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Service Life Prediction of Repaired Structures Using Concrete Recasting Method: State-Of-The-Art

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Abstract

The performance of repaired concrete structures continues to be a major global concern. Regardless of improvements in repairing materials and methods, several repaired concrete structures still fail prematurely, leading to costly and time consuming repairs of repairs. Studies in the field of concrete repairs showed that almost 50% of repaired concrete structures had failed in Europe and USA. Simultaneously, numerous existing concrete structures needs to be repaired as they do not meet today's safety standard. As a result, annually billions of EUR will continue to be spent in order to repair deteriorated concrete structures. The need to mitigate premature failure of repaired concrete structures has to inspire many researchers to develop service life prediction model for repaired concrete structures. However, till today, service life of repaired concrete structures is just an estimate which relies on individual's experience. Scientifically developed service life prediction model for repaired concrete structures is highly desired for optimizing selection of repairing materials and techniques in turn diminishing economic loss due to premature repaired concrete failure. The aims of this paper is generally to review the performance of repaired concrete structures and the current status in the development of service life prediction models for repaired concrete structures specially exposed to exposure class XD (chlorides excluding seawater). Future research and development of service life prediction model for repaired concrete structures is discussed based on today's research and practice on the area.

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Keywords: service life prediction; repaired concrete structure; chloride contamination; numerical models; failure mode of concrete repairs; concrete repair's performance.

1. Introduction

The durability of repaired concrete structures continues to be a major global concern. Regardless of improvements in repairing materials and methods, several repaired concrete structures still fail prematurely, leading to costly and time consuming repairs of repairs. In addition, it is well known that numerous existing concrete structures do not meet today's safety standard anymore, in turn such structures needs to be repaired as total replacement of the structure which is not economically feasible. Accordingly, billions of EUR will continue to be spent in order to repair deteriorated concrete structures each year in many industrialized countries. For instance, more than 50% of Europe's annual construction budget is spent on repair of deteriorated concrete structures including rehabilitating and refurbishing of existing structures [1].

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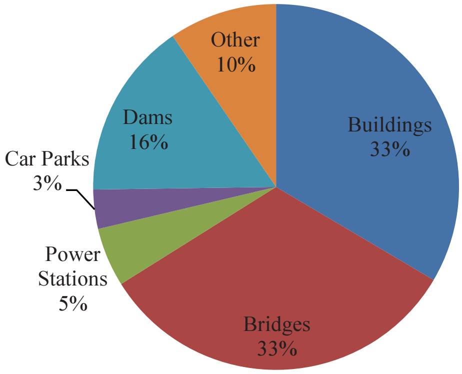

Fig. 1. Distribution of the structures by type, after ref. 4

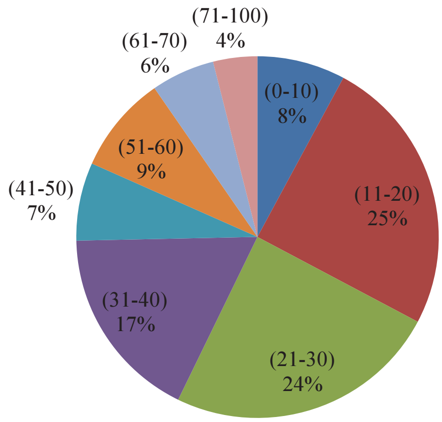

Fig. 2. Age of the structures at repair, after ref. 4

The performance of repaired concrete structures was considered to be unsatisfactory in all part of the world. Just to mention some case studies: the US Army Corps of Engineers conducted inventories of concrete structures and concluded that only a little more than 50% of the repairs are performing satisfactorily [2]. Likewise, more recently European Commission sponsored thematic network, called CON REP NET in which it has been examined about 230 case-histories on repaired concrete structures. The case-histories were located in different countries across Europe in which about 70% are located in North Europe. CON REP NET confirmed that 50% of the repaired concrete structures were failed in which 25% deteriorated in the first 5 years, 75% deteriorated within 10 years, and 95% within 25 years [3].

