T. J. Da Silva received BS in Civil Engineering in 1980 in the Federal University of Uberlândia, Brazil. He developed his PhD research in the Technical University of Catalonia (1998), on Service Life of Reinforced and Prestressed Concrete Structures. This is the main research interests. He has been working as a professor since 1980 in the Department of Civil Engineering of Federal University of Uberlândia.

P. Roca graduate in 1985. He developed his PhD research on Nonlinear Analysis of Reinforced and Prestressed Concrete Shell Structures. He has been working as a lecturer and researcher since 1989 in the School of Civil Engineering of the Technical University of Catalonia. His actual activity is devoted to the evaluation of existing building structures and monuments.

INTRODUCTION

After several years in use, the concrete structures may show a deterioration process due to the maintained action of some aggressive agents, among which the most common are the carbon dioxide and the chlorides. By reducing the reinforcing steel section or the bonding of steel to concrete, carbon dioxide or chlorides action may lead to the failure of the structural elements. Due to the technical and economical importance of these phenomena, many important groups and researchers have been devoted to the investigation of the process of corrosion of reinforcement (1, 7, 10, 13, 17, 20). In spite of the results obtained through this wide research activity, there is not yet agreement on some important aspects, such as the criteria allowing to determine the level of safety of deteriorated structural elements after the information obtained through inspection. In any case, it is clear that the evaluation of the probability of failure of a deteriorated structure requires a very detailed inspection extended to many points of the element.

The use of non destructive techniques allows to obtain the information needed to identify the parts of the structure in corrosion process (7). Electrochemical techniques, in particular, make it possible to estimate the corrosion intensity in these parts (3). However, the full interpretation of the electrochemical tests and, particularly, the determination of the residual cross section of the steel bars, require the previous knowledge of the age at which corrosion began. This age is an important information necessary to obtain the probability of failure of a concrete structure.

Due to the large number of random factors that affect the behavior of the material and their interaction, the determination of the probability of failure of deteriorated structures cannot be carried out in a deterministic way (19). The methods that combine the theory of the reliability and the stochastic analysis with the use of mathematical models of deterioration are at present supplying the best results (5). The use of reliability analysis allow to define the stage of deterioration in the different parts of the slabs making it possible to design the appropriate repair (9). This paper presents a method for the reliability updating of concrete slabs based on the aforementioned ideas.

PROPOSED METHOD

The method for reliability updating of one-way floor slabs is based on stochastic analysis applied upon deterministic models already developed by different researchers to model the depth of carbonation, penetration of chlorides and corrosion of reinforcement. In the analysis, the different parameters considered in those models are treated as random variables. A stochastic treatment is given also to the geometry, the mechanical properties of the structure and the external actions. To take into account the loss of load-bearing capacity criteria, the probability of failure is finally determined from the probability functions of both the resisting response and the external actions.

The principal mechanism of deterioration considered is the loss of section of the bars due to corrosion, both as a consequence of the carbonation or the attack of chlorides. Tuutti's model (20) is used, in which corrosion process is divided in a first period of initiation and a second period of propagation.

The development of the method was carried out through two different phases. A first one was devoted to the analysis and adjustment of the mathematical models, and also to obtain data on the geometry and mechanical properties of concrete and steel. Due to the large variability of the environmental and service conditions, a certain number of different models, proposed to account for different environmental or service conditions, were taken into consideration. During the same phase, a large number of tests on cores or fragments of beams obtained from different buildings, together with destructive tests, were carried out. The same procedure was used to obtain data on the geometry and mechanical properties of concrete and steel. The main result of this phase is a set of initial distributions of probability associated with the considered random variables.

The second phase consisted on the definition of the procedure which should enable to apply the method to actual cases of deteriorated buildings in order to conclude on their safety. The first step is the bayesian updating of the distribution functions by means of additional data obtained through regular inspection oriented to slabs that show pathological manifestations related to the studied processes of deterioration. In situ tests using pH indicators are performed on the concrete cover of the bars. Microcores of concrete, with diameter between 20 and 50 mm, are extracted and tested in laboratory. A preliminary analysis should permit to conclude whether the problem observed is due to the corrosion of the reinforcement. If so, additional tests are carried out to determine the phase of the process of degradation (initiation or propagation). If the steel bars are subjected to a process of corrosion, additional studies are performed to determine the state of the process, i.e., the velocity and the type of corrosion (generalized or in pits). Complementary information must be obtained with regard to the environmental conditions, including the relative humidity, the concentration of CO_2 in the atmosphere and concentration of chlorides in the surface of the concrete, the parameters related to the geometry, the strength of concrete and steel, and the weight of the sustained walls, pavement and the coating of the inferior surface of the slab.

