International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-3, Issue-3, March 2015

Residual Life Assessment of Concrete Structures-A Review

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***Abstract*— Reinforced concrete (RC) structures constructed over decades ago approaching the end of their service life, show serious level of deterioration and hence assessment of service life of structural materials and components is gaining significance. With the increased efforts of researchers, development in computer knowledge and advancement in building materials science, prediction of service life of structures is possible. Recently, computational methods such as Finite Element Method (FEM or FEA), Finite Difference Method (FDM) and Artificial Neural Network (ANN) are becoming popular among researchers for modeling the service life of reinforced concrete structures. This paper presents the methodologies for residual strength evaluation of concrete structural components using Linear Elastic and Nonlinear Fracture Mechanics Principles.**

***Index Terms*— Finite Element Method, Finite Difference Method, Artificial Neural Network.**

I. INTRODUCTION

The technological advancements and changing user expectations, the asset owners are facing a major issue; whether to refurbish the existing building and bring it back to its life or to completely demolish and rebuild. The option of demolishing and rebuilding seems to have practical issues like decanting, access during construction, recycling of wastes and unforeseen costs besides many others. It is also noted that the refurbishment costs in many cases are approximately half the cost of new construction.

Furthermore, with the increasing focus on the sustainability of the built environment, the option of bringing back the serviceable life (Re-life) of buildings (with minimum investments) is finding the best option amongst asset owners. In bringing back the serviceable life, one of the important considerations is to ascertain the residual service life (RSL) of the building as a whole or some of its components. In generic terms, the residual service life is an estimation of the remaining useful service of a building or component taking into account of its present condition and future functioning.

Improving the quantitative assessment of damage in any structure exposed to extreme and exceptional loads is a basic step for risk-mitigation design. For this purpose, non-standard experimental techniques, accurate material models and advanced computational approaches should be developed. Both experimental techniques and numerical methods are needed to solve the still-open problems in severely- corroded or fire/blast-damaged structures. For instance, assessing the decay of bar and concrete bond under chloride attack requires special techniques to accelerate the corrosion rate and to quantify the damage.

Evaluating fracture energy and size effect in concrete structures requires special specimens. Assessing concrete damage via non- destructive test methods based on concrete colorimetry, ultrasounds and x-rays, as well as linking concrete fresh-state properties to those after hardening are bringing in advanced techniques. At the same time, adequate theoretical and numerical models at the meso-structural and structural level are being developed, to be implemented into available FE codes. The remaining service life is significantly dependent upon the existing condition of the asset and future degradation patterns considering durability and functional use. Recently developed methods on Residual Service Life modeling require sophisticated data that are not readily available. Most of the data available are in the form of reports prior to undertaking major repairs or in the form of frequent reports. The information from these available sources can serve as bench marks for estimating the residual service life.

II. RESIDUAL SERVICE LIFE

At many instances during the service period of structure, one may be interested to estimate the remaining or residual service life of concrete elements as well as for the structure as a whole.

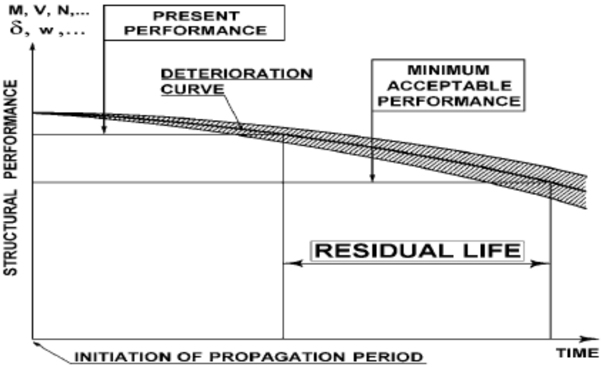

Fig.1 Indicative deterioration of structure with time.

Residual service life assessment requires obtaining firsthand information regarding the current condition of the structure through a thorough condition survey. Such condition survey involves non- destructive and semi-destructive tests to obtain the strength and other properties of the concrete.

