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Models for the Prediction of Service Life of Buildings - A Review

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Abstract

Service life models are a part of critical anchors to achieving sustainable development goals, offering sustainable solutions for infrastructural advancement. In spite of their indisputable usefulness and acceptability in the scientific circle, their real-world deployment is still grossly inadequate. The overall objective of this review is to assess the existing service life prediction models with highlights of their highs and lows. The models identified include deterministic, stochastic and engineering. Areas requiring more intensive research identified include the development of service life database, simplification of the complicated mathematical formats of service life models into simpler more practically-manageable formats, comparative study of expert opinions and computer integrated knowledge, as well as the place of structural elements in service life determination compared to non-structural elements. The study finally notes the areas that will give the required shape and speed of development to service life modeling of reinforced concrete buildings which include the provision of service life database, practical application of service life model for user-guidance, the superiority of service life data from non-destructive testing results to commercial data from manufacturers, placement of experts' opinions at par with computer integrated knowledge system, and using complete building for service life determination rather than building elements. This review will serve as information base on various service life models which should assist early researchers in the subject area and speed up the application from the rudimentary to more advanced stages within the foreseeable future.

Keywords: Service Life Model, Database, Durability, Building Component, Sustainable Development

Introduction

Infrastructure is a major determinant of economic growth in any society and the commonest infrastructure is the building. Buildings are important because they constitute an indicator of the standard of living of the occupants. This makes the maintenance of reinforced concrete buildings an increasingly important topic around the world (Possan, Dal-Molin and Andrade, 2018). It is generally agreed that infrastructure and technology have to be improved in order to achieve sustainable development (Ng'ang'a, 2012). It is the consciousness of and the desire for sustainable development that has steered the interest of many researchers to service life prediction of reinforced concrete buildings. In an attempt to conserve and protect the scarce natural resources while maintaining environmental balance that has been established around a building structure for decades, the option of demolishing and constructing a new building seems unappealing to building owners. On the other hand, refurbishment cost of building can be as high as half of new construction. In the light of this situation, the most acceptable option is to determine the service life of the building, analyze investment options and adopt the most economical option.

Therefore, it has become worthwhile and imperative to develop models for predicting the service life of buildings, which can aid in decision making for repairs, strengthening or demolition (Liang, Kao, Hung, and Oung, 2009). Numerous service life prediction models have been developed and the development is on-going. Some are based on numerical method while others are on computational, empirical, or reliability approach, among others. Though the development of these models is a difficult task, many researchers have nevertheless developed service life prediction models. However, their application remains a challenging task. This paper attempts to carry out a wide-scale review of the available related research works on service life prediction models, highlighting the high and low points of each of the models.

Materials and Methods

This study made use of the relevant materials available in the literature that are under this topic of discussion or closely related to it. The present state of service life modeling was critically looked into and the application at the onset was juxtaposed with the state- of- the- art. This enabled some conclusions to be drawn and recommendations that could help practicing professionals and researchers were also suggested.

History of Service Life

There is abundant literature evidence of the traceability of service life concepts of buildings and structures to when ancient builders discovered that some materials and designs stay longer in service than others (Davey, 1961) as reported in ACI 365 (2000). Early builders used the word durability until recently when the concept of service life came up as the quantitative version of durability. Therefore, throughout history, service life prediction of structures, equipment and other components has been majorly qualitative and empirical (ACI 365, 2000).

According to Lacasse (2008), service life and durability research have been part of construction lexicon over the past 50 years. It was R Legget, the past Chair of ASTM standards development committee on the performance of buildings (ASTM E06), who in the 1950’s first identified durability or more suitably, service life, as a research field (see Legget and Hutcheon, 1958, in Grodin, 1993). Since these early efforts, quite a good number of durability and service life research projects have been initiated with outcomes that are motivating to other researchers. Furthermore, Hendriks, Nunen and Erkelens (2004) noted that service life prediction originated in the 1950’s when the first set of experiments with cyclical loads were performed. The cyclic load tests were continually increased until 1990's when service life now became a field of expertise with the development of guides and standards.

A considerable amount of work has been carried out on concrete durability over the past 50 years through laboratory and field studies. However, the results of these studies are either scattered in the journal literature or spread thinly across some popular textbooks. Furthermore, the rather mostly theoretical approaches to deterioration mechanism with predictive characteristic coupled with complicated mathematical models impose limitation on their widespread practical application (Papadaski and Efstathiou, 2006). Prior to the 1990s, research into the expected service life of building components and materials had been grossly limited but government and professional organisations particularly in the UK and US have thereafter carried out considerable research activities into the lives of buildings and their components (Abott, 2007).

Durability and service life prediction of building materials and projects constitute a multi-disciplinary research field that has gained considerable attention over the last decade. Service life prediction has now become a recognized scientific activity with fairly uniform methodologies available to guide the research and development work. This is mostly due to research efforts carried out in the late 1960’s at the National Bureau of Standards which led to the development of a systematic approach for the assessment of service life and durability of building materials and construction (Frohnsdorff and Master 1990; Frohnsdorff, Sjostrom, & Soronis, 1999).

Currently, the literature is replete with research works dealing with degradation mechanism in which attempts have been made to study the mechanism experimentally or via simulation using fundamental or empirical models. The numerous experimental results obtained and the rather complicated mathematical models limit their wide scale use by concrete engineers, who want to predict the service life of concrete.

Papadakis, Vayenas and Fardis (1991) and Papadakis, Fardis, and Vayenas (1992) were the first to develop a reaction engineering model of the process leading to concrete carbonation resulting in a nonlinear system of differential equations in space and time which lend themselves only to numerical solution. Thereafter, many research works have been executed in the area of service life and durability (Lacasse, 2008; Teply, 2002; and Gaspar and de Brito, 2005).

In spite of the huge research effort on the service life and the maintenance of buildings and components, the application of the methodologies developed so far, nevertheless, remains limited, mainly owing to the complex nature of degradation phenomena but also due to dearth of dependable tools for their modelling. Furthermore, data pertaining to the durability and service life of buildings and materials are usually absent in most architectural and construction projects. Therefore, notwithstanding the importance of methodologies for the prediction of service life and their acceptability in the scientific community, their application remains at a rudimentary level (Silva, de Brito, and Gaspar, 2016).