The first phase of the study led to the election of the more appropriate model to simulate the deterioration phenomena. In the method, several different models are considered to account for the initiation of carbonation (4, 14, 15, 16, 18, 20), while others are considered for the attack of chlorides (8, 14) and the phase of propagation (2, 14). In the following discussion, models are described for each of the deterioration phases or phenomena, one of them being later used in the example included.

The mathematical function normally used for to estimate the depth of carbonation can be written as:

$$x = k \cdot \sqrt{t} \qquad (1)$$

where x is the penetration depth; t : the exposure time; k : a constant which is dependent on the effective diffusivity of CO_2 through the concrete, the concentration difference and quantity of bound CO_2.

Tuutti (20) propose the following equation to evaluate the constant k in (1):

$$C_s / C_x = \pi^{1/2} \cdot k / (2 D^{1/2}) \cdot exp(k^2 / 4 D) \cdot erf(k / 2 D^{1/2}) \qquad (2)$$

where: C_s : CO_2 concentration in the atmosphere; C_x : CO_2 which has reached in the concrete; D : diffusion coefficient of CO_2; erf : error function

The mathematical model developed by Papadakis and al. (15) for physicochemical processes in concrete carbonation is based on differential mass-balances of gaseous CO_2 , solid and dissolved $Ca(OH)_2$, CSH, and unhydrated silicates. The proposed equation in order to estimate the carbonation depth is:

$$x_c = 350 (\rho_c / \rho_\omega) \cdot [(\omega / c) - 0,3] / [1 + (\rho_c / \rho_\omega) \cdot (\omega / c)] \cdot (1 - RH /$$

$$100) \cdot \{ [1 + (\rho_c / \rho_\omega) \cdot (\omega / c) + (\rho_c / \rho_a) \cdot (a / c)] \cdot y_{CO2} \}^{1/2} \cdot \sqrt{t} \qquad (3)$$

where:

x_c is the depth of carbonation (mm); ρ_c, ρ_ω, ρ_a are the mass density of cement, water and aggregates, respectively (kg/m^3); ω / c, a / c are water/cement and aggregates/cement ratios, respectively; RH : relative humidity (%); y_{CO2} : ambient CO_2 content by volume; t : time (years)

In a deterioration due to the action of chlorides, the more important mechanism is the penetration of chlorides for diffusion. The models developed to account for this effect are based on the Fick's second law for diffusion. By considering the Fick equation for the problem in study with some additional assumptions (8), it is possible to derive the following equation:

$$(C_f - C_0)/(C_s - C_0) = 1 - erf(Z) \qquad (4)$$

where: C_f : chlorides concentration in the depth x_{cl}; C_0 : initial chloride concentration in the concrete; C_s : surface chloride concentration; and $erf(Z)$: error function.

The Z value is determined by: $Z = x_{cl} / 2\,(D_{Cl}\, t)^{1/2}$

where: D_{Cl} : diffusion coefficient of concrete with regard to chlorides; and t : exposure time. The experimental determination of the concentrations permits to characterize the value of Z and thus to estimate the depth of penetration of the chlorides.

For the phase of propagation, the more important parameters are the accessibility of the oxygen and the resistivity of concrete. The models associated with this phase consider principally the loss of section of the rebars (2). Faraday's law is utilized assuming that the metal is pure iron. Thus, the corrosion rate is proportional to corrosion intensity. The diameter of the bars can then be obtained by the following equation:

$$\phi_t = \phi_i - 0.0232 \cdot i_{corr} \cdot t \qquad (5)$$

where: ϕ_t : remaining diameter at time t (mm); ϕ_i = diam : initial diameter (mm); i_{corr} : corrosion intensity ($\mu A / cm^2$); constant 0.0232 : factor to translate $\mu A / cm^2$ into μm / year; and t : time (year)

The corrosion intensity constitutes an effective and direct measurement only in the case of generalized corrosion, while becoming uncertain in the case of corrosion for pits. This kind of corrosion can be better estimated by applying a certain experimental coefficient to the values obtained through the measurement of the current of corrosion (3, 20).

After the definition of suitable models for the specific case and after updating the basic variables, the probability of failure is estimated using the representative functions of density of probability for the strengths, live loads (6) and dead loads, through a process of numerical simulation. During that process, the technique of Monte Carlo (12) is used to generate simulated values of the parameters of the problem. In each simulation, the time of initiation (Ti) is calculated according to the selected model. The propagation time (Tp) is then calculated as: Tp = BL - Ti, where BL is the building's life. The values of Ti and Tp are determined for each bar of the reinforcement at each critical section of the slabs. For a value of Tp greater than zero, the diameter of that bar is determined from the rate of corrosion.