Degradation process of repaired concrete structure is a more complex theme compared with normal concrete structure since it requires essential understanding of several additional interacting factors. The factors include the condition of the structure before repaired, the suitability of the methods of repair and quality of the workmanship. Thus, unlike normal (unrepaired) concrete structure, service life of repaired concrete structure depends on the quality of the composite system formed by the repair material and the existing concrete substrate as well as on the proficiency with which the repair works were carried out. Currently, practical application of service life prediction model for real repaired concrete structures is yet limited. Service life of repaired concrete structure is partly based on individual's experience, and partly on condition surveys and laboratory studies made in this research sector. Lack of existing scientific models adversely contributes on today's premature failure of concrete repairs since it complicates the selection of well compatible repairing materials and techniques.

The main aims of this paper are to review the performance of repaired concrete structures and the current status in the development of service life prediction model for repaired concrete structure. The paper also discuss about the state-of-the-art on service life prediction of concrete structures exposed to exposure class XD (chlorides excluding seawater).

2. Performance of Repaired Concrete Structures

2.1. Case-histories

CON REP NET examined performance of various types of repaired concrete structures which includes buildings, bridges, parks, dams, power stations and other structures. The distribution of the case-histories by structure and age of the structures at repair is illustrated in Fig. 1 and Fig. 2, respectively. As it can be seen from Fig. 2 the distributions of the ages are very wide ranged with approximately three-fourth being 0–40 years old. Structures of the case-histories were located in different environments in urban, rural, highway, coastal and industrial areas. The majority of the structures were situated in urban followed by highway, rural and coastal [4].

Corrosion of reinforcement steel is the leading cause of deterioration of reinforced concrete structures [5-7]. It is usually accompanied by a loss of reinforcement cross-section and a build-up of corrosion products. The corrosion products occupy a larger volume than the original reinforcement steel from which they were produced, in turn, exert substantial tensile stresses on the surrounding concrete causing cracking and spalling of the concrete cover. Moreover, through time, structural distress may occur either because of loss of bond between the reinforcing steel and concrete as a result of cracking and spalling or because of the reduced steel cross-sectional area [5-7].

Corrosion of reinforcement steel is recognized as a major limitation upon durability of many existing concrete structures in Europe. Other forms of deterioration due to chemical processes such as alkali-silica reaction and ettringite are less widespread in their occurrence, but can be no less significant in their effects upon some structures. CON REP NET were confirmed that the primary causes of the original deterioration of the case-histories were corrosion of reinforcement steel, frost, cracks, alkali-aggregate reaction (AAR), deteriorated concrete, imperfect construction and others. Corrosion of reinforcement steel was the leading causes of deterioration with 54% and AAR was the least cause of deterioration which accounts for 4% [4].

2.2. Mode and cause of concrete repairs failure

Various deterioration mechanisms affect the durability of repaired concrete structures. CON REP NET confirmed that almost 50% of the repaired concrete structures from the case-histories were failed. After 5 years, 25% of the repairs were unsatisfactory, after 10 years 75% were continued to be unsatisfactory and after 25 year 95% had failed [3]. Modes of failure of the concrete repairs were associated with continued corrosion, cracking, deboning or spalling of concrete. The percentile distribution of each failure mode of the concrete repairs in the case-histories is illustrated in Fig. 3. As it is clearly seen, continued corrosion and cracking are the major modes of failure of the concrete repairs which accounts for 37% and 36% of the failure modes, respectively.

According to the opinion of the CON REP NET thematic network reviewer's, the cause of failure mainly related with [8]:

- Wrong diagnosis of the cause of the initial damage or deterioration of the structure (16%).
- Inappropriate design of intervention works (38%).
- Inappropriate specification or choice of the materials used (15%).
- Poor workmanship (19%).
- Other factors (12%).