Definition of Service Life

It is common to confuse the concept of service life with that of durability, a fact that often results in the misuse of the terms. Service life relates to a period of time while durability refers to the ability of a building and its components to perform adequately during their life cycle (Silva, de Brito, and Gaspar, 2016). According to Papadakis and Efstathiou (2005), durability is a structure's ability to withstand environmental attacks, without its performance dropping below a minimum acceptable limit. Although the two concepts are different, they are closely related and their understanding is imperative for a clear grasp of building life (see figure 1). Both are important concepts in the construction process, whether at design or in-use phase, and they may directly or indirectly cause the reduction of maintenance cost, increase user-comfort and enhance the sustainability of whichever solution is adopted (Moreno, 2012).

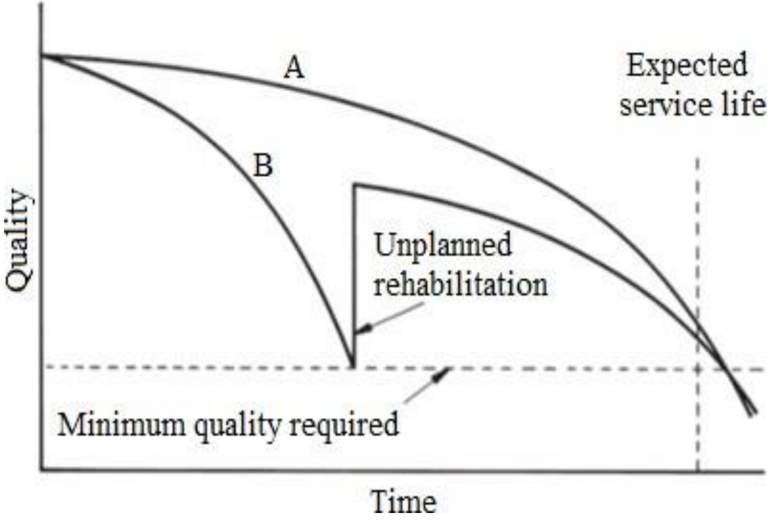

Figure 1: Schema of the concept of "Service Life" of a structure
Source: Alexander, (2018)

Different definitions have been given by different researchers, depending on their focus and perspectives. For example, some researchers have defined service life with corrosion of reinforcement in focus while others consider the general performance of concrete structure. Some also consider reliability in their definition. A few of the various definitions of service life as given by different authors are presented in Table 1.

Table 1: Selected Definitions of Service Life

S/N	Author	Service Life Definition
1.	ASTM (1982)	Service life is the period of time after installation in which the buildings or their parts meet or exceed the minimum performance requirement having been subjected to periodic maintenance.
2.	Abu-tair *et al.* (2002)	End of service life is reached when either failure occurs or major repair is necessary to keep the structure in service.
3.	Martin-Perez and Lounis (2003)	Service life is the time until damage accumulation reaches an unacceptable or limit state.
4.	Rostam (2005)	Service life is the number of years during which the structure shall perform satisfactorily without unforeseen high costs for maintenance.
5.	Life-365 (2010)	Service life of a structure is defined as the period of time after installation until such time when costly repair becomes necessary.
6.	Vorechovska, Teply and Chroma (2010); Chai, Li and Ba (2011)	Service life is the period from installation to depassivation of reinforcement due to carbonation or chlorination occurs.
7.	Zhang and Ba (2011)	Service life is the life before critical chloride concentration causes reinforcement corrosion.
8.	ISO 15686 (2011)	Service life is the period of time after installation in which the buildings or their parts meet or exceed the minimum performance requirement.
9.	Crevello and Noyce (2015)	Technical service life is the period for which a structure is capable of performing according to requirements without major repair, before unacceptable state is reached. Functional service life or Functional working life is the time in service until the structure no longer fulfils the functional requirement. Economic service life is the time in service until the replacement of the structure (or part of it) is more economical than keeping it.

The table presents different definitions of service life that are of general interest. Obviously, the definitions are quite similar and it is worthy of note that some of these definitions (S/Nos. 1, 5 and 8) are found in standard documents while other authors more or less derived their definitions from them. However, because of its tone and its practical language, the definition given by ASTM (1982) S/No. 1 is hereby recommended.

Service Life and Sustainable Development

Building vision throughout the world has been modified by the very topical concept of sustainable development. It is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

The last few decades have witnessed a growing interest in green building and green materials, and a general tendency towards a more sustainable built environment. It is generally acknowledged that current ways of using our resources is unsustainable and it has telling negative effects on the sustainability of the building industry. The most critical of these effects are premature deterioration of buildings and their components, cost for routine maintenance, repairs, before time replacement, likely health effects and service disruption. The repairs have increased embodied energy which can outweigh that of the originally constructed building over the expected life time (Talon, Chevaliar, and Hans 2006).

Building owners are faced with the dilemma of either to rehabilitate and continue to use the existing building or to demolish and rebuild. Meanwhile, the option of demolishing and rebuilding also has a number of challenges such as decanting, access to construction site, waste recycling, and unanticipated costs, among others. More so, it has been noted that the cost of rehabilitating in most cases is approximately half the cost of new construction. Therefore, extending the serviceable life of building (with minimum investments) is finding the best option among asset owners (Urs, Manthesh, Jayaram, and Hegde, 2015). Therefore, to minimize waste and the use of resources, buildings need to stay healthy for a longer period of time which translates to sustainable development (Mc Kay, 2007).

In order to conserve the natural environment, scarce and non-renewable resources, the achievement of quality environment and life, the concept of sustainable infrastructural development cannot be brushed aside; likewise, service life of buildings (Diyoke, 2001; Ibikunle, 2014).

