FIELD STUDIES CONCERNING THE SERVICE LIFE PREDICTION
Service life prediction

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Abstract

The service life prediction for the reinforced and prestressed concrete cross sections subjected to carbonation, chloride, sulfate and nitrate attack, of the reinforced and prestressed concrete building member and structure is presented on the ground of field data collected from the assessment and surveying of more than one hundred constructions. The parameters, which have to be taken into account, are discussed and some examples are given.

Keywords: Aggressive attack, member, RC/PC cross section, service life, structure

1 Introduction

The service life of the existing structures represents an essential parameter, which must be considered when a decision has to be done regarding the future use of these structures.

If the service life of a structure is defined as the period of time between the designing and putting into operation and the moment when an accepted safety level is exceeded, few concepts have to be accurately specified. These concepts could be discussed on a well-known (CEB 1983) schematic representation of the service life, shown in Fig. 1.

1. Firstly, it has to be accepted that a structure is born with some initial damages, which depends on the knowledge of the designer and the performing practice of the period.
2. Then, the building age and the rate of degradation could describe the process. This parameter depends on the characteristics of the building...
materials, the aggressiveness of environment and the protection level of building members.

3. During the lifetime of the building, some accidents like an oversized load (an earthquake, for example) could appear and damage it suddenly. Usually, after this, the rate of degradation increases.

4. Finally, the accepted safety level has to be defined for each member of the structure and for the entire structure, too.

Mainly, the evaluation of the service life consists of the evaluation of the four-presented parameters for:

- The materials which make up the cross section of the building members,
- The cross sections of the members resulting from the association of these materials,
- The members with different composition and loaded cross sections and
- The structure, where each member and its connections participate differently to the safety level.

Actually, the research is focused on the durability of the building materials for which, knowing the rate of degradation means knowing the service life, and models of the degradation processes have been found. Several methods to predict the service life of concrete and reinforcement (as separate materials) and reinforced concrete (as an associate material into an unloaded building member cross section) were grounded for different aggressive environments (Clifton and Knab 1989; Clifton 1993): (a) assessment grounded on the expert experience; (b) comparison with similar situations; (c) using accelerated tests; (d) mathematical and empirical models for degradation processes; (e) using reliability and stochastic analyses.

An important finding resulting from the field studies is that, in practice, the application of these methods could often give inconclusive results, because of the multitude of parameters, which have to be considered. Regarding the material, the main parameters are the chemical components and the porosity, which can be determined from samples extracted from building members. Even so, it is quite
difficult to establish the initial structure of the concrete (type of cement, water/cement ratio and the grading of aggregate) and its long-term changes. Many times, the initial damages were decisive for the in service behavior of the materials. Regarding the environment, the most important parameters are the type of attack, the concentration of the aggressive agent, the exposure time and the moisture variation. The problem is that their variation during the service life of the building is very difficult to establish and so is the rate of degradation.

For composite materials such as the reinforced and prestressed concrete, few models concerning the service life prediction are conceived. Tuutti’s model (Tuutti 1982) show in Fig. 2 is the classic example. In this model, the initiation period, the first part of the service life, can be defined as the time period up to the complete damage and/or penetration of the concrete cover by the aggressive agent. The remaining time period up to the damage of the reinforcement could be considered the propagation period if the RC cross section is unloaded. For a loaded RC cross section, the time up to reaching a certain accepted bearing capacity resulting from the decreasing concrete and reinforcement areas has to be considered as the propagation period.

For a building member, with different composition and loaded cross sections, the assessment of the service life becomes more difficult because, in addition to the previous parameters, some other parameters have to be considered. The extension of the damaged area of reinforcement and/or concrete, the anchorage of the undamaged steel bars in the sound concrete and the balance between the stress and the bearing capacity of the damaged cross sections are the main parameters.

The service life of a structure depends on the service life of each member, but its participation in the strength and stability of the structure has to be considered. In a simple way, the service life of the most important/loaded/damaged member (foundation, column and wall) could represent the service life of the structure, but a probabilistic or stochastic approach could be done too.

Finally, the service life prediction remains an assumption because it is based on field and experimental studies, almost never confirmed by practice because nobody surveys and waits for the failure of a building member or structure.

Taking into account that the chemical processes within the steel and concrete (CEB 1989) are well known, some useful principles and rules to assess the service life of reinforced and prestressed concrete cross sections, members and structures under different chemical attacks were shown further as a result of the field studies.