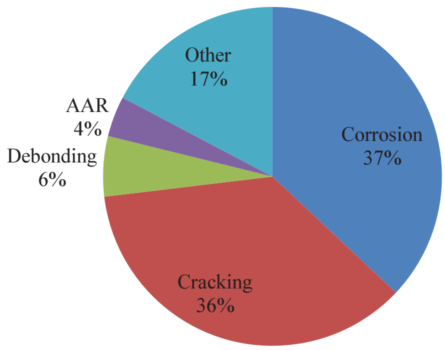

Fig. 3. Failure mode of the concrete repairs, after ref. [4]

Premature failure of repaired concrete structure as well as performance of the majority of repaired concrete structures affects many European and other industrialized countries. Selection of repairing materials and techniques has to be based on scientifically developed service life prediction model in order to mitigate the premature failure of repaired concrete structures.

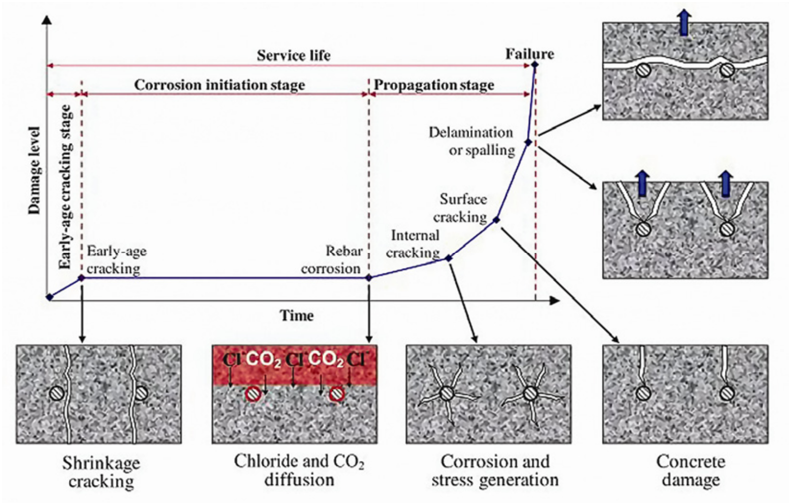

Fig. 4. Schematic of conceptual model of corrosion of reinforcement steel in concrete, adopted from [9]

3. Service life prediction model: research and practice

3.1. Unrepaired concrete structures

In many cases, corrosion of reinforcement steel in concrete structure induced by carbonation and chloride contamination is the foremost cause of premature degradation, loss of serviceability and safety of reinforced concrete structures [10-17]. Consequently, in the past few decades, great efforts have been made in developing service life prediction models for reinforced concrete structure exposed to chloride contaminated and/or carbonated environment. As a result, today, there are several conceptual frameworks as well as practically applicable prediction models for concrete structures exposed to such contaminations [18-26].

Development of service life prediction model for reinforced concrete structure exposed to chloride contaminated or carbonated environment is a complicated process, because corrosion of reinforcement steel requires a quantitative understanding of the environment, transport mechanisms through concrete, the corrosion phenomenon, cracking, and physical deterioration processes. The service life of reinforced concrete structures can be divided in two distinct phases as schematically illustrated in Fig. 4. The first phase is the initiation of corrosion, in which the reinforcement steel is passive but phenomena that can lead to loss of passivity, e. g. chloride or carbonation penetration in the concrete cover, take place. The second phase is propagation of corrosion that begins when the reinforcement steel is depassivated and finishes when a limiting state is reached beyond which consequences of corrosion cannot be further tolerated [5], [9], [27].

Chloride attack is the most typical deterioration factor for many reinforced concrete structures [27-28]. Thus, this section mainly discuss about chloride related deterioration and service life prediction model for concrete exposed to chloride ions (exposure class XD). Corrosion by chlorides is localized (pitting), with penetrating attacks of limited area surrounded by non-corroded areas. Service life prediction of a reinforced concrete structure exposed to chlorides requires understanding of the chloride ingress rate and the chloride concentration at which reinforcement steel corrosion is initiated. Normally, a certain time is required from the breakdown of the passive film and the formation of the first corrosion pit. The initiation time can be considered as the time when the reinforcement steel in concrete that contains substantial moisture and oxygen is characterized by an averaged sustained corrosion rate higher than $2mA/m^2$ [27].