Service Life and Accelerated Aging Test

Tests for durability are sparse while tests for evaluation of service life are even sparser. This is so because testing for durability is a complex task and service life testing is even more complicated. These complications can be traced to the fact that degradation mechanism often depends on numerous factors capable of affecting the process in a synergistic way; moreover, the governing failure mode may vary for different environments. Furthermore, the slow pace of degradation makes accelerated tests difficult and the large number of degradation agents make comparison with actual in-use degradation environment complicated (Martin, Saunders, Floyd, and Wineburg 1994; Marteinsson, 2005; Silvestro, Andrade, and Dal-Molin, 2019).

According to Fagerlung (1985), in order for design to effectively utilise the concept of service life, the traditional accelerated test methods must be replaced by non-accelerated tests. The problems presented by accelerated test are as follows:

(i) It is difficult to convert the exposure time in the test to the time in the real environment.
(ii) The acceleration changes the destruction mechanism, leading to a change in the real behaviour.
(iii) The acceleration can be so large that destruction becomes disproportionate.
(iv) The effect of mutual interaction which is often present when two or more destructive actions are present cannot be revealed when only one destruction mechanism is investigated.

Andrade and Alonso (1993) and Molina, Alonso and Andrade (1993) reported that the use of accelerated testing by some researchers for corrosion caused by chlorides is not suitable because of the localized nature of the corrosion process. Furthermore, the methods employed for the estimation of service life often demands deep understanding of the degradation mechanisms causing loss of performance of the investigated building elements over time. Such information can often be obtained through accelerated aging laboratory tests, in a controlled environment. However, this method has been criticized by many researchers because it is not possible to consider the full complexity of environmental context. Field data collection techniques are usually seen as a preferable method to assess the degradation level of structure or its component in real life service conditions (Gaspar and de Brito, 2005).

Nonetheless, some researchers have opinions that are slightly different; for example Hovde (2004) believes that accelerated aging tests in a scientifically controlled environment and field data survey techniques to assess the degradation level of a building element in service conditions are often pointed out as two complementary approaches to estimate the service life of a given element. Marcotte (2001), on the other hand, believes that mathematical models, reliability and stochastic concepts are often used to overcome the limitations of accelerated ageing test.

From these opinions, it can be underlined that accelerated aging test is considerably useful in-service life and durability work. While this test cannot be taken as total representation of real condition of structure or its elements, a better test method has not been developed. Therefore, its roles cannot be overemphasized and its use will not cease until a new improved method is developed.

Service Life and Reinforcement Corrosion

All over the world today, the real and major durability issue of reinforced concrete structure is the reinforcement corrosion (Xuandong, Yang, Feng, & Ping, 2022). It is seen as the main cause for structural deterioration and the leading durability issue (Papadakis, and Efstathiou, 2006; Selvaraj, Amirthavarshini, and Deepika, 2016 and Xinzheng, 2018)). Although Michel, Geiker, Olesen, and Stang (2012), considered corrosion of embedded reinforcement as the main deterioration process, Crevello and Noyce (2015), believes that other damage mechanisms exist, yet concluded that corrosion of reinforcement is the primary and most noticeable cause of untimely damage to reinforced concrete structure which impacts greatly its service life (Ranjith, Rao, and Manjunath, 2015).
According to Poursaee (2016), corrosion of steel is here to stay and therefore corrosion science and engineering community must attempt to achieve slow rate of corrosion to the level that will make a structure or its components to remain serviceable for its specified service life. For determination of service life of reinforced concrete structure, corrosion models are indispensable as they describe the electro-chemical processes within the concrete that surround it as well as the surface of the steel (Michel, Geiker, Olesen, and Stang, 2012). In the determination of service life and proactive approach to repair of reinforced concrete structure, understanding corrosion degradation and corrosion rate measurement techniques are fundamental (Crevello and Noyce, 2015). The development of service life prediction model for reinforced concrete structures that are located within environments contaminated with either chloride or carbonate is a complex process. The reason is that qualitative understanding of the environment, movements within the concrete, the corrosion phenomenon, cracking and physical deterioration process must be considered (Taffase, and Sistonen, 2013 and Qiongming, Xuckuan and Zhonglin, 2020).

Deteriorating reactions including carbonation and chloride penetration that contribute to limit the service life of reinforced concrete structures are most times investigated as single actions. Meanwhile, if service life of reinforced concrete structure is predicted by selecting one dominant deteriorating process, the results will not be conservative. It therefore became evident recently that synergistic effects have to be considered if different deteriorating mechanisms act concurrently or in succession. Therefore, a model for service life prediction must have a scope that is enlarged to cover the synergetic effect of combined mechanical and environmental loads. However, researchers have not yet established the most severe load combination and study it in particular (Withman, Zhao, Zhang, and Jiang, 2010).

The state of being wholesome in reinforced concrete is affected by corrosion in two different ways with the loss of cross section of the reinforcement being the more obvious of the two ways. The second way by which the integrity of reinforced concrete is affected is the delamination between the remaining reinforcement and the concrete member as well as the concrete cover. This is brought about by corrosion product that occupies more volume than the reinforcing steel had initially occupied (Cheung, and Kyle, 1996 and Pellizzer, Leonel and Nogueira, 2018).

Furthermore, it is reasonable to assume that in reinforced concrete structures, major repair will be necessary once generalized cracking of concrete cover occurs due to corrosion of the reinforcement, an indication that the service life of the structure has ended. The time required for the concrete cover to crack is equal to the period of time necessary for the layer of rust to build up around the bar until it splits the cover (Papadakis, and Efsthathiou, 2005). There is convergence of opinion in the literature that once chloride concentration exceeds a certain value, corrosion initiation is generally deemed to have occurred. The minimum value of this chloride concentration that causes corrosion initiation is one of the most important parameters needed for many service life predictions of reinforced concrete structure. Nonetheless, it has been reported by recent researchers that concentration of chloride is not the only major factor; other major influencing factors are the potential of the reinforcing steel, and presence of void at the reinforcement steel / concrete interface (Taffase, and Sistonen, 2013). Also, service life of concrete structure is usually modelled as a two-stage process of initiation and propagation (Tuuti, 1982), while deterioration is conceptualized into two distinct phases to pattern after the two-stage Tuuti model as shown in Figure 2.