To predict service life of reinforced concrete (RC) structures with the help of various deterministic empirical models or experimental methods are used. Service life

Manuscript received March 12, 2015

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modeling of RC structures involves analysis and prediction of the performance of structure before the deterioration. Service life models may be defined as "procedure which is able to evaluate the desired attributes of a structure to satisfy the need of the user and means required for achieving the goal".

Service life models for a structure are,

a) Empirical models: These are based on previously observed relationships of service life, concrete composition and environmental conditions without understanding scientific reasons, for this relationship such as neural network models.

b) Mechanistic models: These provide prediction of service life based on mathematical descriptions of the phenomenon involved in concrete degradation, such as understanding microstructure of concrete before and during degradation.

c) Semi empirical models: These tend to use more simple mathematical expressions than mechanistic model, predictions are made by fitting parameters based on data from field and laboratory tests and analysis.

Thorough visual survey and document surveys are essential in condition survey for getting a clear picture about the type of distresses existing in the structure, if any. This type of investigation of existing condition is intended to determine the state of the health of the structure, establish a diagnosis and to arrive at a prognosis. Through the prognosis one can estimate the expected residual service life using some of the degradation models mentioned earlier.

For an existing structure, condition of elements can be expressed in terms of condition index through inspection and survey and condition index of all elements can be combined to obtain overall condition index for the structure as a whole. Such condition index indicate the repair priority. Through prognosis change of condition index with time can be estimated.

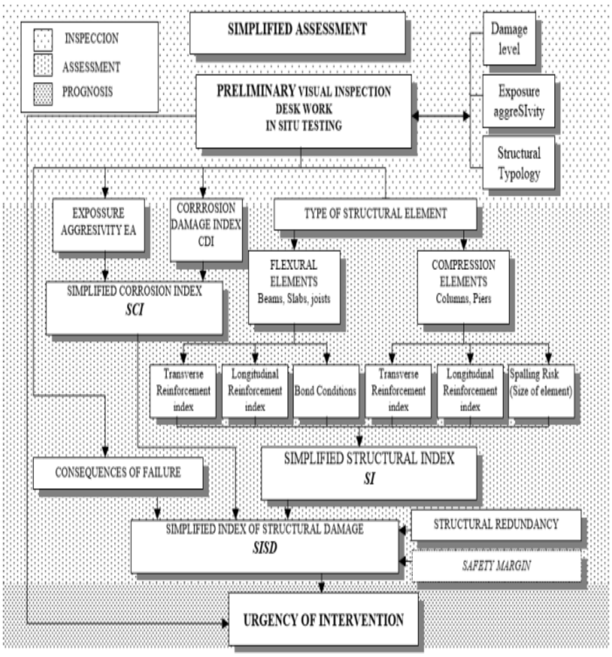

Fig.2 Simplified assesment of structure.

Material properties and state of degradation can be known through condition assessment. When condition assessment is done at regular interval through a planned inspection scheme, performance can be related to time either empirically or through model or using both concepts together. One may take advantage of Markov's theory to predict the future state in such situations.

When expected service life of structure as whole is desired, the safety against load also needs to be considered. For the available strength, the safe wind pressure that can be withstood can be estimated and corresponding design wind speed, basic wind speed etc and the return period of the later can be determined using appropriate distribution.

III. METHODS OF RESDIUAL SERVICE LIFE ANALYSIS:

The analysis of fatigue crack growth in concrete is complicated by its heterogeneous nature. Thus, a statistical/probabilistic framework is needed for modeling of crack growth. Furthermore, a wide range of parameters may influence fatigue crack growth rates in concrete. These include mechanical as well as material parameters, such as fracture toughness, stress amplitude and stress range. A reliability assessment has been performed for fatigue crack propagation by Melchers (1999) [9] considering fracture toughness and the applied stress as primary random variables. Considering LEFM approach for reliability analysis of fatigue crack propagation, two separate types of failure criteria can be used.