With the values generated in the numerical simulation, the resisting moment is then determined at the critical sections of the slab (supports and center). Based on these moments, a equivalent uniform distributed load is calculated as the one which balances with the scheme of resisting moments obtained, with a certain redistribution accepted. That calculated load -or equivalent resisting uniform load (ERL)- is regarded as a measure of the capacity of the slab. As in similar problems involving resisting quantities, it can be seen that the function that best adjusts to the distribution of the obtained response is the log- normal.

In the same process of numerical simulation, the dead load is represented by the variable DL. The value of this variable is obtained from the mass density and the geometry of the components of the cross section of the slabs and the wall. The function which best represents this variable is the normal (12). The variable which describes the live load LL is defined by taking into account the period of return and the age of the building. Generally, this variable fits well to a function of extreme type I (Gumbel) (12).

By using a FORM (first order reliability moment) (12) the updating probability of failure is estimated buy the equation:

$$Pf = P\,(ERL - DL - LL \leq 0) \qquad (6)$$

The probability of failure is then evaluated for the slab or the part of it studied. With this information and the data extracted from the inspection, it is possible to determine which parts of the slab are to be repaired or treated, and to which level the treatment should be extended in order to attend to required probability of failure.

EXAMPLE

As a theoretical example of application, the method is applied to a floor slab in a residential building in use for 38 years (Fig. 1, 2) affected by a degradation process caused by carbonation. According to the inspection observations, the maximum value of carbonation depth is 18 mm. The influence of the inferior coating of the slab on the carbonation and corrosion processes will be considered negligible.

In this case, the model of Papadakis et al. and Andrade, defined by the equations (3) and (5), respectively, are considered the most representative. The updated values of the variables are listed in Table 1, while the variables considered are defined through Fig. 1, 2, 3 and the mentioned equations.

Additional variables are: dehor = density of the concrete; fcviga = uniaxial compressive strength of the concrete in the beams; fcsitu = uniaxial compressive strength of the concrete in the compression layer; fypret = yield limit of the prestressing steel; Eypret = Young's modulus of the prestressing steel; vacar1= live load 1 (people); vacar2= live load 2 (furniture, etc.) and vacar3= room free area rate.

The application of the presented method yields results shown in Fig. 4. It can be seen the probability of bending failure at the inspection date, i.e., after 38 years of use, is 2.26×10^{-4}. This limited value could be expected due to the reduced cover and the aggressiveness of the environment.

It can be concluded from these calculations that after the first years of use, this part of the structure should have been repaired in order to avoid beginning to corrosion. Furthermore, it is possible to foresee the need of reinforcing repairwork.

CONCLUSIONS

A method is proposed for reliability analysis of reinforced and prestressed one-way floor slabs, based on a stochastic treatment of the processes of degradation at the structural level. In this method, the geometry, the mechanical properties of the materials, the actions and the environmental variables considered in the models of deterioration are all treated as random variables characterized by probability functions. Initially, available data, as well as the bayesian updating based on inspection, are both considered in order to define the probability functions associated to the main variables.

Because of the possibility to take advantage of new data made available through inspection, the method can be regarded also as a systematic procedure to integrate and explore collective experience obtainable in the future through regular inspection campaigns.

As illustrated through the example included, the method, combined with the needed inspection, makes it possible to determine if a floor slab should be repaired during a certain period, and to which level this repair should be extended in order to satisfy an acceptable probability of failure.

Although applied to the particular case of floor slabs in buildings, the main features of the proposed method could be extended to other structural reinforced and prestressed concrete structural members and constructions. The probabilistic method thus seems to be very suitable for reliabilty evaluations of the structural safety of deteriorating buildings structures. Moreover, this method allow the development of service life analysis (9).

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TABLE 1—UPDATED BASIC INPUT VARIABLES.