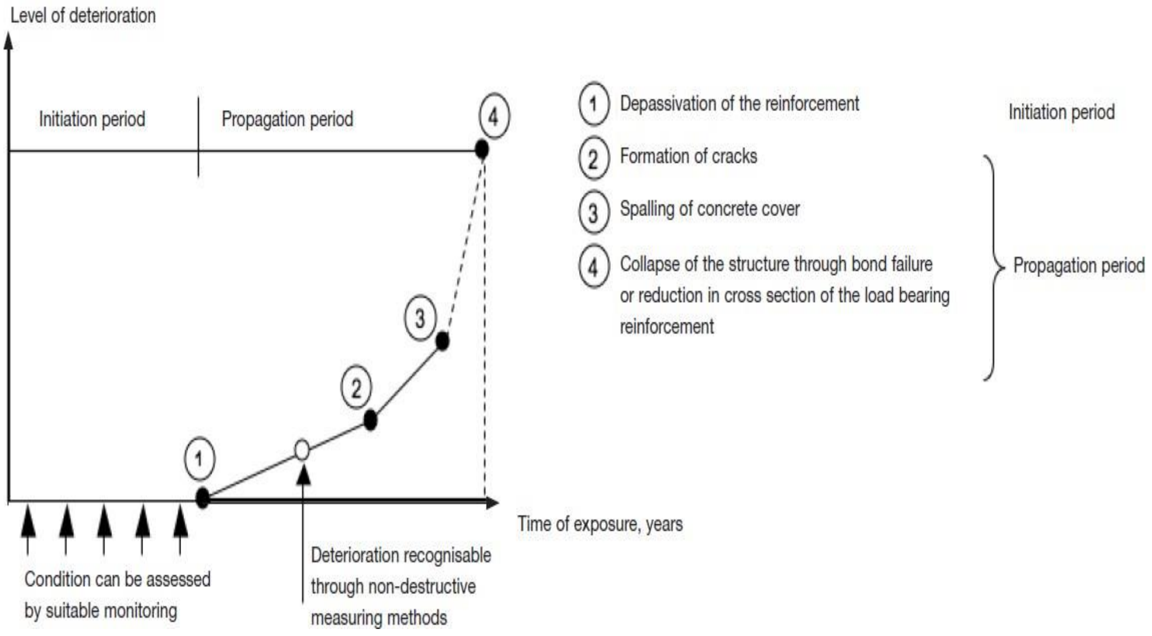

Figure 2: Two-Stage Tuuti model (source: Alexander, 2018)

The 2-stage Tuuti model is represented mathematically by Eqn (1):

$$t1 = ti + tp \tag{1}$$

where: *ti* is initiation time and *tp* is the propagation time.

However, it has been observed that service life of a structure has three major phases:

(i) time after construction and before corrosion initiation;

(ii) time between corrosion initiation and crack formation; and

(iii) time period after crack formation before failure of structure (Ying and Vrouwenvelder, 2007; Verma, Bhadauria, and Akhtar, 2014; Poursaee, 2016).

In service life modelling, climatic conditions vary the corrosion rate of the embedded steel in concrete. In particular, the relative humidity and temperature are the main determining factors for the rate of corrosion. For this reason, a reliable prediction cannot be obtained with a single corrosion rate of any particular climatic condition. More so, the properties of concrete on specific degradation process vary with the corrosion rate. It is recommended in the literature that a period of time should be selected when measuring the rate of corrosion which stands for the annual corrosion rate value for estimating service life.

Although these approaches provide reasonable values, they are encumbered by many uncertainties. For example, full understanding of the threshold free chloride level that will initiate steel corrosion has not been reached. Effect of different loadings on structure, chloride diffusion constant and concentration, surface chloride, are some of the other uncertainties. Furthermore, the concentration of surface chloride on concrete varies with time. Also, the rate of diffusion of chloride may not be uniform over a surface because concrete is a heterogeneous material. The period of initiation is considered to be longer than the period of propagation and therefore these periods can be modelled as random variables that can be defined by their statistical distributions since structures and environments are not the same (Selvaraj, Amirthavarshini and Deepika, 2016).

Service life prediction tends to increase in difficulty with the number of materials in a building component. The difficulties increase even more with systems consisting of many components. Even at that, just as the service life of a building material or component can be predicted if enough information is available, also with enough information, it should be possible to predict the life of a complete building from the predicted service lives of the building elements and construction materials in that same building (Frohnsdorff, and Martins, 1996). Likewise, after the determination of concrete mix design and structural qualities, together with the environmental conditions of the concrete location, service life can be predicted with fundamental mathematical models that simulate the deterioration mechanism and rate of chloride penetration and carbonation. Other chemical attacks are some of the basic phenomena upon which the prediction is based (Papadakis and Efsthathiou, 2005).

Service Life Technical Committees and Standards

The National Institute of Standards and Technology (NIST) introduced the technique of a systematic approach to assess the service life and durability of building materials and construction (Fohnsdorff, and Master, 1990). The NIST was the first to bring understanding as to how a systematic method could be established to evaluate durability using information that was processed into a knowledge base. This formed the basis for the initial development of a standard method by which the durability of material could be readily and systematically evaluated (ASTM, 1982).

According to Lacasse (2008), performance concept in building construction technique came to focus by the efforts of building researchers through these activities. At this time, efforts to advance durability and service life were highlighted in a symposium co-sponsored by the International Union of Testing and Research Laboratories for Materials and Structures (RILEM), the American Society for Testing and Materials (ASTM), and the International Council for Building Research Studies and Documentation (CIB). Likewise, researchers in Canada, UK and Japan are not left behind; they had already developed the key elements for a method of selecting building materials and testing them. These efforts formed the basis adopted in their guide to service life and similar guides like BSI and CSA. For example, reasonable efforts had been recorded in this regard as early as 1953 in Japan (CSA, 1995; AIJ, 1993; and BSI, 2003).

