IJE TRANSACTIONS B: Applications Vol. 34, No. 02, (February 2021) 572-580

International Journal of Engineering

Journal Homepage: www.ije.ir

The Effect of Stochastic Properties of Strength Reduction Function on the Time-Dependent Reliability of Reinforced Concrete Structures

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PAPER INFO

Paper history:
Received 30 May 2020
Received in revised form 03 September 2020
Accepted 03 September 2020

Keywords:
Time-dependent Reliability
Reinforcement Corrosion
Stochastic Model
Strength Reduction Function
Probability of Failure

ABSTRACT

Quantitative calculation of structural safety using its specific limit-states is of great importance. Due to the stochastic properties of strength, loading, and environmental reduction functions, these parameters cannot be considered as deterministic variables. In this paper, a probabilistic model including the stochastic properties of the strength reduction factor was proposed to calculate the time-dependent reliability of concrete structures. In this model, the statistical properties of applied loads were also considered. The strength reduction model was calculated quantitatively using the statistical properties of the reducing agent. In this research, the major factor contributing to the strength reduction is the reduction in the cross-section of the steel bars, reduction of bonding strength, and the spalling of the concrete cover due to reinforcement corrosion induced by chloride ingress. The results of this model were compared to the calculation of reliability using the direct implementation of strength values and another simplified method that only considers initial strength as a random variable. In the methods under investigation, the effect of the uncertainty of reducing factor on the mean and coefficient of variation of results was also studied. The results showed that the probability of failure increases between 25 to 50% when the uncertainty of the reducing factor is taken into account. The proposed model has more realistic results than the simplified model, and these results could be improved for achieving more exact outcomes with lower uncertainty.

doi: *10.5829/ije.2021.34.02b.31*

NOMENCLATURE

c	Concrete clear cover (cm)	P_{fD}	Deterministic failure probability
C_{cr}	Threshold chloride ions required to corrosion initiate (kg/m^3)	P_{fi}	Instantaneous failure probability
C_s	Chloride ion content at the surface of concrete (kg/m^3)	P_{fR}	Real failure probability
C_0	Initial chloride content in concrete (kg/m^3)	P_{fS}	Stochastic failure probability
Dc_0	diffusion coefficient of chloride ions in concrete (Cm^2/year)	q, Q	load
D_0	Reinforcement diameter (mm)	r, R	strength
f_Q, f_R	Probability density function of load and strength	R_0	Initial strength
f_θ	Probability density function of θ	s, S	load
F_Q, F_R	Cumulative distribution function of load and strength	t	time (year)
g, G	limit-stat function	t_L	life time
i_{cor}	corrosion current density (μA/cm^2)	T_i	corrosion initiation time (year)
L	Structural reliability	V_i	Coefficient of variation of i

Greek Symbols

θ	Strength random coefficient
λ_Q	mean occurrence rate of live load

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Please cite this article as: S. A. Hosseini, N. Shabakhty, S. S. Mahini, The Effect of Stochastic Properties of Strength Reduction Function on The Time-Dependent Reliability of RC Structures, International Journal of Engineering, Transactions B: Applications Vol. 34, No. 02, (2021) 572-580

1. INTRODUCTION

Structures are affected by environmental agents and aging over time. These phenomena are associated with time-dependent changes in material properties and lead to a decline in the system performance in the operational lifetime [1]. Reinforcement corrosion due to carbonation and chloride ion penetration affects the efficiency of reinforced concrete (RC) structures. In aggressive environments, premature failure of RC systems due to reinforcement corrosion was considered one of the most critical durability issues [2,3]. The key causes of exposure to chloride ion are the deicing salts, seawater, and airborne salt [4]. The net cross-sectional area of the reinforcements is reduced during the corrosion process, and the resulting damaging effects emerge. Cover cracking, decrement of the concrete cross-sectional area and bond reduction between the concrete and the reinforcement are the most significant effects of reinforcement corrosion, which affect the strength and workability of the structures [5,6].

