Ordinary and Long-Term Durability of Reinforced Concrete Structures

by M. Collepardi

Synopsis: Durability of reinforced concrete structures (*RCS*) seems to be poor when compared with those of ancient un-reinforced structures. When ordinary durability (service life of 40-50 years) is needed, the poor behavior of *RCS* stems from human negligence in adopting the well consolidated and available experiential knowledge. However, for long-term durability requirements (service life of 100 years and more) the inherent vulnerability of the steel-concrete system must be taken into account.

The inherent vulnerability of *RCS* substantially depends on the following "weak points"of concrete:

(*i*) Low tensile strength

(*ii*) High modulus of elasticity

(*iii*) Microcracking caused by restrained thermal and drying shrinkage or service loading.

This paper critically examines some possible future scenarios to achieve long-term-durability in *RCS*, including:

a) Improvement in the corrosion behavior of the metallic reinforcement through the use of corrosion inhibitors, protection of the reinforcement with a coating, change in the composition of reinforcing bars, or cathodic protection.

b) Use of non metallic reinforcement.

c) Increase in the tensile strength and/or ductility of concrete mixtures based on rubber-like polymer additions.

d) Surface coatings for concrete protection.

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INTRODUCTION

Paradoxically, modern concrete structures, with metallic reinforcements, are less durable than the ancient un-reinforced concrete structures.

Some Roman plain concrete structures are still in excellent condition even after 2000 years or more. Those which today appear in form of romantic ruins owe the lost of their integrity more to extra-ordinary traumatic and cumulative events of the past - earthquakes, fires, wars - rather than to degradation processes inherent to the material itself. For the front cover of the Proceedings of the Kumar Mehta Symposium (1) the editors selected a picture of the *Pantheon* dome in Rome, a still sound, intact and majestic building made of concrete with a lime-pozzolan mixture as binder and crushed bricks or natural pumice as lightweight aggregate. On this picture, the editors placed an inscription referring to this concrete: "*But concrete can be durable*".

The long term durability of this ancient cementitious material highlights even more the relatively poor behavior - in terms of durability - of modern reinforced concrete structures (*RCS*), most of which have lost their original serviceability in less than one century, and in some cases in less than a few decades. When referred to modern reinforced concrete the above inscription should be changed into "*Can it be durable?*"

To find possible answers to this question, this paper will address the three aspects of the problem:

- The meaning of durability of modern concrete structures
- The causes of deterioration in *RCS*
- Conceivable scenarios to design and achieve long-term-durability in *RCS*.

WHAT DOES DURABILITY MEAN?

The durability of a reinforced concrete structure is the capability of the structure of maintaining its original **functional and structural characteristics** for the expected service life and exposure conditions it was designed for. It does not necessarily coincide with the durability of concrete, the latter being the capability of the material by itself of keeping the original **properties** for a certain period of time. In fact, the durability of *RCS* depends not only on the durability of the concrete, but also on aspects of design (cover thickness, density and positioning of reinforcing bars, and surface protection, if any) and on the **execution techniques** (transport, placement, compaction, and curing of the concrete mixture).

Standards and recommendations are available in Europe (2), America (3), and Japan (4) for the durability of concrete and *RCS* exposed to various aggressive environments, including humid air, sea water, freezing and thawing, and de-icing agents, when a service life of 40 to 50 years is required. In the present paper this will be termed **ordinary durability** compared with **long-term durability**, which refers to a longer service life, with a minimum of 50 years up to 200 years (5) and even more. Long-term durability is needed, for instance, in infrastructural works of particular social importance which require great investments (e.g., underwater tunnels, long span bridges, highway networks, etc.) or structures of particular architectural interest (e.g., monumental works, churches, state buildings, etc.). Significant examples of the latter structures are the *Grande Arche* in Paris and the *Opera House* in Sydney.

Wondering whether these monumental buildings will last, for instance, for at least 500 years is more than legitimate, if we compare the experienced service life of reinforced concrete buildings in the present century with those of ancient monumental works built in this millennium.