According to Frohnsdorff, Sjostrom and Soronis (1999), the establishment of ISO TC 59/SC3/WG9, design life of building in 1993 was the beginning of standardization activities. One of the first to adopt the service life prediction methodology instituted by CIB AND RILEM was a European initiative called Eurocare. They discussed the methodology and its standardization with the commission of the European community and the European Standard's Organization (CEN).

Moreso, some national standards and codes of practice were the basic documents obtainable to assist the early standardization work apart from RILEM technical recommendation. These documents include; the British guide to durability of buildings and building elements, products and components (1992), the Japanese principal guide for service life planning of building (1993), and the Canadian Guideline on durability in building (1994) (Frohnsdorff, Sjostrom, and Soronis, 1999).

It is worthy to note however that Frohnsdorff, Sjostrom, & Soronis (1999) suggested that a joint CIB/RILEM research cooperation on service life prediction should be established and this started in 1982.

Also, the standardization activities in ISOTC59/SC14 are strongly supported by the work of the joint CIB W80/RILEM 175-SLM committee on service life prediction, while the primary user of the committee products was SC14. As at today, there exist consensus guides and standards for durability and service life development by ACI being the world leading organization in area of concrete-based knowledge development (ACI, 2020).

Method/Approaches to Prediction of Service Life of Reinforced Concrete

Generally speaking, there are different methods through which the service life of concrete can be predicted. According to Clifton (1990), the available approaches are as follows:

(i) Experience based estimate: This type of service life prediction is not reliable as the results is dependent on the experience of whoever is handling the estimation.

(ii) Performance of similar materials-based estimates: Deductions from performance of similar materials was adjudged ambiguous and that comparing the durability of old and new concrete is not direct.
(iii) Accelerated testing estimates: One of the most important conditions to be met before accelerated testing can be satisfactory for service life prediction is that the in-service deterioration and the degradation mechanism that generated it should be similar to that of the accelerated test and this is often a difficult task to achieve.
(iv) Reliability and stochastic estimates: The concepts of reliability and stochastic have been applied to service life prediction model development and the models developed have their background on the theories that support the fact that service life cannot be accurately predicted.
(v) Mathematical and simulation-based estimates: modelling based on chemistry and physics of degradation and computer simulation are very useful on service life prediction.

In the last decades, various decision-making tools including methods of service life prediction have been developed to aid the process of construction maintenance. Nevertheless, different short-comings such as inadequate grasp of mechanisms degradation and their effect on construction elements, absence of dependable methods for quantification of the durability and service life of buildings, and complexity of degradation phenomena, have been observed (Van, Tristan, Stephanie and Anne, 2018). Furthermore, predicting the service life of buildings and their components is a time-consuming and difficult assignment. A number of factors are associated with it which includes material quality, design and execution level, the indoor and outdoor environmental conditions as well as the use and maintenance condition (Zhang and Ba, 2011; Hovde, 2004; Lounis, Lacasse, Siemes, and Moser, 1998).

In an attempt to define the service life prediction methods, the need arises to know and introduce the maximum acceptable level of performance which defines the end of the service life of the element being considered (Silva, de Brito, and Gaspar, 2016). In spite of the fact that service life concept is simple, its prediction or simulation is extremely difficult. This is because an acceptance criteria must be defined, which varies with time; place; stakeholder; social; economic; political; aesthetic and environmental context of the building under analysis (Gaspar, 2009).

Furthermore, as service life can hardly be accurately predicted, the challenge of today, therefore, is how to use available information to get the most reliable estimate (Madrigal, Lanzarote, and Fran Bretones, 2015). According to Shoet and Paciuk (2004), models and methods currently used for the prediction of the life cycles of building elements can be grouped into: analytical models, statistical models, empirical models and experimental methods. While analytical methods identify the mechanisms of wear and tear and simulate them, they use a performance limit criterion to determine the service life. In the statistical methods, statistical and probabilistic means are employed for predicting and assessing performance and probability of failure (Lounis, Vanier, Lacasse, and Kyle, 1999). On the other hand, empirical methods use previous experience with the same or similar construction, and occupation or climatic exposure, to assess service life (British Standards Institution, 1992). Analytical (mathematical-physical) models of service life are very complex even if the variables are independent. This is because they take into account the stochastic characteristics of the variables which always require a large amount of information on variables and their relationships (Marteinsson, 2005). Analytical models for service life functions are few and in general, service life estimation is made on the basis of empirical models. Generally, the literature groups service life prediction methods into three distinct categories: Deterministic, Stochastic and Engineering models (Moser, 1999; Lacasse and Sjostron, 2004). However, these main groups can be subdivided into different parts according to Silva *et al.* (2016). The categories and different parts as described by these authors are as follows:

Deterministic models: These models are often developed based on the knowledge of influencing factors that affect the degradation of the building component under study. Most analytical models fall into this group and the factor method "Classical approach" is the most popular and thus considered as the representative of deterministic models in some literature. When the modes of actions of these factors are studied and well understood, the degradation behaviour of material and components is then modelled, after which the degradation factors are converted to functions expressing their action with time until the maximum acceptable degradation level of element analyzed is reached. The notable advantages of these methods are; their understanding and application is easy; and they maintain their operability even when all the variables related with modelled phenomena are known. Nevertheless, the method has been criticized mainly as a result of its simplistic way of handling complex subject such as service life of building and its components.

Also, it should be understood that the purpose for which empirical methods have been developed is to evaluate the durability of a building or its components under actual condition of service and this is based on data collected during field work. The physical and functional degradation of elements are converted to quantitative information and the numerical data so generated can be used to obtain service life through graphical procedure and a statistical analysis of the evolution of degradation overtime (Silva, de Brito, and Gaspar, 2016). However, the universal applicability of an empirical model should not be considered as a weakness provided it is reasonably accurate and can be applied practically to reinforced concrete structures under similar condition to those used in obtaining the data used in its development (Otieno, 2014). Deterministic models based on regression analysis, are divided into three parts:

(i) Simple regression analysis (linear and non-linear): simple regression models are based on degradation curves that show the loss of performance of the element overtime.
(ii) Multiple linear regression analysis: The most significant variables to the description of degradation of element are analyzed and causal relationships between variables and their implications on service lives are analyzed.
(iii) Multiple non-linear regression analysis: This has to do with the application of various non-linear regression analysis to generate service life models.