To evaluate the failure probability of a system, strength reduction mechanisms and their stochastic properties as well as the load history have to be taken into account [7]. A major factorin the structural reliability is the uncertainty of load and strength parameters [8,9]. Some uncertainties do not change over time, but others known as stochastic processes do [10].

The out-crossing rate approach is connventionally employed for calculating the reliability of structures under the effect of reducing factors [11,12]. It leads to a lower bound estimation for the probability of failure. Considering the random properties of strength parameters, Mori and Ellingwood introduced an approach to calculating time-dependent reliability [13]. Accordingly, loads are assumed as a stochastic process and modeled as a Poisson process. The method introduced by Mori and Ellingwood is based on the calculation of the probability of failure using the adaptive Monte Carlo sampling method. The method has been employed for the assessment of the lifetime of many concrete structures [14,15]. Vu and Stewart adopted this method to calculate the time-dependent reliability of concrete bridge deck [16]. The important issue associated with the calculation of time-dependent reliability in this method is how to employ the strength reduction model. The manner of strength reduction over time influences the calculation of reliability [17]. In this method, strength at each time, $R(t)$, is obtained based on multiplying the initial strength, R_0, in the strength reduction function, $G(t)$. In this model, the effect of variations of strength parameters and reducing factors on $G(t)$ and also the effect of these variations on reliability are considered qualitatively, and the stochastic properties are considered only in the initial strength. However, only a few studies have been conducted on the effect of strength reducing factor and its stochastic properties on structural safety [18,19].

In this study, a strength reduction function was obtained by considering the stochastic properties of reducing factors and the statistical properties of materials. The stochastic properties of reducing agent and strength parameters were applied using a coefficient factor multiplied by the ratio of degraded strength at each time to the initial strength. In this paper, chloride ions ingress into the concrete is considered as the environmental aggressive factor that causes degradation of concrete strength over its lifetime. Bending strength at each time is calculated using the Monte Carlo random sampling method, and then the statistical parameters of strength are obtained for different scenarios. The reliability of the RC beam is calculated using the obtained stochastic coefficient. Time-dependent reliability was also calculated by two other methods: (1) considering degradation function as deterministic and applying stochastic properties of strength only in initial strength; and (2) direct implementation of degraded strength with its stochastic properties in reliability calculation. Results indicate that without considering the stochastic properties of environmental factors on the reduction function, the reliability value will be an upper limit of reliability which does not coincide with real conditions.

2. TIME-DEPENDENT STRENGTH AND STOCHASTIC LOAD PROCESS

To consider load and strength uncertainties, these variables are assumed as random variables [20]. The stochastic properties of load and strength and time variations of the strength of a structure exposed to the Q and S loads are schematically shown in Figure 1. These loads have the probability density function $f_{S,Q}$ and are exerted on the structure with varying intensities of (S_i) and (Q_i) over time. In this figure, strength value decreases over time, so the strength probability density function is shown as $f_R(r,t)$ at any time. As seen in this figure, if structural reliability at any time is calculated only on the basis of the instantaneous strength and load values, the resulting value will be the upper limit for the reliability at that time. The reason is that at that specific time, the collective effects of the previous times and the loading history are not taken into account.

In RC structures, material properties, environmental condition and some structural parameters change in the service lifetime. The probabilistic models of structural strength reduction are obtained using either mathematical models or the accelerated testing methods. Sometimes, a combination of both methods is employed [21-23]. The mathematic models used in the analysis of time dependent reliability are generally qualitative models [18]. The need for quantitative models for the prediction of future structural performance has led to the development of stochastic strength reduction models based on the Gamma model [24,25] and analytical models based on the effect of the reducing factors on the structural performance [26]. The application of this model with statistical distributions covering uncertainties of parameters leads to a better assessment of the stochastic behavior of structures. Moreover, through the reliability methods, a model for structural failure probability is obtained which helps develop a probabilistic model for prediction life time of structure. Mori and Ellingwood (1993) defined strength at each time, *R(t)*, as follows for the assessment of time-dependent reliability of degraded structure:

$$R(t)=R_0G(t) \tag{1}$$

where, R_0 is the initial resistance and *G(t)* is the resistance reduction function, which is defined qualitatively based on the type of reducing factor as a linear, parabolic or square root function. In calculations of reliability, the *G(t)* function is assumed to be deterministic and randomness of strength at each time is applied through the stochastic properties of initial strength.