1. Failure occurs when the crack of size 'a' developed exceeds the predetermined or specified critical size ac and the failure function is represented by, $g = a_c - a$

2. Failure occurs when the stress intensity factor K at the leading edge of the crack exceeds the fracture toughness KC and the failure function can be represented by, g = KC-K.

As described earlier the failure due to fatigue crack propagation takes place when the crack propagation curves become asymptotic at a particular load cycle. The probability of failure can be obtained using $P=(-\beta)\ \Phi$ where β is the Reliability Index and defined as the minimum distance of the limit state function with respect to origin in a space of standard random variables.

Li et al (1999) [7] presented a comprehensive experimental program aiming to investigate strength and serviceability deterioration of concrete structures, based on following (1) halfcell potential (2) depth of chloride penetration and (3) chloride concentration. Deterioration of concrete element due to reinforcement corrosion have been divided into two phases initiation and propagation. Initiation phase starts with the construction and ends with the depassivation of the reinforcing steel. Propagation phase begins with the depassivation of the reinforcing steel and ends with the structural failure or complete dissolution of reinforcing steel.

Liang et al. (2002) [8] proposed a mathematical model to study the service life of RC bridges based on Fick's 2nd law of diffusion and other previous models. The corrosion process has three stages, the initiation time (tc), the depassivation time (tp), and the corrosion (propagation) time (tcorr). The total service life of pier for the existing RC bridge can be expressed as t = tc + tp + tcorr.

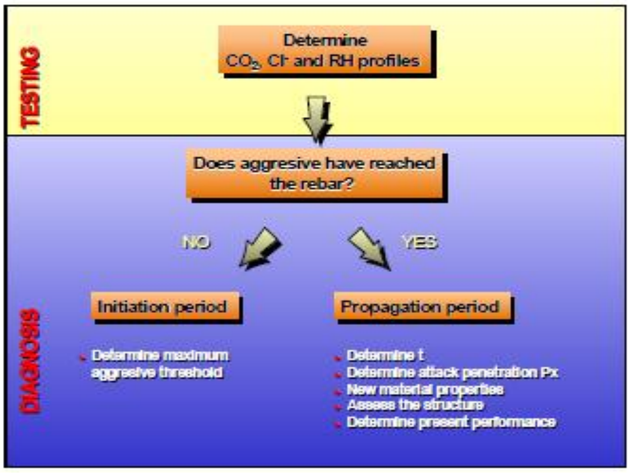

Fig.3 Diagnosis Process

Bamforth (2003) [3], stated that the service life can be defined by the time to achieve a maximum acceptable probability of the serviceability of a limit state being reached. That is the margin against safety is no longer achievable. This method does not specify the time at which the serviceability criteria would be reached.

Hovde and Moser (2004) [6] have shown that the ISO methods can be used to incorporate a probability distribution for these factors and thus specify a distribution for ESL rather than deterministic estimates. The method is based on the formula noted in below:

$ESL = RSL \times f_A \times f_B \times f_C \times f_D \times f_E \times f_F \times f_G$

Where, ESL = Estimated Service Life, RSL = Reference Service Life, f_A: Quality of component, ,f_B: Design Level, f_C: Work execution, ,f_D: Indoor environment f_E: Outdoor environment, ,f_F: In use conditions, ,f_G: Maintenance.

It is expected that any one (or combination) of these factors can affect the chosen service life. Thus suitable factors can be assumed (or derived) to estimate the ESL. Even under the conditions of rigorous analysis it has not been possible to verify the accuracy of these predictions. Thus the shortcomings in the ISO approach have prompted other researchers to develop new methods or models.

Coronelli and Gambarova (2004) [5], used nonlinear FEA and developed a suitable numerical procedure for studying structural behavior of RC beams subjected to corrosion. Effects of corrosion are modeled and validated by comparing with available test data. They considered several aspects such as reduction in steel area, changes in the ductility of carbon-steel bars, concrete area reduction because of cover cracking and spalling, changes in the strength and ductility of concrete in compression and changes in tension stiffening because of cover cracking. This study considered almost all aspects of corrosion for modeling corrosion process and results are validated with available test results.