2 The service life prediction of the reinforced and prestressed concrete

2.1 To carbonation

The time up to the complete carbonation of the concrete cover could be considered the initiation period for the reinforced concrete cross sections subjected to carbonation. The phenomena has been studied and many models were elaborated, but the practical assessment of the initiation period has to be made for each real case because the results are very scattered (see Fig. 3). Knowing the exposure time and the corresponding carbonation depth, enables determination of
the depth of cover carbonation. The test for determining the carbonation depth is one simple test.

The propagation period starts after cover carbonation, but its end has to be defined. The appearance of cracks due to reinforcement corrosion is the first sign that the bearing capacity of the cross section begins to decrease, however time failure is a long way off. Experimental studies (Gosav 1998) show that, for a reinforced concrete cross section, the real breaking load is 2...3 times larger than those computed using the design values of the material strengths.

Fig. 3: The carbonation depth for different ages of the concrete as results from field tests

A certain damage percentage of the reinforcement area could be accepted and the time period necessary for this degradation to occur represents the propagation period.

The remark is not valid for the prestressed cross sections, where the smallest decrease in the tensioned reinforcement area could produce failure. Consequently, only the initiation period has to be considered as the service life of a prestressed concrete cross section.

2.2 To chloride attack

The diffusion time of the chloride ions through the concrete cover could be considered the initiation period. The diffusion coefficient is the parameter that describes the phenomenon and it could be measured on sample extract from the building members (Clifton et al. 1991). Taking into account that the concrete components bind a certain percentage of the chloride ions, for reinforced concrete cross sections, the initiation period could be extended with the necessary time that this process requires. Therefore, the free chloride contents in concrete, near reinforcement, could show the border between the initiation and propagation period. The free chloride test could be made in situ using adequate equipment.

Similar to carbonation, the end of the propagation period for chloride attack could be the moment when a certain percentage of the reinforcement cross section is damaged.

For prestressed concrete cross sections subjected to chloride attack, because pitting corrosion can take place before the binding chloride ions by the concrete components, to consider the initiation period as the service life is rational.
The degradation of reinforced concrete due to chloride action depends on environmental parameters and concrete characteristics. The field observations demonstrate that an accurate correlation between these two is very difficult to establish in practice, so to improve the service life assessment, a long term survey is necessary. A relevant example is illustrated in Table 1, where the exposure conditions and the chemical characteristics of concrete exposed for ten years in a saline environment (in a salt exploitation site) are shown (Gosav 1988).

As shown in figure 4, in a dry environment, salt dust covers the element but does not damage it (the first element from Table 1). The tests demonstrate that the moisture variations affect the damage amplitude much more than the chloride contents from the atmosphere and from the concrete. This fact clearly results if the exposure conditions and the chloride contents for the elements 4 and 2 from Table 1 are compared. The damages of these elements are shown in Fig. 5 and Fig. 6.

The cement proportion and the compactness of the concrete (actually, the concrete class) are important parameters too as it results comparing of the chloride contents in elements 2 (usual concrete class) and 3 (high concrete class) from Table 1.

Table 1: Exposure conditions and concrete components in a saline environment

<table>
<thead>
<tr>
<th>Tested element</th>
<th>Moisture Conditions</th>
<th>Fix dust residue (%), at 105°C</th>
<th>Cl⁻ (mg/l)</th>
<th>Na⁺ (mg/l)</th>
<th>pH</th>
<th>Cl⁻ (%)</th>
<th>Na⁺ (%)</th>
<th>Ca²⁺ (%)</th>
<th>CaO (%)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Inside column (fig. 4)</td>
<td>dry, without moisture variation</td>
<td>60</td>
<td>40.8</td>
<td>19.3</td>
<td>5.8</td>
<td>1.77</td>
<td>42.18</td>
<td>124.5</td>
<td>*</td>
<td>9.2</td>
</tr>
<tr>
<td>2 Outside column (fig. 6)</td>
<td>climatically annual and daily moisture variation</td>
<td>3.63</td>
<td>11.91</td>
<td>146.3</td>
<td>*</td>
<td>7.5</td>
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<tr>
<td>3 Outside prestressed beam with bonded tendons (fig. 7)</td>
<td>760</td>
<td>459.7</td>
<td>267.1</td>
<td>5.8</td>
<td>1.24</td>
<td>32.20</td>
<td>152.7</td>
<td>*</td>
<td>7.6</td>
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<tr>
<td>4 Inside column (fig. 5)</td>
<td>Daily large moisture variation. Vapor with salt (not dust)</td>
<td>93</td>
<td>55.0</td>
<td>35.65</td>
<td>7.3</td>
<td>1.24</td>
<td>*</td>
<td>*</td>
<td>13.3</td>
<td>7.7</td>
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<td>0…1cm width</td>
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<td>0…2cm width</td>
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<td>Rust of reinforcement</td>
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</tbody>
</table>