Michelangelo - who is perhaps the most famous world-wide sculptor and painter, but who was also a very fine architect - designed *Palazzo Farnese* in Rome in the 15th century. This building is still in service as the residence of the French Embassy in Italy. Can we hope for a five-century service life in modern reinforced concrete architectural works such as that achieved by many Renaissance buildings in Italy, as well as in other countries in Europe? Although Michelangelo was more an artist than an engineer, he always took into great account the quality of the materials he used to achieve the longest possible durability for his masterpieces - the marble for the *David* statue in Florence, the colors and the mortar substrate for the *Cappella Sistina* in Vatican, as well as the stones, bricks and mortars for the *Palazzo Farnese* or the *Capitolium Square* in Rome.

Is the present experiential knowledge of modern construction materials lower than that available to Michelangelo and to other architects of the past? If not, why are the durability problems of *RCS* debated in hundreds of papers, seminars, conferences, and books? According to the author of the present paper, the answer to this key-question can be found by examining two fundamental durability problems in *RCS*:

a) **Human negligence** in adopting the well consolidated and available experiential knowledge for ordinary-durability *RCS*.

b) **Inherent vulnerability** of the steel-concrete system for long-term-durability *RCS*.

Both of these aspects are discussed in the next section.

DETERIORATION CAUSES OF RCS

Human negligence: In *RCS* exposed to aggressive environments, a service life of 40-50 years (ordinary durability) may not be achieved when one or more of the following recommended actions are not performed (Table 1):

- *Selection of adequate materials* in terms of specified cements, sound and well graded aggregates, chemical and mineral admixtures.
- *Proper mixture-proportioning* in terms of water-cement ratio (*w/c*) and air-void system as needed for strength and durability requirements based on environmental exposures.
- *Adequate structural design* in terms of concrete cover thickness, position and density of reinforcements, form and dimensions of structural elements.
- *Careful execution techniques* in terms of workability and transport-related slump loss of the fresh concrete, placement, compaction and curing of the concrete mixture.

Two types of human negligence may occur. The first type - the most frequent - involves the selection of a high *w/c* in relation to the aggressiveness of the environment; the absence of an air-entraining agent in structures exposed to freezing and thawing cycles; the selection of a thin cover in reinforced concrete structures exposed to carbonation or chloride penetration; the addition of uncontrolled amounts of mixing water on the job site because of concrete slump loss; and inadequate or lack of curing after demoulding. All these forms of negligence occur due to the gap existing between the available know-how in concrete durability science (6) and the relatively poor knowledge of concrete technology of design-engineers, architects, and especially contractors. Neville (7) has highlighted this gap and ascribed it to the poor attention paid by schools and universities to teaching concrete technology compared with that devoted to structural design. According to Neville "*Inadequate knowledge of factors influencing the behavior of concrete has harmful consequences in the operations of manual and technical staff. This situation exists because learning about concrete is considered almost below the dignity of the person undertaking sophisticated structural calculations*" (7).

The second type of human negligence is related to some aspects of cement production and concrete manufacturing processes which can objectively be managed with some difficulties in the pratical field experience (Table 2). One of these aspects deals with the selection of inert aggregates, not prone to alkali-silica-reaction (*ASR*), when concrete must be produced on a large scale - as is usual for real life *RCS.* So far, reliable and quick tests to detect potential *ASR* in each individual grain of a big batch of aggregate are still not available. The routine use of fly ash and other supplementary cementitious materials remains the best way of preventing *ASR* in concrete structures where there is the risk of using alkali-reactive aggregates and a low alkali portland cement is not available (8, 9).

Another and more recent aspect of the second type of human negligence (Table 2) deals with the risk of delayed ettringite formation (*DEF*) occurring when high sulfate content clinker is used in the production of modern portland cements (10). According to the available standard tests, only the total sulfate content of cement - and not that of the clinker phase - may be checked. Therefore, the *DEF*-induced concrete distress can not be managed easily. This type of deterioration has been growing, in prestressed concrete structures and particularly in concrete ties, since the last decade. This is due to two concurrent events, besides the exposure to humid environment (Fig. 1): the unwitting increase since the 80s in the sulfate content of the clinker phase related to the use of sulfur-rich wastes and fuels in the kiln, and the increase in microcracking related particularly to the high, uncontrolled and non uniform stress distribution in prestressed and/or steam-cured concrete structures (11). Therefore, this type of human negligence could be eliminated through better control in the clinker production process by cement producers, and in the stress distribution in the *RCS* by design engineers.

Inherent vulnerability of RCS: In contrast to what happens in the laboratory, real structures are subjected to static and dynamic loads. Moreover, the additional deterioration which is observed in real *RCS*, compared with that of the specimens stored in a laboratory, is due to the following "weak points" of concrete (Table 3):

(*i*) Low tensile strength.