To study the application of loads to structures various models have been proposed. These models consider the effect of concurrency of loads as well [15]. the occurrence and changes of the transient loads applied to the structure during time and place is assumed as a random process (Q_n in Figure 1). For these loads, in addition to the randomness of the intensity of the applied load, the duration of load is also random. The stochastic modeling of these loads is carried out based on the assumption that their occurrence is described by Poisson point process.

3. TIME-DEPENDENT RELIABILITY ANALYSIS

Assuming the strength model *R* and loading model *Q*, the structural component reliability at each time is expressed as follows:

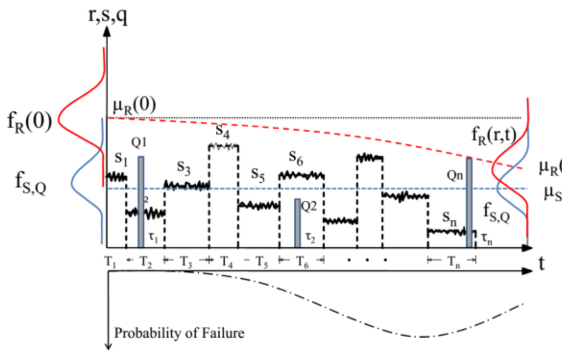

Figure 1. strength degradation and stochastic load process

$$L(0,t)=P\left[R(t)>Q(t)\right]=\int_0^\infty F_Q(r,t)f_R(r,t)dr \tag{2}$$

where, f_R is the strength probability density function and F_Q is the probability distribution function of the load. In order to calculate reliability at a specific time (e.g. t_L) all load events prior to this time shall not exceed the strength of the member.

In Equation (2), which is used to calculate reliability, the effect of the randomness of influencing parameters has to be taken into account. Hence, using the law of total probability, the number of occurrences of loads and initial strength are changed to the random variable, and reliability is obtained as follows:

$$L\{(0,t_L)\}=\int_0^\infty\int_0^\infty \exp[K_1]f_S(s)f_{R_0}(r)dsdr$$

where

$$K_1=-\lambda_Q t_L\left[1-\frac{1}{t_L}\int_0^{t_L}F_Q\{R_0G(t)-s\}dt\right] \tag{3}$$

where, f_{R_0} is the probability density function of the resistance of the structure, f_s is the probability density function of the load *S* and F_Q is the probability distribution function of the load *Q*. Also, λ is the mean occurrence rate of this load. In addition, in this equation, it is assumed that among the *S* and *Q* forces applied to the structure, *S* is applied permanently and the stochastic properties of the strength are applied only through the initial strength R_0 , where the randomness of aggressive agent is omitted. If actual values of structural strength are used at any time, there is no need to estimate strength based on the initial strength and the strength reduction function. Hence, in Equation (3), actual values of calculated strength (obtained based on the stochastic properties of the effect of the reducing factor) are used instead of the initial strength probability distribution function, $f_{R_0}(r)$, and strength degradation function.

In this paper, stochastic properties of strength are defined through a coefficient factor that represents the randomness of the ratio of strength at each time to initial strength:

$$G(t)=\theta(t)g(t) \tag{4}$$

where, *g(t)* is a deterministic function indicating the ratio of mean strength at each time to initial strength, and *θ(t)* is a random variable that applies the effect of the randomness of strength reducing factors to the strength reduction function. The mean value of *θ(t)* is equal to one and time-dependent coefficient of variation of this parameter is similar to the values of the strength reduction function. In order to apply the stochastic properties of corrosion to the strength reduction function, Equation (4) is put into Equation (1) to obtain the strength model at each time for the calculation of time-dependent reliability:

$$G(t) = R_0 \theta(t) g(t) \tag{5}$$

By changing the strength reduction function to a function with stochastic properties, Equation (3) changes as follows:

$$L\{(0,t_L)\} = \int_0^\infty \int_0^\infty \int_0^\infty \exp[K_2] f_\theta(\theta) f_S(s) f_{R0}(r) d\theta ds dr$$

where

$$K_2 = -\lambda_Q t_L \left[1 - \frac{1}{t_L} \int_0^{t_L} F_Q\{\theta R_0 g(t) - s\} \right] dt \tag{6}$$