Puatatsananon and Saouma (2005) [12], developed a 2-D coupled model, based on the reduction of concrete porosity due to calcium carbonate, using nonlinear Finite Difference program. This model analyzes the deterioration of RC caused by chloride and carbonation, considering the effect of temperature and relative pore humidity. Carbonation results in formation of calcium carbonate and release of water and heat, which affects diffusivity of concrete. In this study a coupled equation governing moisture, heat and carbon dioxide flow through concrete has been proposed. Porosity and temperature considered in this study are important parameters governing the diffusion of harmful ions in the concrete.

Neural network analysis is an analytical technique that can be applied to complex problems described by a large amount of data. It does not require knowledge of processes involved, however, it identifies the relationships among a set of data. Hence, it may be applied where other mathematical tools are not applicable. Huang developed an ANN model to predict deterioration of RC bridges based on data from previous maintenance and inspection. MATLAB programs has been used and developed to construct the ANN prediction model. Deterioration of bridges is a complex problem, as it includes several parameters. Therefore, use of ANN provides more reliable result, which has been applied in this study.

The MEDIC method is based on a typical classification of a given element into four degradation schemes that quantify the past and future degradation behavior. Thus the predictions are based on the combination of a priorly defined probability distribution curves. Developing these curves requires considerable level of expertise and judgment was stated by Venkatesan S (2006) [17].

Sain and Chandra Kishen (2007) [13] conducted numerical studies on three-point bending concrete specimens considering tension softening effect. Based on equivalent strain concept, ultimate moment capacity was calculated using the fundamental equilibrium equation for the progressive failure of concrete beams. It has been observed from the past works that there are numerous tension softening models to account for softening effect. Using these models the research work carried out towards crack growth analysis, residual life and residual strength are very less.

There is a scope to conduct crack growth analysis, remaining life and residual strength prediction of concrete structural components accounting for tension softening effect. This paper presents methodologies for residual strength evaluation of concrete structural components using linear elastic and nonlinear fracture mechanics principles. By employing tension softening models, the effect of cohesive forces due to aggregate bridging has been represented mathematically. Along with appropriate expressions different tension softening models such as linear, bilinear, trilinear, exponential and power curve have been described. These models have been validated by predicting the residual life of concrete structural components and comparing with the corresponding experimental values available in the past reports. By using power model and modified bilinear model predicted remaining life is in good agreement with the corresponding experimental values.

Pan and Wang (2009) [11], presented a FE based model to evaluate the service life of RC Structures in three Key steps - chemical ingress, steel corrosion and concrete cracking. Chemical ingress has been modeled using principle of mass conservation. Steel corrosion and increased diametric expansion are formulated using Faraday’s law and concrete cracking is simulated using a cohesive fracture approach. Developed FE model is validated using laboratory results. In this study, three phases of service life for concrete structure has been considered instead of two phases which is usually adopted by researchers. Developed model can be considered as reliable as it is validated through laboratory results.

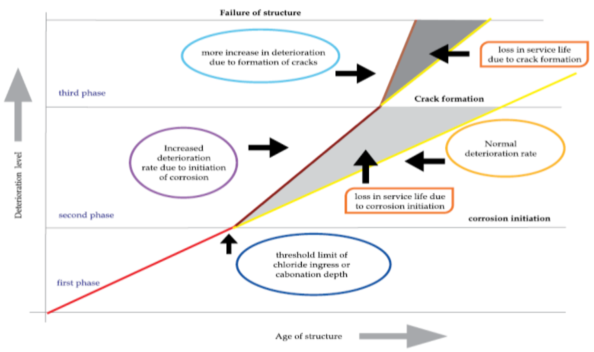

Fig.4 Life cycle of a RC Structure.