There is general agreement in the literature that corrosion initiation is generally deemed to occur once chloride concentration exceeds a given value or threshold. The amount of chloride at the reinforcement steel of a specific structure that is necessary to sustain local passive film breakdown, and initiate the corrosion process is called chloride threshold or critical chloride content [7], [27], [29-30]. It is still one of the crucial parameters required for many service life prediction of reinforced concrete structure. However, there is not reliable value of chloride threshold as a review conducted by [31] has shown that they are significantly scattered over a wide range of values.

Moreover, recent studies revealed that concentration of chloride ions is not the only major factor, the potential of the reinforcement steel and the presence of voids at the reinforcement steel/concrete interface are also among the most dominant influencing factors which governs initiation of corrosion of reinforcement steel in a given concrete structure. Interface of reinforcement steel/concrete are highly dependent on conditions during casting, compaction and the transformation from fresh concrete to a solid material. Corrosion of reinforcement steel in concrete is almost always exclusively initiated on the back side of the steel (with respect to casting direction and chloride ingress) regardless of binder type and water/binding ratio [31-33].

Type of binders and water/binding (w/b) ratio are another factors which affects the corrosion process as they affect the rate of chloride ingress into the concrete structure. Cement replaced with fly ash, has beneficial effects regarding chloride penetration resistance as well as electrical resistivity of the concrete. Lower w/b ratio results in longer corrosion initiation times for reinforcement steel in concrete since the diffusion time of aggressive ions to the steel surface is prolonged [33].

In general, chloride ingress into concrete structure and the subsequent corrosion initiation of reinforcement steel is a complex processes, which are influenced by numerous factors which many of them are interrelated. The factors may include reinforcement steel - concrete interface, concentration of hydroxide ions in the pore solution (pH), electrochemical potential of the steel, binder type, surface condition of the reinforcement steel, moisture content in the concrete, oxygen availability at the reinforcement steel surface, water to binding ratio, electrical resistivity of the concrete, degree of hydration, chemical composition of the reinforcement steel, temperature, chloride source (mixed-in initially or penetrated into hardened concrete), type of cation accompanying the chloride ion and presence of other species (e.g. inhibiting substances) [31], [34-35].

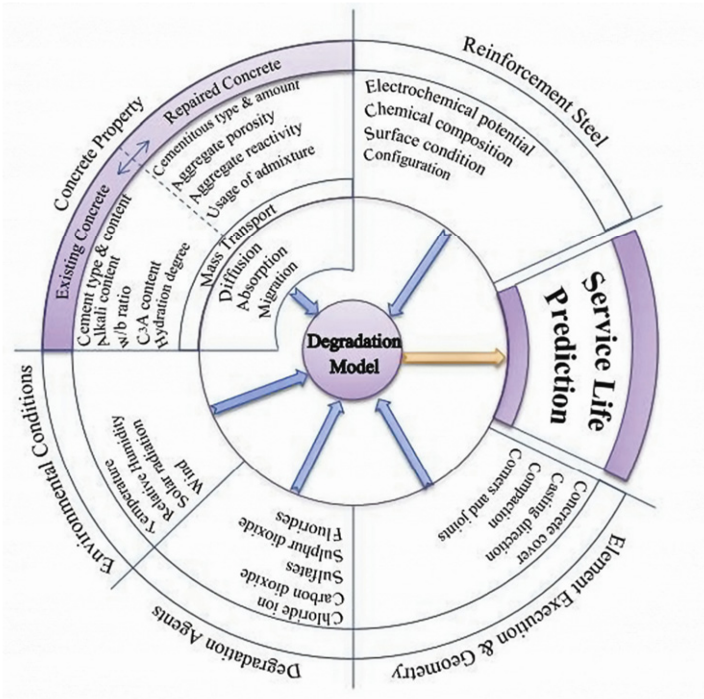

Fig. 5. Major interaction of factors that affects service life of repaired concrete structures