By calculating strength at each time, the strength reduction function and its statistical parameters are obtained. Moreover, the best probabilistic distribution that reflects the randomness of this function is fitted to it to calculate $\theta(t)$. There is some uncertainty in the calculation of statistical parameters of the coefficient $\theta(t)$; thus, the calculated time-dependent reliability from Equation (6) have uncertainty too. Therefore, for the evaluation of this coefficient, time-dependent reliability is calculated based on applying degraded strength directly in Equation (3). Using stochastic properties of real strength at each time changes Equation (3) as follows:

$$L\{(0,t_L)\} = \int_0^\infty \int_0^\infty \exp[K_3] f_{R(t)}(r(t)) f_S(s) dr(t) ds$$

where

$$K_3 = -\lambda_Q t_L \left[1 - \frac{1}{t_L} \int_0^{t_L} F_Q\{R(t) - s\} \right] dt \tag{7}$$

where $f_{R(t)}$ is probability density function of real strength at time "t". Equation (7) is the best tool for evaluating time-dependent reliability if stochastic properties of degraded strength are known at each time.

4. ANALYTICAL MODEL

4. 1. Strength Degradation In this paper, the time-dependent reliability of reinforced concrete beam under the effect of chloride induced corrosion is studied. For this, the bending strength of the RC beam is calculated based on the cross-sectional reduction of corroded reinforcement, bond strength reduction and the spalling of the concrete cover due to reinforcement corrosion induced by chloride ingress.

In the period of corrosion propagation, it is critical to use parameters that can be immediately measured to determine the extent and severity of corrosion. Measuring the weight difference between corroded rebar and reference rebar is the most reliable method in this respect. For the measurement of the corrosion rate of reinforcement in structural concrete, many electrochemical and non-destructive techniques are available that the corrosion rate estimated in terms of a corrosion current density, i_{cor} [27,28].

Different models for estimating the remaining the cross-section of the reinforcement have been proposed based on the type of corrosion [29]. The time-variant diameter of reinforcement at time t is calculated as follow:

$$D(t) = D_0 - 0.0278 i_{cor}(I) \times (t - T_i)^{0.71} \tag{8}$$

where, T_i (year) is the corrosion initiation time and $i_{cor}(I)$ ($\mu A/cm^2$) is the corrosion current density in the corrosion initiation year.

The reinforcement corrosion due to chloride ingress is started when the chloride ion concentration at the reinforcement reaches a threshold value (C_{cr}). Fick's second law of diffusion is the most acceptable method that describes the penetration of chlorides through concrete [30]. Accordingly, the corrosion initiation time is calculated as follows:

$$T_i = \frac{c^2}{4D_{c0}} \left(erf^{-1}\left(\frac{C_s - C_{cr}}{C_s - C_0} \right) \right)^{-2} \tag{9}$$

where, C_{cr} is the threshold concentration of chloride ions required to corrosion initiate (kg/m^3); C_s is the chloride ion content at the surface of concrete (kg/m^3); C_0 is the initial chloride content in concrete (kg/m^3); D_{c0} is the diffusion coefficient of chloride ions in concrete (Cm^2/year); c is the concrete clear cover of reinforcement (cm); and erf is the error function.

Bond reduction between corroded reinforcement and concrete is evaluated by a model proposed by Bhargava et al., and concrete cover spalling is estimated based on empirical crack propagation model by Rodriguez *et al.* [14, 31].

