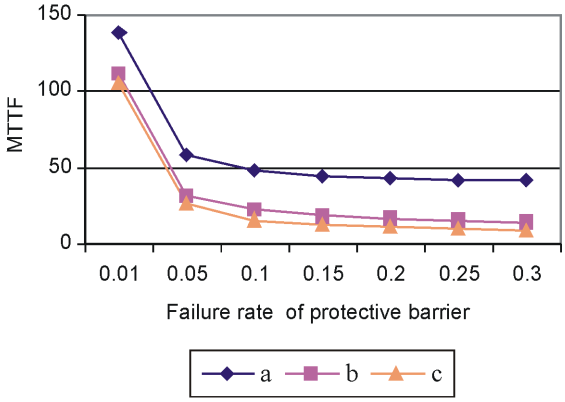

Fig. 7. System MTTF for the varying λ_b: a – λ_c = 0.03; λ_s = 0.20; b – λ_c = 0.15; λ_s = 0.20; c – λ_c = 0.75 λ_s = 0.20

The failure rate for entire protection system may be defined in terms of the system reliability

$$\lambda_{CPS}(t) = -\frac{1}{R(t)} \frac{d}{dt} R(t). \quad (24)$$

Then, inserting Eq (20) for three-component system, we have

$$\lambda_{CPS}(t) = \frac{\lambda_b \lambda_c \lambda_s (A + B + C)}{\lambda_c \lambda_s A + \lambda_b \lambda_s B + \lambda_b \lambda_c C}, \quad (25)$$

where

$$A = (\lambda_c - \lambda_s) e^{-\lambda_b t};$$
$$B = (\lambda_s - \lambda_b) e^{-\lambda_c t};$$
$$C = (\lambda_b - \lambda_c) e^{\lambda_c t}.$$

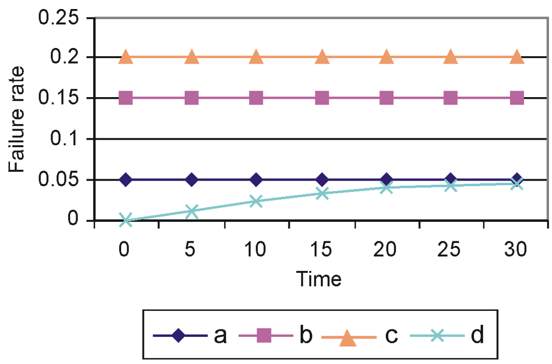

Fig. 8. Failure rates of protective barrier (a), concrete cover (b), steel reinforcement (c), and entire system (d)

Fig. 8 shows the failure rate for protection system along with the failure rates for single members. For even though the member failure rates are constants, the failure rate for the system is function of time, having zero failure rate at t = 0. The failure rate then increases to an asymptotic value of λ_b, as $t \to \infty$.

6. Reliability verification

The reliability of CPS is understood as the capacity of the system to fulfil the protection function with given probability for the specified service time. Based on the relationships between reliability and time for different systems and aggressive exposures, as presented in section 5, the service time of protective system T_{CPS} is defined as the time when the reliability of the particular system falls below an acceptable level.

From Eq (1) the reliability of protection system can be determined as follows

$$P\{T_{CPS} \geq t_d\} = P\{T_{CPS} = t_b + t_c + t_s \geq t_d\} \geq P_{t\arg}, \quad (26)$$

where t_b is service time of protective barrier as a function of type and thickness of cover; t_c – the time for concrete cover deterioration as a function of cover quality and thickness; t_s is time for reinforcing bars to cause acceptable corrosion level as a function of environmental conditions, type of structure and reinforcement.

Generally, the structural target reliability level P_{targ} depends on the methods of reliability analysis, failure causes and modes, and failure consequences. The acceptable level P_{targ} is chosen by limit states (SLS, ULS) requirements and is influenced by economic considerations.

Normally, for materials and components target reliability can be accepted as $P_{targ} = 0.9$.