3.2. Repaired concrete structures

Corrosion induced by chloride ions would be more complex in case of repaired concrete structure because of continuing corrosion and a number of additional influential factors which do not exist in unrepaired construction. Fig. 5 illustrates the main interaction of influential factors that affect the service life of repaired concrete structures. Fundamental understanding of the repaired concrete structure including the interaction of the repair systems with the existing concrete substrate is highly required. The impact of some parameters in repaired concrete structure may result in opposite effects what supposed to be in unrepaired structure. For instance, chloride ions concentration in the concrete structure before repair is nonlinearly space-dependent. However, right after repair, the chloride distribution property will become time and space dependent because of the difference between the age and diffusion coefficients between the old and repair concrete [36]. In another perspective, the existence of the interfacial transition zone between repair concrete and the substrate concrete increases the risk for corrosion of reinforcement steel in and near the interfacial transition zone [37]. These show that a thorough understanding of the effect of chloride ingress in repaired concrete structure is most important.

Regardless of improvements in repairing materials and methods, performance of concrete repairs are still poor all over the world. The need to mitigate premature failure of repaired concrete structure had motivated some researchers to develop service life prediction model for repaired concrete structure, however, to the author's knowledge, yet there are very few service life prediction models for repaired concrete structure, e.g. [36], [38]. The models are based on numerical methods that simulate the corrosion processes of reinforcement steel in concrete which is induced by ingress of chloride ions. The beginning of development of such kinds of models is highly valued. Yet, needs improvements and should encompass various influential factors for practical application.

In the model, the effect of continuing corrosion is not taken into consideration and it rely on the concept of chloride threshold to define the corrosion resistance of the reinforcement steel in the repaired concrete structure. Nevertheless, it is well addressed that chloride threshold value in published literature are scattered over a wide range of values and more recent literature confirmed that chloride threshold cannot be a unique value as it is a function of various variables. It also assumes that the bond between the original concrete and repair material is to be perfect and the effect of the interfacial transition zone between the repair and substrate concrete are neglected. In this regard, an advanced study that considers most influential factors in the deterioration model of repaired concrete structure to service life prediction model is vital.

4. Conclusions

Regardless of improvements in repairing materials and methods, several repaired concrete structures still fail prematurely, leading to costly and time consuming repairs of repairs. Efficient mechanisms that can predict the service life of repaired concrete structure is highly desired for optimizing selection of repairing materials and techniques in turn diminishing economic loss due to premature repaired concrete failure. In recent years, very few service life prediction models were developed for repaired concrete structures. The models are based on numerical methods that simulate the corrosion processes of reinforcement steel in concrete which is induced by ingress of chloride ions.

The existing models contain simplifications and approximations. For instance, the effect of continuing corrosion is not taken into consideration and it relies on the concept of chloride threshold to define the corrosion resistance of the reinforcement steel. It also assumes that the bond between the original concrete and repair material is to be perfect as well as neglect the effect of the interfacial transition zone. The combination of such assumptions, simplifications and generalizations compounded with the complex behaviour of repaired concrete structure leads to a considerable uncertainty in the output of the service life prediction model.

Thus, more efficient model which considers combined effect of various deterioration factors as the real-world and able to predict the service life of repaired concrete structures accurately is highly desired for optimizing selection of repairing materials and techniques. Indeed, developing service life prediction model for repaired concrete structure would not be an easy task since its service life is highly dependent on various factors that differ from those associated with existing unrepaired concrete structure. Therefore conducting more research on service life prediction of repaired concrete structure using advanced modelling techniques is necessary in order to obtain more accurate results. The modelling techniques should be able to deal with the nonlinear behaviour of several complex interacting factors. The research need to be supported by laboratory and field data of long term exposed structure in order to address the effect of repair position in the existing structure, its geometry, and other limitations.

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