variable	unit	mean	C. V.	PDF	variable	unit	mean	C. V.	PDF
vanfor	m	4.25	0.001	N	hbloq	mm	149.5	0.10	LN
ancfor	m	6.45	0.001	N	hbloq0	mm	82.0	-	D
postab	m	1.25	0.005	N	hbloq1	mm	67.5	-	D
Ptabiq	kg/m	221.4	0.150	LN	alfab1	degree	45.6	-	D
entvig	m	0.61	0.200	N	diam	mm	3.5	0.04	N
esppav	mm	20.3	0.015	N	recub	mm	14.0	0.17	N
pepav	kg/m^3	1800.	0.010	N	dcap2-3	mm	2.0	0.19	N
espreg	mm	28.7	0.250	N	dcap4,5,6	mm	10.0	0.19	N
pereg	kg/m^3	2112.	0.010	N	dcap7	mm	20.0	0.19	N
hcapa	mm	40.6	0.090	N	dcap8	mm	130.0	0.19	N
ptecho	kg/m^2	18.0	0.120	LN	vacar1	kg/m^2	130.0	0.26	N
hviga	mm	151.8	0.010	N	vacar2	kg/m^2	70.0	0.19	N
hbinfv	mm	50.8	-	D	vacar3	m^2/m^2	0.52	0.21	LN
hbsupv	mm	41.3	-	D	fcviga	MPa	42.7	0.10	N
binfv	mm	81.2	0.010	N	fcsitu	MPa	29.3	0.20	N
bsupv	mm	49.8	0.010	N	fypret	MPa	1620.0	0.04	N
binfav	mm	30.0	-	D	Eypret	MPa	$2x10^5$	-	D
bsupav	mm	30.0	-	D	y_{CO2}	%	0.08	0.28	N
dehor	kg/m^3	2366.	0.030	N	i_{corr}	$\mu A/cm^2$	0.8	0.44	LN
Pbloq	kg/m^3	117.0	0.100	LN	RH	%/100	0.69	0.11	LN
					W/C	kg/kg	0.59	0.10	LN

N=normal LN= log-normal D=deterministic

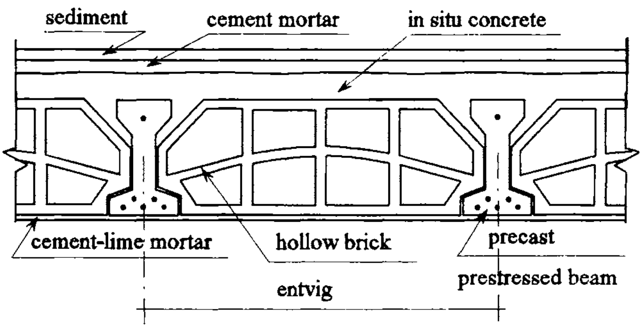

Fig. 1—Slab cross-section.

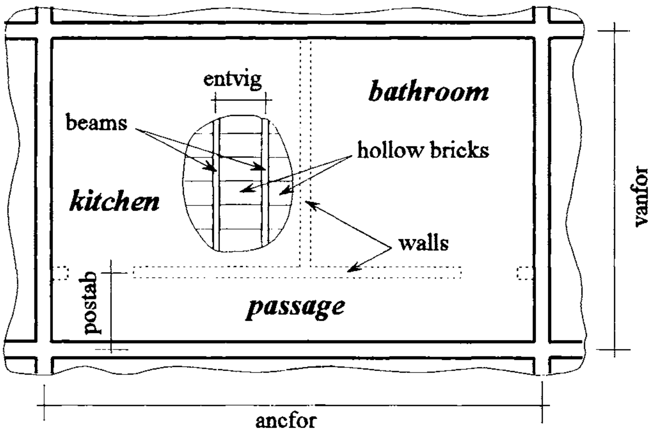

Fig. 2—Plan of a floor panel.

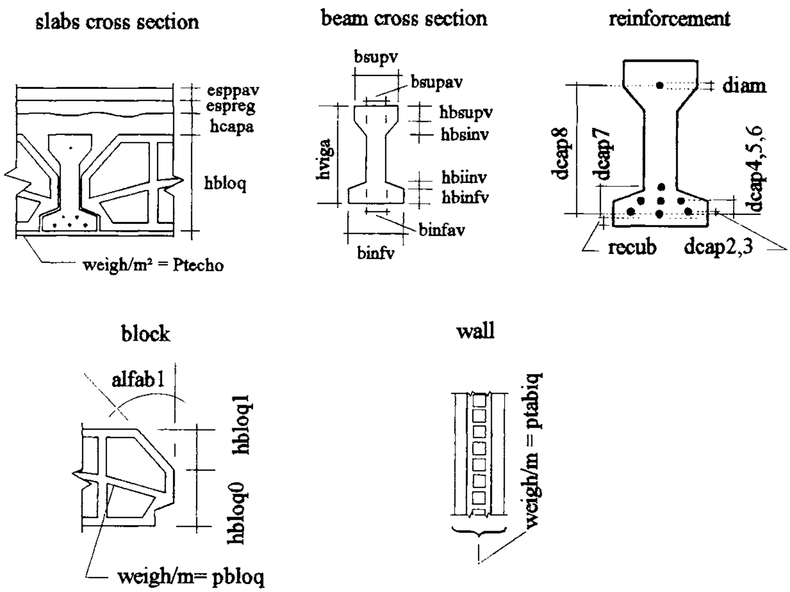

Fig. 3—Cross-section geometry and its variables.