Construction and Building Materials 79 (2015) 245–254

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The challenge of the performance-based approach for the design of reinforced concrete structures in chloride bearing environment

Federica Lollini *, Maddalena Carsana, Matteo Gastaldi, Elena Redaelli, Luca Bertolini

Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Via Mancinelli, 7, 20131 Milano, Italy

HIGHLIGHTS

- The probabilistic model proposed by *fib* was used for the design of RC element in the splash zone.
- Different combinations of concrete composition and type of reinforcement were considered.
- Definition of input parameters for the model was a critical issue.
- Values for the input parameters were determined through literature survey.
- The model sensitivity to the estimated input values depended on the type of steel.

ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form 15 October 2014
Accepted 24 December 2014
Available online 28 January 2015

Keywords:
Probabilistic approach
Service life
Durability
Chlorides
Stainless steel
Galvanized steel

ABSTRACT

The performance-based approach, published by the International Federation for Structural Concrete (*fib*), was applied for the design of a RC element in a marine environment, with corrosion resistant reinforcement, to analyse the potentiality of the model as well as the possible reasons which limit its use. Results showed that the *fib* model allows to compare different solutions and to consider the benefits connected with the use of preventative measures. However the definition of reliable values for some input parameters, as the critical chloride threshold for corrosion resistant reinforcement, is demanded to the designer and this aspect clearly limits a widespread use.

1. Introduction

In reinforced concrete (RC) structures, corrosion of embedded steel is the main form of premature damage worldwide. Corrosion may take place due to carbonation of concrete or chloride penetration from seawater or de-icing salts and may have several consequences on the serviceability and safety of reinforced concrete structures leading, for instance, to cracking or spalling in localized areas [1–6]. When one of these adverse events occurs, a repair becomes necessary to restore safety or serviceability targets. As a result, owners of civil infrastructures as well as buildings have to spend an increasing percentage of their budgets on repair and maintenance of existing RC structures. Thus, there is an increasing interest in extending the service life of new RC structures and reduce maintenance and repair costs over the design service life.

Numerous strategies are now available for enhancing the service life of reinforced structures, as, for instance, low-permeability concrete, coatings, cathodic prevention or corrosion resistant steel (e.g. stainless steel and galvanized steel) [1]. Higher initial construction costs associated to the use of these preventative measures, under specific environmental conditions, may lead to remarkable reductions in the future repair costs. The selection of the most suitable design solution amongst the wide range of preventative approaches nowadays available requires a quantification of all the associated costs in comparison to the expected extension of the life of the structure. Hence, the first essential step in the cost-benefit evaluation of any preventative measure is the prediction of its actual contribution in increasing the service life. This can only be achieved by predicting the performance of the structure as a function of time and the environmental actions, i.e. through service life modelling. At this aim, several models have been proposed in the literature

* Corresponding author. Tel.: +39 02 2399 3144; fax: +39 02 2399 3180.
E-mail addresses: federica.lollini@polimi.it (F. Lollini), maddalena.carsana@polimi.it (M. Carsana), matteo.gastaldi@polimi.it (M. Gastaldi), elena.redaelli@polimi.it (E. Redaelli), luca.bertolini@polimi.it (L. Bertolini).

http://dx.doi.org/10.1016/j.conbuildmat.2014.12.044
0950-0618/

[1]. Nowadays, performance-based approaches are becoming more popular, since they aim at a tailor-made design in which every structural element should be specifically designed in a way that it can withstand the actual local conditions of exposure during the required service life. Among the models proposed in the recent years, the "Model Code for Service Life Design", issued by the International Federation for Structural Concrete (*fib*) in 2006 [7], is often used being considered one of the most authoritative [8]. This includes a probabilistic performance-based approach for the modelling of the effects of the environment on the structure and the calculation of the probability that a pre-defined limit state, which corresponds to an undesired event (e.g. initiation of corrosion, cracking or spalling of concrete cover), will occur. Currently the use of the *fib* Model Code, as well as other probabilistic performance-based design approaches, is still limited in the design of RC structures, whilst deterministic models often implemented in commercial software are more used [9,10]. A more widespread use of probabilistic performance-based models would be extremely useful in order to compare different design solutions, to quantitatively assess the benefits connected with the use of preventative techniques and to determine the reliability of different design combinations. The main limitation to the use of service life models is the lack of knowledge about the realistic nature of their output. Indeed the evaluation of the reliability of service life predictions of reinforced concrete structures is quite a difficult task, since nowadays available models are quite 'young' compared to the length of usual service lives of RC structures and feedback data are not available yet. Attempts have been made to apply the models to existing structures [11–13], but in this case, if the long-term performance can be evaluated through inspection, there is lack of compliance tests used as model inputs. Nevertheless, the lack of experience on the reliability of service life predictions should not be a reason for rejecting any type of modelling. Such an approach, in fact, would leave designers of reinforced concrete structures without any tools for a sound comparison of different design scenarios. This, especially when preventative measures are considered, would lead to irrational choices that may over- or underestimate the role of each solution considered. A wiser approach would be a cautionary use of presently available models, considering them as a summary of the previous experience. Nevertheless, even the use of available models is often more complicated when additional preventative measures, such as corrosion resistant bars, are considered since there is lack of specific parameters.