Figure 2 shows the cross-section of a 4-m long simply supported RC beam. This beam is subjected to the live and dead loads. Also, it is assumed that this beam is subjected to chloride induced corrosion with corrosion current density of 1 µA/cm^2 and 3 µA/cm^2. These values cause moderate to severe effects on the concrete beam, respectively [14,32]. In order to study the effect of the strength reducing factor on the resistance reduction function, coefficients of variation V_i, of 0.1 and 0.3 are assumed for corrosion current density [14]. When the concentration of chlorid ions around the reinforcement reaches a critical value, reinforcement corrosion is initiated [32]. In order to calculate the corrosion initiation time for this model, the diffusion model was used based on Fick's second law [33].

For calculating corrosion initation time, the threshold chloride concentration is assumed as a uniform random variable within the range of 0.6- 1.2 kg/m3 [34]. Applying this assumption and using Equation (9) for a moderat environmental condition, Hosseini reported the random properties of the corrosion initiation time [35]. The mean corrosion initiation time for this beam is assumed to be T_i=10 years with the coefficient of variation (V_T) of 0.3.

The bending strength of RC beam reduces over time because of a reduction in the cross section of reinforcements, the bond reduction between the reinforcement and concrete, and reduction in concrete section due to cover spalling. The bending strength of the beam in the middle was calculated at each time considering the section dimensions and materials properties as random variable using the Monte Carlo Sampling method (MCS) [5]. In the MSC, a series of values of random variables with specified probability distribution is generated using invers transform method. If a_i is the generated uniformly distributed number within the rane of 0-1, the inverse transform method is adopted to equate a_i to the cumulative distribution function of random variable x_i as follows [36]:

$$F_X(x_i) = a_i \quad \text{or} \quad x_i = F_X^{-1}(a_i) \tag{10}$$

where F_X is the cumulative distributation function of random variable x.

Table 1 presents the mean values of the strength reduction function, $M_{G(t)}$, and the coefficient of variation of this function, $V_{G(t)}$, for i_{cor}=1.0 and V_i=0.3. Based on the results, the coefficient of θ(t) follows the lognormal distribution. Statistical properties of this parameter during the corrosion propagation period are shown in Table 1. These stochastic parameters are used in Equation (6) to calculate reliability at each time.

The mean value of $\theta(t)$ is equal to 1.0 and its standard deviation is determined proportionally to the strength reduction function $G(t)$. To calculate the

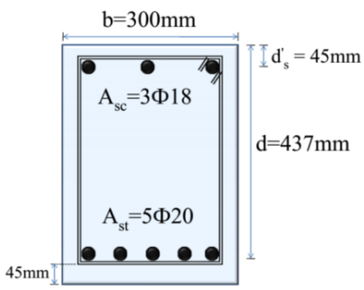

Figure 2. Cross-section of reinforced concrete beam at mid span

TABLE 1. Statistical parameters of strength degradation function and coefficient factor (i_{cor}= 1.0 μA/cm^2, Vi=0.3)

Time (Year)	$\sigma_{\ln(\theta)} \times 100$	$-\mu_{\ln(\theta)} \times 100$	$\mu_{G(t)}$	$V_{G(t)}$
1	0.59	10.91	1.0	0.11
10	0.44	9.26	0.95	0.11
20	0.17	5.88	0.81	0.11
25	0.17	5.84	0.77	0.12
30	0.18	5.98	0.74	0.15
35	0.18	6.03	0.71	0.16
40	0.19	6.19	0.68	0.15
45	0.19	6.22	0.65	0.14
50	0.21	6.41	0.63	0.13
55	0.20	6.38	0.61	0.13
60	0.22	6.58	0.59	0.13

stochastic properties of $\theta(t)$, samples generated from the MCS method are divided by the mean values at each time. Next, the statistical properties of the samples are calculated.