* Not performed analyzes
2.3 To sulfate attack

Because sulfate gradually attacks the concrete through thin successive layers spalling (Fig. 8), the initiation period for reinforced concrete cross sections could be considered the time to complete damage of the concrete cover. It has to be taken into account that the sulfate affected concrete depth is not alkaline as the in field tests demonstrate (Fig. 9). Though this layer is more compact due to the gypsum and ettringite formed in the pores, the reinforcement is still exposed to corrosion because oxygen can diffuse due to the moisture variation. The process is not so dangerous for reinforced concrete cross sections that the previous
assumption, that the initiation period finished after the completely damage of the concrete cover, is realistic (Gosav 1990a), unless alkalinity is lost.

![Fig. 8: Sulfate attack of the concrete](image1)

![Fig. 9: Sulfate ions penetration profile in concrete](image2)

If a certain reducing of the reinforcement area due to corrosion is accepted, as previously, for reinforced concrete cross sections, the end of the propagation period is that necessary to reach this accepted damaged reinforcement area.

2.4 **To nitrate attack**

Nitrate attack is a combination of the previous two phenomena (chloride and sulfate). The nitrates penetrate, by diffusion, into concrete and disintegrate it on a certain depth (Fig. 10). The reinforcement is affected not only by corrosion, but by an embrittlement phenomenon that takes place (Fig 11), and the reinforcement cross sections are reduced through cracking (Gosav 1990b). An important finding is that the corrosion rate of reinforcement due to nitrate attack is reduced after repassivation of the reinforcement, but further, reduction of the reinforcement cross section area is due to embrittlement. The field and laboratory studies developed until now do not point out the relationship between exposure time and the appearance of the first crack, nor if the cracking takes place gradually or suddenly in the steel bar. However, on the basis of the known field data, it is realistic to accept that the embrittlement is a later phenomenon than the corrosion.

Knowing this, the initiation period for the reinforced concrete cross sections is that necessary for a part of the concrete cover to be damaged, and the rest be penetrated by nitrates. Because of the mechanism of the reinforcement deterioration, both through corrosion and embrittlement, the propagation period has to be more carefully assessed. Assuming that the time up to the cracking of reinforcement due to embrittlement is larger than the period up to the first fine crack appearance in the concrete cover, the second could be considered like the end of the propagation period for reinforced concrete cross section.

For prestressed concrete cross sections, the initiation period has to be considered the time up to nitrate reach the reinforcement through diffusion, so a diffusion coefficient or the concentration of the nitrates at the depth of the reinforcement have to be experimentally found.
Because the embrittlement is clearly more dangerous to the prestressing reinforcement, this initiation period, defined previously, has to be considered as the service life.

Fig. 10: Damage of concrete and reinforcement due to the nitrate attack

Fig. 11: Intercrystalline crack into the steel reinforcing bar (500:1)

3 Service life prediction for reinforced and prestressed concrete members

3.1 Reinforced concrete members

At first view, the service life of a building member is the service life of that damaged cross section for which the bearing capacity related to the corresponding stress generated by the exterior load exceeds an acceptable value. By knowing the service life of the damaged cross sections predicted as previously shown for different type of attack, the service life of the building reinforced concrete member results. Experimental studies (Gosav 1998) show that this rule could be applied only for locally damaged reinforced concrete beams and columns.

Unfortunately, the problem is not as simple for beams with large exposed reinforcement because some other parameters could become decisive. Experimental studies performed on reinforced concrete beams with exposed reinforcement (Eyre and Nokhasteh 1992; Cairns and Zhao 1993; Raoof and Lin 1993) demonstrate that the following parameter influence their bearing capacity: (a) length of the exposed reinforcement; (b) position of the exposed reinforcement on the member length; (c) depth of the removed concrete over the damaged reinforcement; (d) undamaged anchorage length of the steel bars; (e) bond between the compressed concrete area and the tensioned reinforcement area; (f) percentage of the exposed reinforcement.

A solution consists in imposing some limits to the damage extent so that reaching the limit means the end of the member service life. For example, these limits could be: (a) reinforcement exposure length less than 1/3 from the beam clear span; (b) anchorage length into the sound concrete minimum 50 diameters; (c) debonded bars only on the cover side, the other side being in contact with concrete on minimum half of perimeter. Assuming these conditions, the assessment of the service life of the reinforced concrete members could be made following the rule presented at the beginning.
A question resulting from the field studies is why reinforced concrete members (as in Fig. 5 and Fig. 6) are more damaged than it was assumed previously for the end of their service life, yet do not fail. The answer is that bearing capacity reserves result from the difference between the design values of the materials strengths and the real ones, the plastic adaptability of the reinforced concrete cross sections and members and connections to the bearings and redistribution of the stresses (Gosav, 1998).