According to Paulo, Branco, de Brito (2014), the factor method proposed by ISO 15686 standard ISO (2000), is the most commonly accepted example of a deterministic model. It should be noted however, that other types of deterministic models can be obtained through mathematical laws which can be used to model the degradation of structural elements. Example of this is Gompertz laws or Weilbull curves. More so, practical solutions to service life problems have been achieved with this method and the method has been widely used. It has also formed the basis for the international standard for the durability of buildings (ISO, 2011).

Stochastic models: Stochastic method is a method of modelling that sees and considers degradation for each property at a point in time as a stochastic process and therefore establishes for it, a probability of degradation (Madrigal, Lanzarote, and Fran Bretones, 2015 and Wu, Zhou, Kou, and Jiang, 2015). The complexity of degradation mechanism necessitates the use of probabilistic model to predict the service life of construction elements. Most empirical models are stochastic/probabilistic models. In this method, the degradation of construction elements is viewed as a stochastic process that is, a set of random variables that define probability parameter affecting the average degradation curve. Realizing or developing this type of model can be complex due to the requirement of extensive and realistic information that needs to be collected over a considerable period of time. Owing to the complexity of this type of model, most of the proposed stochastic models in the literature focus on reinforced concrete subjected to a degradation agent (usually chloride attack) (Silva, de Brito, and Gaspar, 2016; Lounis, Lacasse, Siemes, and Moser, 1998); popular examples are the Markov chains (empirical models developed using logistic regression) and the MEDIC method.

Engineering models: Engineering model is a simple deterministic equation developed by the combination of deterministic and probabilistic approaches to service life model. The method is a symbiosis between the two methods earlier mentioned. The model is easy to learn, understand and apply as deterministic methods, but allows the description of the degradation process in a stochastic way (Re Cecconi, 2002). These models must neither be too simple nor too complex but can possess an acceptable level of complexity. They are implemented using probabilistic data and can be used to identify the degradation phenomena in a more analytical way. Some of the most popular engineering models are the failure modes and effects analysis (FMEA), the performance limit methods and the probabilistic approach of the factor method (Silva, de Brito, & Gaspar, 2016). Computational models of Artificial Neural Networks and Fuzzy logics are developed using deterministic algorithm and as such can be grouped under engineering models owing to the fact that the trait of both deterministic and stochastic models can still be found in them. However, some are purely stochastic.

The Factor Method

There are two distinct methods of service life prediction today, the probabilistic method and the factorial method (Moser and Edvarden, 2002). However, members of CIB W80-RILEM 175 SLM suggested that each method of service life prediction should be categorized into the following groups: Factor method (representing the deterministic methods); Probabilistic methods and Engineering method (Re Cecconi, 2002).

The Factor Method (classical approach) is the simplest possible approach to service life prediction. It consists of combining reference service life (*RSL*) value with seven different factors, according to equation (2) in Re Cecconi (2002).

$$ESL=(RSL)\ A\ B\ C\ D\ E\ F\ G \qquad (2)$$

ISO 15686-1 (ISO, 2011) defines the factors as follows:

A is Quality of component;
B is Quality of Design;
C is Workmanship level;
D is Internal environment;
E is External environment;
F is In-use condition;
G is Maintenance level; and
E S L is Estimated Service Life, *RSL* is Reference Service Life

It is the most commonly accepted example of **deterministic** model as proposed by ISO 15686 standard ISO (2000). With this method, the service life of an element or system can be quantified under specific conditions using the deterministic approach, provided a reference service life for that specific condition is available which will be modified by the factors dependent on that specific condition (Madrigal, Lanzarote and Fran Bretones, 2015).

The Markov Chain Model

The Markov chain model is the most common **statistical/stochastic** service life model that is in use today. In this type of model, the Markov chain is used to approximate an average condition rating obtained through a regression function as shown in equations (3) - (7) (Racutanu and Sundquist, 2002).

Let:

E (t, p) = values of condition ratings at time t
Y (t) = regression function for average condition rating

$$E(t, p) \cong Y(t) \qquad (3)$$

The regression function Y(t) is expressed thus:
$Y(t) \cong Q(t).\ R^T = Q_t.\ R^T = Q_o.\ P^t.\ R^T$ (4)

Combining equation (3) & (4), it follows that:

$E(t, p) = Q(t).\ R^T = Q_t.\ R^T = Q_o.\ P^t.\ R^T$ (5)

where subscript ^{T} is transformation
Q(t) is state vector
P is transition probability matrix
R is vector of condition rating

The transition probability matrix can be expressed as (n x n) matrix P, where;

$$P = \begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,n} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,n} \\ \vdots & \vdots & \cdots & \vdots \\ P_{n,1} & P_{n,2} & \cdots & P_{n,n} \end{bmatrix} \quad (6)$$

$$Min \sum_{t=1}^{N} |Y(t) - E(t,p)| \quad (7)$$

And the diagonal transition elements $P_{1,1}$ $P_{2,2}$...$P_{n,n}$ may be obtained using non-linear minimization equation (7) or more advanced numerical method.

When compared with regression or deterministic model, service life models developed on Markov chain theory accommodate stochastic nature of service life of structural elements and are properly developed on simple matrix operations.

The Japanese Model for Durability Design of Concrete Structures

One of the popular engineering (empirical) models published by the Japan Society of Civil Engineers is the Japanese durability design model developed by the subcommittee on durability design for concrete structures (Bjegovic, Selih, Mikulic, and Stipanovic, 2003). The developers of this model believe that durability design of concrete structures is based on verification of the condition of equation (8) for each structural element:

$T_P \geq S_P$ (8)
where:

T_P is the durability index determined by design
S_P is the environmental index based on environmental conditions

$T_P = 50 + \sum T_P(I,J)$ (9)

I and J are durability points (determined for all parameters that influence the durability of the structure such as cracks, concrete protection, shape and dimensions of elements, among others)

$S_P = S_O + \sum (\Delta S_P)$ (10)
S_O is the value of environmental index for normal environmental condition.
ΔS_P is the additional index for severe environmental conditions.