The coefficient of variation of $\theta(t)$ and mean values of degradation function over time are shown in Figures 3 and 4 for different corrosion scenarios. As shown in these figures, before starting the corrosion effects, the coefficient of variation of bending strength is approximately equal to 0.12. This parameter begins to increase after the onset of corrosion due to the effect of the uncertainty associated with the reducing agent. An abrupt increase was observed in the coefficient of variation related to the time of concrete spalling and reduction of the bond strength. It is clear from Figure 4 that V_θ is sensitive to the uncertainty in the corrosion current density, so that with larger coefficient of variation of the i_{cor} , the coefficient of variation of $\theta(t)$ increases. However, as shown in Figure 4, this increase does not affect the mean residual strength. It can also be

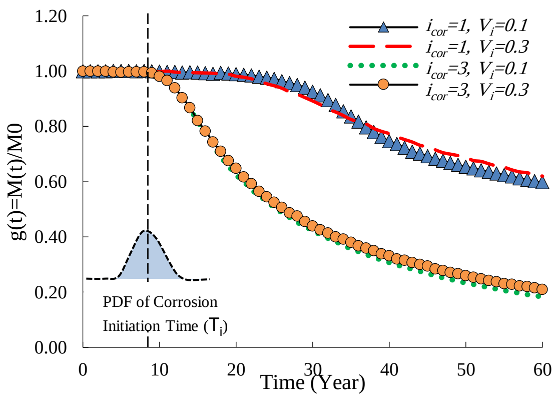

Figure 3. The mean values of degradation function

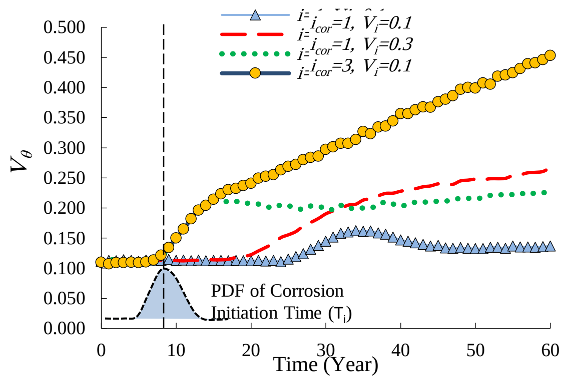

Figure 4. Coefficient of variation of $\theta(t)$

concluded from this figure that due to the significant changes in the coefficient of variation of resistance over time, using the stochastic properties of initial resistance is not a valid assumption in reliability calculations.

4. 2. Time-dependent Reliability In this part, the failure probability of RC beam is calculated in three ways. The first method consists of calculating reliability based on Equation (3). In this method, stochastic properties of resistance at each time is only applied to the strength reduction function through the initial strength. The failure probability obtained through this method is shown by P_{fD} which stands for a deterministic reduction function. In the second method, reliability is obtained through Equation (6) and stochastic properties of strength are also calculated both through initial strength and by coefficient $\theta(t)$ to the time-dependent reliability. Probability of failure calculated in this method is introduced as P_{fS}. In the third method, the resistance at each time is directly calculated through the MC random sampling method and the resulting values are also directly used in the calculation of reliability. The probability of failure based on this method is shown as P_{fR}. In all of the three methods, the Monte Carlo and numerical integration methods are employed simultaneously to calculate the reliability and probability of failure. Loads applied to the RC beam are live and dead loads. Live load is applied to the structure transiently with a mean occurrence rate of λ while the dead load is permanently applied. It is assumed that the loads are statistically independent. Occurrence of live load follows the Poisson distribution and has *extreme type I* probability density function [32]. Dead load is applied permanently with a normal probability distribution function.

The probability of failure calculated by all of the three methods are shown for V_i=0.1 and V_i=0.3 in Figures 5 and 6. It is clear from these figures that the probability of failure that is calculated on the basis of random properties of the initial resistance, P_{fD} , is less than P_{fS} which uses the random properties of the resistance reduction function. In fact, the effect of the stochastic properties of the reduction factors has elevated the probability of failure during the time. It is also evident from Figures 5 and 6 that raising the uncertainty in the reducing factor applied through V_i has led to higher probability of failure in all the three methods. The results indicate that the probability of failure is low in the first and second methods. This situation, especially when the uncertainty in the decreasing factor is low, shows a greater difference. As shown in Figures 5-8, for the bending strength up to the time of spalling and reduction of the bond strength, the probability of failure from all the three methods is equal. This means that the values of P_{fD} can be used to estimate the probability of failure during this time, but after that, other methods should be employed. Moreover, the results show that the proposed method has better results than the P_{fD} method. In Figures 5-8, P_{fi} represents the instantaneous probability of failure calculated regardless of the load history effect. This instantaneous failure probability is less than real values, which is sometimes used for the probability of failure of structures.