A good knowledge and assessment of the damaged elements could lead to a more accurate prediction of the service life. In this stage of the research development, some absolute rules to take into account the damages of these elements can not be given. The experience and the good practice of the expert are integrals.

3.2 Prestressed concrete members

As previously shown, for prestressed concrete cross sections damage of the reinforcement is not accepted and the end of the service life is considered the moment when the entire concrete cover is affected by the aggressive agent, which is dangerous for the tensioned reinforcement. Taking into account that a prestressed concrete member could suddenly fail when a part of reinforcement breaks, its service life has to be more carefully predicted. A maximum safety prediction is to assume that the service life is that of the most affected cross section. But, on a prestressed concrete member, there are quite large areas where the cross sections are over-reinforced (for example, because the same straight tendons reinforced the pin ended girder over their entire length even if the bending moment decreases towards ends). This could be a reason to accept a certain amount of damage of the reinforcement in the over-reinforced cross sections.

It is important to observe that damage of the prestressing reinforcement means the end of service of a tensioned wire and consequently, of a tendon or a cable. It results that the service life of the members with post tensioned reinforcement is that of the most affected cross section, because the breaking of an unbonded reinforcement leads to the decreasing of the bearing capacity for all cross sections. The breaking of a bond tendon means the loss of adherence on certain lengths for both sides of the damaged area and transfer lengths of the stress between the de-tensioned reinforcement and concrete has to be considered (Gosav 1998). All cross-sections along these transfer lengths, both sides of the damaged area, have to be considered as damaged. If a reinforcement damage is accepted, the service life of the remaining cross section is that of a new one but with less reinforcement with the respective to concrete cover.

Taking into account these remarks, the service life of a member with pre-tensioned reinforcement could be considered as the service life of the most affected cross sections from the more loaded areas and the most damaged ones from the less loaded areas. For the cracked prestressed members, the previously shown predictions are not available because the tensioned reinforcement is directly exposed.

Beyond these rational remarks about the service life prediction of the prestressed concrete members, the field studies point to some very interest facts. For example, a 15m span and 8 tendons reinforced member does not collapse even if one tendon looks like in Fig. 7 and another is corroded after 10 years exposure.
in a saline environment. Another prestressed concrete member subjected to the same environment, but with initial fine cracks due to under-prestressing, collapses after the same period of time.

4 Service life prediction for reinforced concrete structure

To predict the service life of a structure is a very complicated problem but, simplifying, it could be defined in two ways: (a) as a minimum of the service life of the component members; (b) as a service life for which a characteristic of the structure exceeds an acceptable value.

Concerning the first assumption it has to be taken into account that the members have different contribution in the assurance of the safety level of the structure. A hierarchy, starting with the most important and ending with the least one, is the following: foundation → column and/or wall → girder → beam → slab. Moreover, for each member type, a new hierarchy could be adopted according to the loading level (for example, a central column is less loaded in flexure than a corner one). It results that it is rational to consider the service life of the structure as the service life of the member with the minimum bearing capacity/stress ratio. A more accurate prediction has to take into account the safety reserves resulting from a redistribution of the stresses due to the spatial working manner of a structure and the plastic behavior.

The second manner consists in predicting the time up to that a characteristic of the structure exceeds a certain accepted value. These characteristics could be: (a) stress (e.g. the compression into the column); (b) bearing capacity (e.g. the shear force at the ground level); (c) displacement (the horizontal at the top level); (d) the ductility.

5 Conclusion

Based on field studies and some tests performed on damaged members, some practical rules regarding the assessment of the service life of a cross section, member and structure from reinforced and prestressed concrete, subjected to different chemical attack, are suggested in this paper. The present data are not sufficient for an accurate service life prediction and the experience of the expert is still the most important factor. Only future field data systematically collected and analyzed, correlated to accelerated tests and an extensive experimental program regarding the behavior of the damaged members and structures can improve the service life prediction.
6 References


CEB BULLETIN D’INFORMATION No. 162 (1983) Assessment of Concrete Structures and Design Procedures for Upgrading (Redesign)


Tuutti K. (1982) Corrosion of Steel in Concrete. Swedish Cement and Concrete Research Institute, Stockholm