Several other models that are basically engineering in nature have been developed based on Computer integrated knowledge and these models need very few input data that can be easily obtained in order to predict the service life of reinforced concrete elements. Examples are Clinconc, Duracrete DuCOM and Life-365.

According to Marteinsson (2005), if a model is to be practically useful for producers and the construction market, the input parameters for service life estimation must be limited and for the factor method, this condition is met.

Service life prediction literature has provided considerable evidence that the factor method is potent enough to predict service life of reinforced concrete buildings.

Sundry Refinements of the Factor Method

Moser and Edvardsen (2002) in their work "engineering design methods for service life prediction", worked on the heavy drawbacks of the factor method and the probabilistic method. The authors were able to work on the simplicity of the factor method by expanding it towards the more sophisticated models using the recursive Delphic method. The relevant factors in the factor method were replaced by density distributions instead of plain factors. This has greatly improved the information content, the relevance of the results and the method in society of service life prediction methodologies. Thus, this engineering method will give fewer errors and fewer traps will be stepped into and yet yielding nearly as good results as the sophisticated, specialized, too cumbersome or too complicated probabilistic models.

Hendricks *et al*., (2004) describes the link between environmental load in the building and other sectors. The use of the factor method is described when making environmental calculations while additional information is given for enhanced calculations. Two new factors were introduced, making all the specific aspects of building situation to be mentioned. The introduction of the factor that describes the accessibility of a product to be replaced and the combination with the replacement of component which is referred to as “trend” and its related component which are not mentioned in ISO standard prompted the authors to call it the improved factor method as adding these two factors will bring the estimated service life of component closer to the actual service life rather than just as representative for the technical service life. The authors however concluded that the reliability of this method can be enhanced if statistical distribution is added to estimate a better service life without the necessity for huge data on components deterioration.

Re Cecconi (2004) developed a software tool that joins the fast and easy approach of the factor method (a deterministic method) to the better accuracy of the engineering method. Since service life planning and service life prediction are today ruled by the ISO 15686 standard and researchers want to have a method that is easy to use like the factor method and that better follows the uncertainty of input data, the author has made an attempt to evolve factor method to an engineering method by using probabilistic input data. The author used Monte Carlo technique to model input data. He further described statistically, every element of the factor method given three values, the minimum, maximum and most probable value which seems to be more applicable in practice than others based on the mean and variance. The author concluded that though the tool may be difficult to use at the input stage, a more useful result is however obtained.

Marteinsson (2005), in his work "Service Life Estimation in the Design of Buildings: a Development of the Factor Method" discussed the contributions of the factor method in service life planning, modification and development of the methodology. He noted that the factor method is a potent tool that could be used to compare different design scenarios in a standardized or structured way. He further discussed the fact that there are only few examples that demonstrate the use of this methodology, and that has led to much discussion of the method by researchers. However, the relevance of this method in the future is a function of how practically applicable it is. The author further discussed how precise this methodology could be on the basis of material property distribution, and the fact that limited consequences of failure are associated with it.

Hovde (2005) presented a proposal to support the estimation of service life of building elements or materials at the architectural and structural engineering design stages of a building. Requirement of design lives of buildings, building components and services, and the meaning of each of the factors involved were also explained. The paper also explained the factor method and refers to some developments and evaluation of the method that are on-going internationally. General examples of how an appropriate value for each of the factors and the conditions under which different values may be chosen formed the main part of the paper. The author finally emphasized the need to construct service life data base for reference service life (*RSL*) of building elements and materials as well as an appropriate range of values for the factors.

Venkatesan *et al*. (2006), used state-of-the art approaches to estimate the residual service life of a case study building façade using information from reports before major repairs were undertaken and seasonal audit reports of public asset building in Melbourne. The authors developed a Bamforth's service life model for the building façade under study, estimated the residual service life of the case study building by simply multiplying factors derived on judgement basis. Rigorous estimate of residual service life was also made based on probability distribution of factors in the ISO method while MEDIC method was also used to estimate the residual service life of the case study building facade. The authors compared the estimates for the residual service life with expert opinion and concluded that a combination of residual service life method may be necessary in actual estimation of service life of buildings and that meaningful estimate using state of the art residual service life methods can be obtained, which can then be evaluated using expert opinions to arrive at informed decision. Finally, they recommended that for successful use of existing residual service life methodologies, record of reference service life of elements under a particular condition and the identification of rigorous basis for ISO factor method is essential.

Daniotti, Spagnolo and Paolini (2008), developed an enhanced factor method that has the ability to guide users in correctly assigning the values of the factors without tampering with the simplicity of the method, but making it more objective. The authors used experimental durability test method to develop the factor grid using specific software for different simulations. The evaluation grids were able to drive the user of the factor method in obtaining the correct value of each factor. Furthermore, the factor grid was defined in the paper and the main degradation actions were individualized, characterizing each factor with the use of specific sub factors which are needed to determine how much influence or in what way they can affect service life. This has improved the factor method proposed by ISO 15686 making it more objective and reliable as against the limit of subjectivity.

El-Dash (2001) used the factor method for the determination of service life of some public buildings under harsh weather in Kuwait. Data were collected for the assessment of structural behaviour of twenty-six buildings belonging to Kuwait University. The buildings were located in two regions, the buildings that in the first category stand at between 100-400m away from the coast while the buildings in the second category were located at 5km away from the coast. The assessment of the buildings was via visual inspection, material testing and structural analysis. Values were assigned to different predictive factors with the help of the findings as against using deterministic values, while the uncertainty in the prediction process was incorporated in statistical form. The high value, the low value and the most likely value were introduced by the author. However, the reference service life used in computing the service life in the work was the one proposed by service life authorities.