Cheung et al (2009) [4], evaluated the chloride penetration process in varying environment to predict the corrosion initiation time. Corrosion initiation time is controlled by the speed of chloride transfer and depassivation process within the structure. Variation of environmental conditions on the surface of RC had very significant impact on the corrosion process. Therefore, microclimatic variation on the concrete surface has been investigated in this research. The corrosion performance model is formulated considering change in environmental conditions and simulates the coupled diffusion process and corrosion performance. A set of realistic environmental conditions is proposed based on exposure conditions and material properties. Surface chloride concentration shows a quasi- linear increase with the n^{th} root of time and this increase is relatively fast and reaches a quasi-constant content in the time span of about five years expressed in equation as below,

Cs (t) = Cs_ref. tn t < 5 years
Cs_ref. 5n t > 5 years

Where Cs_ref = chloride content (% wt. of concrete), n = empirical coefficient and in most cases is usually proposed as 0.5. The parametric analysis results suggest that the corrosion initiation time in tropical/ subtropical regions depends mainly on the annual mean relative humidity (h), the source chloride Concentration (C), concrete cover depth (d) and w/c ratio.

Song et al (2009) [15],predicted service life of RC structures through micromechanics based corrosion model. They divided service life in four parts corrosion initiation period (ti), corrosion propagation period (tp), corrosion acceleration period (ta) and deterioration period (td).

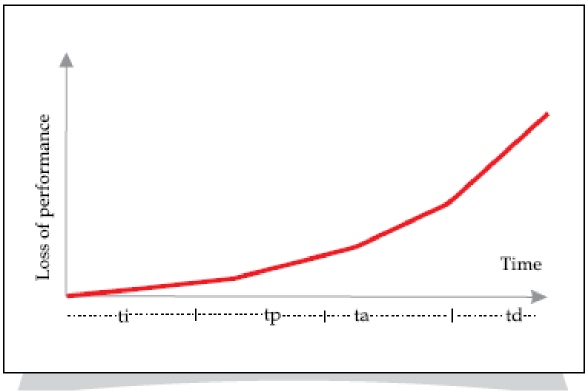

Fig.5 Different phases of service life.

This model consists of three models – chloride penetration, electric corrosion cell model and oxygen diffusion model, to evaluate the rate of corrosion and accumulation of corrosion products. In these models a corrosion cracking model has been combined to evaluate critical amount of corrosion product required for initiating cracking in concrete cover. All these models are implemented in FEA program for corrosion analysis and predicting the service life of RC structures and the results are compared with test results. It has been observed that increase in cover thickness reduces the corrosion initiation time. For analysis of chloride transport, a governing equation of mass transfer has been used. Effect of temperature, aggregate and humidity on the chloride diffusion coefficient can be considered using Nernst-Planck’s equation and Debye-Huckel’s theory. It has been found that the service life of RC structures decreases with increasing crack width, increasing w/c ratio and decreasing pH of pore water. This model comprises of several models in combination with corrosion cracking model to provide better results. It is a better technique to combine different approaches for obtaining more realistic results.

Okasha and Frangopol (2010) [10], presented a computational methodology for predicting life cycle and estimating the service life of bridges through latest modeling tools. This methodology considered techniques such as incremental nonlinear FEA, quadratic response surface, modeling using design of experiments concept and Latin hypercube sampling. Recently, use of incremental nonlinear FEA (INL-FEA) in computation has been emerged due to the advances in the FEA field and rapid increase in the speed and power of computers. In INL- FEA, the specified loading has been applied incrementally until a failure mode occurs and the load at which the failure mode occurred has been defined as the resistance of the structural system. This study presents several latest modeling tools with more emphasis over FEA technique. This study can be utilised by researchers to estimate service life of structures through computational methods.

Sain and Chandra Kishan (2012) [16] showed that multiple cracks can be represented as an equivalent single crack using damage index. The damage index, defined using the minimum eigen value of the stiffness matrices is independent of the size of the specimen for geometrically similar specimens. An energy based equivalence approach is proposed to model multiple discrete cracks in the form of a distributed damage zone. The stiffness reduction factor is computed using both fracture mechanics and damage mechanics theories and the results show that both the theories agree well with each other. Treating the multiple cracks as an equivalent single crack highly simplifies the complexity involved in modeling multiple cracks in concrete structures. By representing multiple cracks as an equivalent damage zone, that is reducing the modulus of elasticity of that zone, the modeling becomes much simpler as there is no need to consider the stress concentrations occurring at the crack tip and hence more efficient.