This paper applies the performance-based approach proposed by the *fib* Model Code for the design of durable RC structures and discusses some critical aspects related to its use. To point out these aspects and provide a guide in the identification of possible options for the durability design, including the use of corrosion resistant reinforcement, the design of a RC element exposed to a marine environment was considered.

2. Design of a RC element in a marine environment

The design of a RC element exposed in the marine splash zone (XS3 exposure class according to EN 206) on the coast of the Mediterranean Sea was simulated. Different design options in terms of types of concrete and reinforcement were considered. As far as the type of concrete is concerned, a Portland cement, OPC (CEM I according to EN 197-1) and a ground granulated blast furnace slag cement, BF (CEM III/B) were taken into account with a water/binder (w/b) ratio of 0.45, as suggested by the EN 206 standard, which provides guidance on the selection of designated concrete as a function of the exposure environment. Different types of reinforcement were considered: conventional black steel, galvanized steel and stainless steel of grades 1.4307 and 1.4462, i.e., respectively a low carbon austenitic stainless steel with composition of 18% Cr, 8–10% Ni and a duplex stainless steel with composition 22% Cr, 5% Ni, 3% Mo, according to the standard EN 10027. The service life was modelled through the *fib* Model Code and the limit state equation was solved by means of the Monte Carlo simulation method (10^6 simulations were performed for each case).

2.1. Limit state equations

The service life can be defined as the sum of the initiation time, which ends when the steel is depassivated, and the propagation time, which finishes when a given limit state takes place, beyond which consequences of corrosion cannot be further tolerated and a repair work is needed [2]. This distinction between initiation and penetration periods is useful in the design of RC elements, since different processes and variables should be considered in modelling the two phases [6]. For a structure exposed to a chloride-bearing environment, the initiation of corrosion can be assumed as the limit state, since the propagation time is relatively short and it can be neglected [1]. The initiation period is defined as the time required for chlorides to reach a critical threshold at the depth of the outermost steel bars. The probability of failure, p_f, is evaluated as the probability that the initiation limit state function, g, reaches negative values:

$$p_f = P\{g < 0\} = P\{\mathrm{Cl_{th}} - \mathrm{Cl}(d_c, t_{SL}) < 0\} \quad (1)$$

where: $\mathrm{Cl_{th}}$ is the critical chloride threshold; d_c is the depth of the outermost rebar; t_{SL} is the target service life; $\mathrm{Cl}(d_c,t_{SL})$ is the content of chloride in the concrete at a depth, d_c, and at a time, t_{SL}.

The target service life, t_{SL}, which needs to be defined in the design phase, is guaranteed if the probability of failure p_f is equal or lower than a preset target probability, P_0, which should be also defined in the design phase.

In the *fib* Model Code, the initiation limit state function, g, is evaluated as:

$$g = \mathrm{Cl_{th}} - \left\{ C_0 + (C_{s,\Delta x} - C_0) \cdot \left[1 - erf \frac{d_c - \Delta x}{2 \cdot \sqrt{D_{app,0} \cdot t}} \right] \right\} \quad (2)$$

where: C_0 is the initial chloride content of the concrete; Δx is the depth of the convection zone where, beside diffusion process, other mechanisms of chloride penetration can occur; $C_{s,\Delta x}$ is the substitute chloride surface content, C_s, at the depth Δx; $D_{app,0}$ is the apparent coefficient of chloride diffusion through concrete.

The apparent coefficient of chloride diffusion of concrete is determined as:

$$D_{app,0} = k_e \cdot D_{RCM} \cdot k_t \cdot A(t) \quad (3)$$

where: k_e is the environmental transfer variable and is a function of the temperature of the element (T_{real}); D_{RCM} is the chloride migration coefficient; k_t is a transfer parameter and $A(t)$ is the subfunction considering the 'ageing'.

The subfunction $A(t)$ is evaluated as:

$$A(t) = \left(\frac{t_0}{t} \right)^a \quad (4)$$

where: t is the time, t_0 is the reference point of time and a the ageing factor.

Since all the functions and parameters involved in this model cannot be reported in this paper, reference to the *fib* Model Code is made for a detailed description [7].

2.2. Selection of values for the design parameters

The parameters involved in Eqs. (2)–(4), the preset target probability, P_0, and the target service life, t_{SL}, need to be determined in the design phase. Some of them should be chosen by the designer