Corvacho and Quintela (2011) worked on establishing specific criteria for the application of ISO 15686 factor method for service life estimation. This was done by full characterization, definition of performance requirement, collection of standards and other regulatory documents, study of the possible degradation mechanism, search for the available reference service life, identification of the relevant factors affecting service life estimation, proposal of sub-factors and evaluation of criteria to be considered in a specific framework and theoretical application of the factor method using conventional factors value in order to allow for comparison of different situations. Several worked examples of the construction of frame works for the determination of factor values were presented but the authors only considered the great part of construction elements, concrete structural elements are completely exempted from this work.

Moreno (2012), explained how to use ISO 156886 for estimating the service life of building project in his review. The paper discussed in general with an illustrative example of the most important factors affecting the durability of buildings, and addressed it properly with a case study. The author described and differentiated the concepts of reference service life and the design service life. He also emphasized the fact that the knowledge and experience of the user cannot be ignored as the method directly depends on it and concluded that material quality and maintenance are the two important factors that mostly affect the durability and service life of buildings in Mexico. He however recommended the factor method as a very fast and efficacious estimation method mainly in systems such as an entire building. One hypothetical case was presented as an example and the reference service life given by a construction guide in Mexico was used.

Hernandez-Moreno *et al*., (2014) made use of ISO 15686 ISO (2000) method to estimate the service life of an architectonic project of a dome designed with adobe technology in the city of Toluca, Mexico, in which seven factors were used in estimating the service life of the dome. The authors concluded that although the method was not perfect, this method presents a very good option when a rough estimate of service life of building or its component is required with fewer details and without delay. They also opine that professionals in the building industry and developers will find this method very useful at the early stage of design especially in pre-design and planning stage. It should be noted that the authors used a deterministic (single) value for the seven factors used for the factor method and the reference service life was taken from the Canadian Standard Association document. Furthermore, the authors only used the ISO 15686 factor method for estimating service life of building and building component (for building not yet constructed) but did not mention service life prediction.

Madrigal, Lanzarote and Fran Bretones (2015) developed a table for the two most typical systems in outer walls and roofs which must be filled with the characteristics of the construction element under study. The method aims to estimate the service life and depending on the condition of the system, correct it according to certain factors. This method is based on the factor method given by ISO 15686 but factors affecting durability of walls and roof were given a better definition than in ISO 15686 with a clear way of obtaining each of these factors. The authors have opened up a line of research which needs attention of researchers. This is because they have only worked on roofs and walls and given a few examples to apply this proposed method to main structural elements of building structure.

De Pinho (2016) exploited the strength of the factor method in the prediction of service life of ETICS (External Thermal Insulation Composite System); a bibliographical research and field work were used in this research. Simple visual inspections of façade exposed to various degradation agents were used to collect data which were registered and systematized in an inspection and diagnosis sheet. Specific software was used to analyze the information gathered in the field work and the development of the service life prediction models was initiated. Degradation scale was set according to defect type that was used to calculate some numerical indicators which enabled degradation quantification and the graphical determination of deterioration patterns. Unlike the ISO 15686 ISO (2000), the reference service life used in this work was modified by 11 factors, ranging from type of system, color, ease of inspection etc. Although this work was based on ETICS, it has nevertheless demonstrated the strength and technicalities in the factor method of service life prediction. More so, the work has also shown that factor method of service life prediction allows well and can accommodate application of statistical tools. However, there is need to apply this method to structural elements of building also and not just the non-structural components.

Results and Discussion

Looking at the numerous research papers on Models, standards, codes and guides for service life prediction of reinforced concrete buildings, it can be concluded that the philosophical foundation needed has been laid, waiting for good superstructures which are predictive models that are practically applicable. These significant contributions are expected to have collectively provided a substantial depth of knowledge to the field of service life prediction for reinforced concrete buildings such that service life model and modeling for reinforced concrete building would have reached an advanced stage at the present time.

However, service life prediction for reinforced concrete buildings is still under consideration for inclusion in building design process in spite of the numerous standards, codes and guides that have been developed. Till date, durability assessment and service life prediction are still being anticipated to become a part of project documentation. Meanwhile, this field of research has been identified in the early 1950's.

Moreso, researchers today are more interested in building components than the whole building. This explains why more research papers are available in the literature on non-structural components of the building than the structural elements. Although most of these researchers obtain their information from industries which make their job quite easy but the possibility of the industries to be biased cannot be ruled out. It is therefore important for research institutes to be more involved in building material research projects.

In most cases around the world, depending on the mind and status of building owner, desire to change any of the non-structural components of the building for aesthetic or function reasons may arise anytime within the service life of the building. Whether such components are working under total efficiency or not, the owner may want it replaced with better component. It may be therefore more appropriate to consider structural elements in a building as main determinant of service life of the building in as much as they cannot be replaced throughout the service life of the building.

Furthermore, the fact that development of models for service life prediction is a continuing process cannot be denied. Many researchers have developed several models which have not been validated despite the fact that accelerated aging process were used in developing these models. This reason coupled with the fact that most of these models have numerous impute parameters that are not easy to obtain have made these models to remain on the literature pages without practical application. Today there are service life models such as Life-365, ClinConc, fibBulletin 34, DuraCrete, Stadium, Concrete works e.t.c which have being developed over a decade ago some of which are fully probabilistic, a serious issue of concern is whether researchers are making serious efforts to improve on or further develop these models.

Conclusions

Various models for service life prediction of reinforced concrete buildings have been reviewed. The following conclusions follow from this review:

(i) Useful and reliable information must be available in form of service life database.
(ii) In order to enhance wider acceptability and use of a prediction model for service life of buildings, demonstration of practical application is required as methodologies presented in the form of guidelines are not sufficient to guide users.
(iii) Manufacturers can only give service life information for their own products. However, service life information needed for prediction of service life of structural members can only be obtained from the buildings through non-destructive testing.
(iv) Expert opinions should still be placed at par with computer-integrated knowledge system.
(v) Further research on service life modelling should focus on whole building rather than building components.
(vi) In order for service life prediction of reinforced concrete building to be more generally acceptable and practically relevant, structural elements should be assigned the level of importance they deserve in prediction models.

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