(*ii*) High modulus of elasticity which is responsible for the transformation of restrained thermal or drying shrinkage into relatively high tensile stresses.

(*iii*) Microcracks formed as a consequence of (*i*) and (*ii*).

These microcracks represent preferential paths for the penetration of aggressive environmental agents - such as air, water, and sulfate, chloride, and alkali ions - through the mechanisms of diffusion and capillary absorption through the cracks. This means that the concrete cover can be penetrated by the aggressive agents independently of the porosity of the cement matrix. This promotes the corrosion of the steel reinforcement, characterized by a disruptive expansion which accompanies the change of the iron into the corresponding oxides (rust). Once this process is initiated, the microcracks in the concrete cover grow into macrocracks and then, after an initial induction period, the duration of which depends on the aggressiveness of the environment, the degradation process increases very rapidly (12).

When ordinary durability is required - as for *RCS* with an expected service life of 40 to 50 years - the presence of microcracks in the concrete cover and their transformation into macrocracks plays, in general, a role of negligible importance provided that all deterioration causes related to human negligences are avoided (Table 1) and very severe aggressive environments are excluded. On the other hand, when long term durability is needed - as for *RCS* with an expected service life of 100 years or more - one cannot ignore the mechanism of formation of microcracks in the concrete cover and their subsequent transformation into macrocracks due to the corrosion of the reinforcement. Moreover, even when ordinary-durability *RCS* are required, microcracking of concrete should be avoided in case of very severe environmental exposure (e.g., the tidal zone in maritime works or frequent freezing and thawing accompanied by de-icing salt treatments). The steel reinforcing bars, specifically used to counteract the low tensile strength of concrete and the possible failure of plain concrete structures subjected to tensile or flexural stresses in service, paradoxically have become the main reason of concern for the long-term durability of *RCS*. Concrete structures, even when microcracked by restrained thermal or drying shrinkage, could theoretically perform as long-term-durable structures, in the absence of reinforcing bars, provided that a low *w/c*, an adequate air-void system, effective compaction, and proper curing were adopted. However, today's concrete structures cannot be designed without the use of steel reinforcing

The next section examines some conceivable scenarios to produce *RCS* with long-term durability, as alternatives to those currently used for *RCS* with ordinary durability.

FUTURE SCENARIOS FOR LONG-TERM-DURABLE RCS

For new *RCS* to be competitive, in terms of durability, with ancient unreinforced structures, three main scenarios are possible:

a) Improvement in the corrosion behavior of the metallic reinforcement,

b) Use of non-metallic reinforcement,

c) Higher tensile strength and/or more ductility of special concrete mixtures, and

d) Surface coatings for concrete protection.

a) Metallic Reinforcement with improved corrosion behavior: The improvement should consist in a significant reduction of the corrosion process of the reinforcement, even when, due to exposure to aggressive environments, the reinforcement is **embedded in a micro-cracked cement matrix**. In other words, even in the absence of the passivating action of the cement-matrix, the reinforcement should resist **by itself** the corrosion promoted by CO_2 or Cl^- ions and fed by humid air (O_2 and H_2O). The corrosion rate - in terms of reduction in the cross section of the reinforcement - should be as low as few μm/year in order to achieve two important objectives:

(*i*) Reliable safety, from a structural point of view, of *RCS* exposed to aggressive environments for a long service life

(*ii*) Absence of any disruptive action of the reinforcement which could transform microcracks into macrocracks in the concrete cover and then be detrimental to the long-term durability of the *RCS*.

Based on the available experiential knowledge (13), the following options are theoretically available for the long-term protection of metallic reinforcing bars:

- Use of corrosion inhibitors as concrete admixtures,
- Protection of the reinforcement with a coating,
- Change in the composition of reinforcing bars to more durable alloys (e.g., stainless steel), and
- Cathodic protection methods.

However, so far none of the above protection methods appear to be sufficient to provide corrosion protection unless a crack-free long-term durable concrete is used (Table 3). For instance, the use of corrosion inhibitors does not protect the reinforcement from corrosion when cracked *RCS* are exposed to sea water or any other Cl^- source (14). In spite of a low-porosity cement matrix, concrete microcracks and cracks (> 0.1 mm wide) act as preferential paths for the aggressive agents which, hence, have direct access to the surface of the reinforcement close to the crack tip.