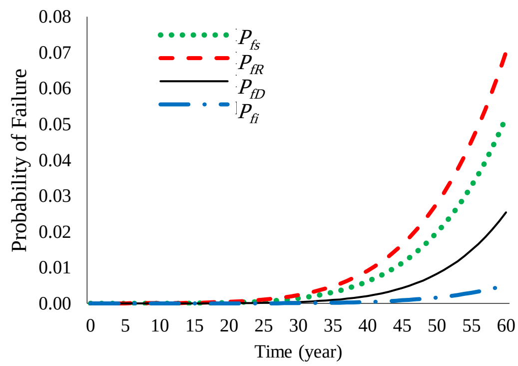

Figure 5. P_{fD} , P_{fS} and P_{fR} for corrosion current density of 1.0 μA/cm^2(V_i=0.1)

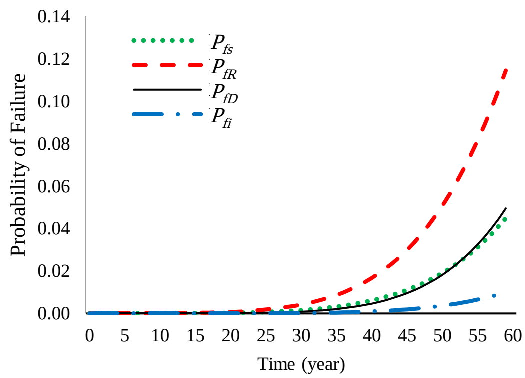

Figure 6. P_{fD} , P_{fS} and P_{fR} for corrosion current density of 1.0 μA/cm^2 (V_i=0.3)

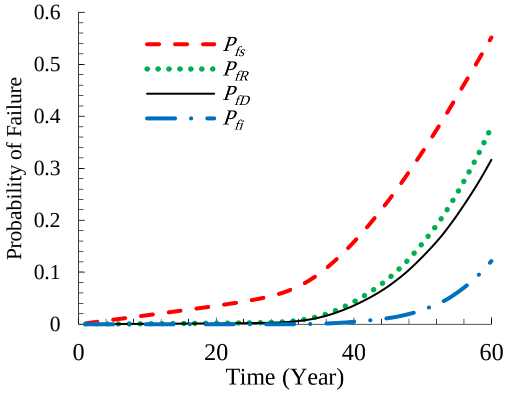

Figure 7. P_{fD} , P_{fS} and P_{fR} for corrosion current density of 3.0 μA/cm^2(V_i=0.1)

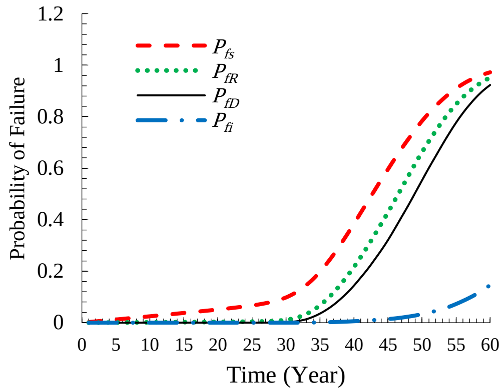

Figure 8. P_{fD} , P_{fS} and P_{fR} for corrosion current density of 3.0 μA/cm^2(V_i=0.3)

Figures 9 and 10 show the coefficient of variation of the proposed method (V_{Pfs}). As shown in thess figures, because the number of samples is constant in the MC method, the amount of uncertainty has diminished due to higher probability of failure. It should be noted that the value presented in this figure represents the