The calculation of failure probability for a protection system is not difficult, if the potential failure modes for individual elements are known. The reliability of component *i* can be expressed also as

$$R_i(t) = P\{t_i \geq t_{di}\} = P\{d_i \geq x_i(t)\} \geq P_{t\arg.i}, \quad (27)$$

where $x_i(t)$ is loss of thickness d_i of a member at time *t*.

Protection model has been illustrated numerically assigning hypothetical values to the constants involved. It is necessary to assume that the rates of deterioration λ_i are functions of the mechanical, chemical and geometrical properties of components and external aggressive environment. Various deterioration models of reinforced concrete components have been investigated and extensive reviews of such research can be found in publications. A need exists for analysis of the model of realistic component failure rates. This step is beyond the scope of the present paper.

7. Conclusions

1. A model of three-component corrosion protection system (CPS) for reinforced concrete structures in aggressive environments is developed; it combines the non-identical with different properties of individual components. The performance of multi-component corrosion protection system is proposed to generate with non-repairable cold standby models. This model can be applied in a number of real situations, when protection system is not easily accessible for maintenance/repair or repair is time-consuming and costly (underground structures, pipes, industrial chimneys).

2. The system of differential equations for three-component system with one active unit and two spares in cold standby (Fig. 1) is set up to describe the transition states of protection system [Eqs (11), (12)]. The components of the system are modelled with an exponential failure rate, different for each component. Exponentially deterioration rate of components was accepted due to simplicity of analysis. The transition states for one protection barrier (single component system) or protection barrier and concrete cover (double component system) is also presented.

3. The reliability indices such as reliability [Eqs (20), (21)], mean time to failure [Eqs (22), (23)] and failure rate [Eqs (24), (25)] of multi-component protection system are analyzed and defined by using Markovian deterioration/renewal process. To study the sensitivity of parameters the simulation results, considering the number of components and different values of component failure rates on overall protection system reliability indices, is presented. Taking into consideration the performance of concrete cover and reinforcement, additional improvement can be achieved that is frequently observed in practice. It is obvious that protective barrier reliability has the most influence on overall system reliability.

4. Application of cold standby redundancy and Markov modelling is a suitable tool to assess the overall reliability of corrosion protection systems. Results of investigation presented in this paper are the first attempt to model the performance of multi-component corrosion protection of reinforced concrete structures as redundant standby system. The model could be extended by using other probability distributions, introducing maintenance/repair scenarios and cost benefit analysis of various protective systems for particular applications.

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GELŽBETONINIŲ KONSTRUKCIJŲ SU DANGOMIS KOROZINĖS APSAUGOS MODELIAVIMAS REZERVINE SISTEMA

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S a n t r a u k a

Įvairios apsauginės dangos naudojamos gelžbetoninėms konstrukcijoms stipriai agresyvioje aplinkoje apsaugoti. Straipsnyje nagrinėjama daugiasluoksnė antikorozinė apsauga, susidedanti iš apsauginio barjero, betoninio apsauginio sluoksnio ir plieninės armatūros. Sistema modeliuojama kaip trijų nevienodų komponentų šaltai rezervinė sistema. Ši sistema yra neremontuojama. Tai atvejai, kai sistema sunkiai pasiekiama, remontas ilgai trunka arba brangus. Tariama, kad sistemos visų komponentų irimo intensyvumas yra eksponentinis ir skirtingas. Remiantis šiomis prielaidomis, naudojant Markovo suirties (atnaujinimo) teoriją, kai kurie svarbūs patikimumo rodikliai, tokie kaip sistemos patikimumas ir vidutinis laikas iki suirties, gali būti nustatyti. Skaitinis pavyzdys iliustruoja analitinio modelio taikymą ir jo jautrumą vertinant antikorozinės apsauginės sistemos patikimumą.

Reikšminiai žodžiai: antikorozinė apsauga, neremontuojama sistema, rezervinė sistema, Markovo procesas, patikimumas, laikas iki suirties.

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