Coated reinforcements, and in particular epoxy-coated reinforcements (*ECR*), can lead to an "extra life" in the functionality of *RCS* (15) by prolonging the service life defined as the time from the construction of the structure to the total loss of its functionality (Fig. 2). However, due to the diffusion of water molecules through the coating and the subsequent loss of its adhesion to the steel surface (16), an underfilm corrosion can occur in uncracked *RCS* and, to a greater extent, in microcracked structures.

The use of galvanized (17), copper-clad (18), stainless steel-clad (19) or solid stainless steel bars (20) can prolong the service life due to the shift in the Cl^- threshold above which corrosion of reinforcing bars is promoted. This threshold can change from 0.4% by mass of cement in ordinary steel to about 1.2% or 3.5% for galvanized or stainless steel-clad and solid stainless steel, respectively. However, in very severe exposure conditions (such as tidal zones, structures semi-immersed in a Cl^- rich ground, or structures treated with de-icing salts) where high chloride content can be accumulated, the threshold value can be reached in a relatively short time particularly in microcracked *RCS*. Therefore, galvanized or stainless steel appears to be successful for long-term durability of *RCS* provided that the constructions are exposed to carbonation only in the absence of chloride.

Cathodic protection of the reinforcement (21), by using an impressed electrical current, seems to be a very promising method even if, because of the high financial investment in its installation, so far it is more used in rehabilitation works rather than in new constructions*. Theoretically, the protection of *RCS* from corrosion is just a question of a sufficient decrease in the electrochemical potential of the reinforcement (cathode), whatever Cl^- penetration occurs through the cement matrix or the preferential paths of microcracks. However, the decrease in the cathodic potential raises both the maintenance cost during the service life and the risk of other concurrent electrochemical processes (e.g., cathodic reduction of $2H^+$ to H_2 and consequent embrittlement of steel in prestressed concrete structures). Presently, the main concern for the cathodic protection method is in the proper distribution of the auxiliary anode which should be applied close to the cathodic steel reinforcement. With respect to the past experience in the traditional cathodic protection of steel in soil or in sea water, there are clear logistical problems which are specific to *RCS*. In particular, due to the concrete resistivity, the flow and distribution of cathodic current from the anode to the steel reinforcement network can be obstructed. Therefore, the reinforcement in close proximity of the anode receives more current and is over-protected, whereas more distant reinforcements receive only a small fraction of the impressed current and remain under-protected (22). In conclusion, it seems that cathodic protection can be a successful and reliable method to provide long-term durability for new constructions, provided that a specific and tailor-made electrochemical design is adopted concurrently with the structural design of the *RCS*.

b) Use of non-metallic reinforcement: Fiber Reinforced Polimer (FRP) bars in general consist of organic or inorganic high-strength fibers in a resin matrix. The most commonly used FRPs for civil engineering applications are carbon (CFRP), aramid (AFRP), and glass (GFRP). The use of FRP reinforcing bars to replace steel reinforcing bars is one of the many techniques to improve the corrosion resistance of *RCS*. They are utilized as reinforcement for reinforced and prestressed concrete members, as well as for repairing or strengthening existing concrete structures (23, 24).

Although the use of FRP reinforcing bars is presently impeded by the lack of design procedures for practicing engineers, the FRP bars are certainly on the horizon of new *RCS*, and ACI is expected to issue soon a design guide for these bars (24).

c) Special concretes with higher tensile strength and/or ductility: Long-term durability (crack-freedom) can be achieved in *RCS* by an increase in the tensile strength and/or a decrease in the modulus of elasticity of the concrete (25). Concrete cracks when the tensile stress induced by restrained thermal or drying shrinkage exceeds its tensile strength. Due to creep of concrete, some of the stress is relieved and it is the residual stress - after stress relaxation from creep - that determines whether cracking will occur (Fig. 3). In general, high compressive strength concretes are intrinsically prone to microcracking, even to a greater extent than ordinary strength concrete, since the increase in the

* According to Pedeferri (21) "cathodic prevention" should be used for new RCS, whereas "cathodic protection" would be related to the rehabilitation of deteriorated constructions.

compressive strength is accompanied by an increase in the elastic modulus which is higher than that in the tensile strength. Therefore, unless some specific ingredients are used to manufacture special concretes, pursuing a crack-free concrete with high tensile strength (Fig. 4) or low elastic modulus (Fig. 5) does not seem to be a practicable approach.