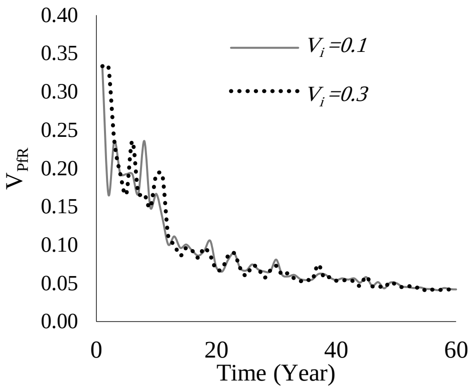

Figure 9. Coefficient of variation of P_{fS} i_{cor}= 1 μA/cm^2

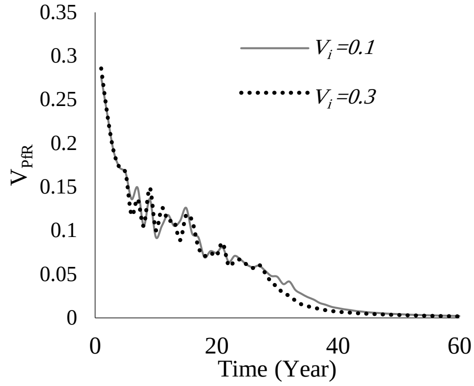

Figure 10. Coefficient of variation of P_{fS}, i_{cor} = 3 μA/cm^2

instantaneous uncertainty, and the calculation of the total uncertainty follows the cumulative effect of the preceding times.

5. CONCUSION

In this paper, the effect of stochastic properties of strength reducing factor on the estimation of time-dependent failure probability of concrete beam was studied. The reducing factor considered in this research was the effect of reinforcement corrosion on the bending strength of the RC beam. The stochastic properties of this effect on bending strength were simplified using a coefficient factor. The probability of failure at each time was calculated through the effect of the coefficient factor on the mean strength value. Also, a comparison was made between the results obtained based on the real values of strength and those with the use of the deterministic mean strength only. According to the results, the application of uncertainties of the reducing factor leads to more accurate results by the application of the coefficient factor for the calculation of the probability of failure. For chloride ingress as an aggressive agent, the simplified qualitative method (P_{fD}) can be used before the initiation of the occurrence of spalling and the reduction of the bond between reinforcement and concrete, for the ease of calculation. However, after the initiation,the stochastic properties of reducing agent should be taken into account.

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Persian Abstract

چکیده

محاسبه ایمنی سازه به صورت کمی و بر اساس تابع شرایط حدی تعریف شده برای آن منجر به ارزیابی عمر سازه می‌شود. به دلیل خواص تصادفی مقاومت، بارهای اعمالی به سازه و همچنین اثر عوامل مخرب محیطی، نمی‌توان پارامترهای موثر را به صورت قطعی در نظر گرفت. در این پژوهش یک مدل احتمالاتی مقاومت که در برگیرنده خواص تصادفی عوامل کاهنده مقاومت می‌باشد برای محاسبه احتمال خرابی سازه بتنی پیشنهاد شده است. در این مدل خواص تصادفی نیرو نیز در نظر گرفته شده است. عامل اصلی کاهنده مقاومت که مورد بررسی قرار گرفته است شامل خوردگی میلگرد ناشی از نفوذ یون کلر به همراه اثرات آن بر مقاومت خمشی بوده است. نتایج حاصل از مدل پیشنهادی با دیگر مدل‌های موجود مقایسه شده است. نتایج نشان می‌دهد که در نظر گرفتن عدم قطعیت به صورت مدل پیشنهادی موجب محاسبه احتمال خرابی بزرگتری برای سازه مورد نظر می‌شود که بیانگر نزدیک بودن به شرایط واقعی سازه است. محاسبه احتمال خرابی وقتی که اثر عدم قطعیت صرفاً مقاومت اولیه در نظر گرفته می‌شود باعث محاسبه قابلیت اطمینان سازه به صورت دست بالا (بین ۲۵ تا ۵۰ درصد) و غیر محافظه کارانه خواهد شد. نتایج نشان می دهد تا زمان قبل از رخداد پوسته شدن و کاهش باند بین بتن و میلگرد می‌توان از مدل‌های ساده شده موجود استفاده کرد و بعد از این رویدادها، نتایج مدل‌های قبلی غیر محافظه کارانه خواهد بود.