A Rama Chandra Murthy et al (2012) [1] predicted residual strength using this tension softening models and observed that the predicted residual strength is in good agreement with the corresponding analytical values in the past works. Altogether the variation of predicted residual moment with the chosen tension softening model follows the similar trend as in the case of residual life. With respect to past works, it can be concluded that the predicted residual moment using modified bilinear model may be correct.

B.Bhattacharjee (2012) [2] stated reliability based design concepts are well accepted principle and one can describe the failure event in terms of two variables i.e., load variable ‘S’ and resistance variable ‘R’. The failure then can be defined as: {failure}={R<S}. In the case of service life design the resistance is a function of time and even load can be similar. Failure probability is thus defined as $Pf(t)=P\{R(\tau)<S(\tau)\}$, for $\tau \leq t$. R and S are considered to be stochastic quantities with time dependent or constant density distributions
There can be two principles namely;

(i) Performance principle
(ii) Service life principle.

In the performance principle R and S needs to be related and then evaluated according to the reliability concepts mentioned above. In the service life principle: service life ‘tL’ needs to be estimated and compared with target service life ‘tg’ using same reliability concept above.
There can be, deterministic, stochastic and life time safety factor approaches.

In the deterministic approach performance principle leads to the condition that R(tg)-S(tg)>0;
while service life principle requires that the condition tL-tg>0.

In the stochastic approach the requirement corresponding to performance based principle can be expressed as: P{failure}tg=P{(R-S)<0}tg<Pfmax;
Where Pfmax is the maximum allowable failure probability.
The requirement in case of service principle can be expressed as P{failure}tg= P{(tL-tg)<0}<Pf max;
In both the cases distribution of R, S and those of tL need to be known either from available data or reliable simulation. However, neither seems to be feasible at the current state of research. In the life time safety factor method the design service life is obtained multiplying target service life by a factor of safety as td=γttg; where γt is life time safety factor.

Sanjeev et al (2014) [14] observed that service life of a structure has three major phases – (1) time after construction and before corrosion initiation (2) time between corrosion initiation and crack formation (3) time period after crack formation before failure of structure. Initially after the construction even in corrosion free environment, concrete structures deteriorate with increase in age at a constant rate in the first phase of the service life. When chloride ion more than threshold value penetrates into concrete or when pH of pore solution reduces below 9 due to carbonation corrosion initiates and the first phase of service life ends. During the second phase of service life after the corrosion initiation, deterioration rate of the structure increases and performance degradation in RC structures is faster than first phase. During the second phase of service life increase in volume of corrosion products results in the formation of cracks on the concrete surface. Formation of cracks and increase in crack width with time speed up ingress of harmful ions and, thus, further increase the deterioration rate in third phase of service life. This increased deterioration rate leads to the early failure of RC structures with the end of third phase of the service life.

IV. CONCLUSION

Modeling is a powerful tool to provide understanding of significant processes and their interactions that define service life of RC structures. In the last century predicting the service life of buildings materials and components was only a distant vision. However, today it is possible to incorporate the predictions of service lives into the design process. It is due to effort of researchers, development in computer knowledge and advancement in building materials science. Various models for predicting the service life of structures exposed to harsh environmental conditions have been developed.

Computational methods for modeling service life, performance and deterioration mechanisms of concrete structures have been developed and detected due to advancement in software technologies and rapid increase in speed and power of computers. Researchers have applied methods such as FEM, FDM and ANN for solving governing equations defining movement of various harmful ions casing deterioration of structures. However, expertise is needed for the development of computational model.

ACKNOWLEDGMENT

The authors of the present paper would like to acknowledge the authors of the papers mentioned in reference.

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