These special concretes exist in form of polymer-modified concretes characterized by a monolithic co-matrix in which the organic polymer matrix and the cement gel matrix are homogenized (26). In general, polymer modified concretes show a significant increase in tensile and flexural strengths and a negligible increase in compressive strength. This is due to the contribution of the polymer phase interpenetrating throughout the cement phase. Figure 6 illustrates the influence of the addition of styrene-butadiene rubber (*SBR*) latex on the flexural strength of concretes with and without steel fibers (26). It seems that polymer-modified concrete, particularly with steel fiber additions, is a promising material for preventing microcracks induced by restrained length changes and, therefore, for assuring long-term durability of *RCS*. However, it is seldom employed because it is very expensive compared with traditional concrete mixtures. The polymer modified concrete has been used in Japan (27), USA (28) and Europe (29) only in some special applications, such as bridge deck overlays or patching work.

d) Surface coatings for concrete protection: Because of the high cost of polymer modified concrete, polymer-modified mortars have been developed to act as a protective coatings as thin as 1-2 mm on the surface of the concrete substrate. Due to the relatively low thickness of these coatings, the cost increase related to the coating application is much lower compared with using polymer-modified concrete in bulk for *RCS*. On the other hand, the cost increase of the coating application becomes negligible for *RCS* with long-term durability if one considers the reduction in the cost for rehabilitation of these structures, particularly when subjected to very severe environmental exposures.

There are two main types of surface coatings depending on their modulus of elasticity: the rigid coatings, particularly epoxy- and urethane-based material (30), are designed, for instance, to withstand wheeled traffic, but they must be replaced on a scheduled basis. Without traffic, these coatings would be expected to last longer; however, due to their intrinsic rigidity these coatings when exposed to thermal changes, cannot deform to bridge the cracks in the concrete substrate and guarantee crack-freedom and long-term durability of *RCS*. From this point of view flexible coatings perform much better provided that they are not designed to withstand abrasion or impact stress.

The original idea pursued by Swamy et al. (31) was to employ a flexible coating combining an acrylic elastomer (based on an aqueous 2-ethylhexyl polyacrylate emulsion) with mineral filler and inorganic pigments. Subsequent developments by Coppola et al. (32) led to flexible mortars made from the same acrylic polymer aqueous emulsion combined with cement and fine aggregates. In these materials, thanks to the consumption of the water of the emulsion by reaction with the cement, the hardening time is reduced. These coatings are by themselves resistant to the aggressive agents present in the environment (water, CO_2, Cl^-, and $SO_4^{=}$ ions), are sufficiently flexible so that they can deform and bridge the un-avoidable cracks in the rigid concrete substrate, and can retain these characteristics regardless of the environment in which they are placed.

Experimental results on the performance of these flexible coatings are available as a function of the exposure time in the laboratory, underwater, and exposed to outdoor natural environment (31, 32). It should be pointed out that, similar to field experience with reinforcements having improved corrosion behavior, also in this case the available data refer to exposure times of only a few years. In conclusion, no direct field experience of real long-term durability (> 50 years) is available at this time. However, in contrast to what happens to new types of reinforcement embedded into concrete, the long-term behavior of flexible surface coatings can be directly monitored and, in case of failure, the coating can be reapplied or modified.

CONCLUSIONS

Modern reinforced concrete structures are less durable than the ancient un-reinforced concrete structures because of the corrosion risk of the steel reinforcement embedded in a wittle concrete.

Human negligence in adopting available experiential knowledge on proper design, placing, and curing of concrete is considered to be responsible for the lack of ordinary durability (up to 50 years of service life). However, the lack of human negligence is only a pre-requisite to achieve long-term durability (100 years or more).

Initial microcracks, produced by restrained thermal and hygral length changes or loadings in service, act as preferential paths for the environmental aggressive agents. This is detrimental to the long-term durability of reinforced concrete structures even when proper concrete mixtures are designed, placed, compacted, and cured.

The shift from ordinary to long-term durability can be achieved through one of the following developments:

- Improvement in the inherent corrosion resistance of the reinforcement.
- Increase in the tensile strength and strain capacity of the concrete.
- Use of surface coatings to protect the concrete substrate from penetration of the aggressive agents.