A novel diagnostic prognostic approach for rehabilitated RC structures based on integrated probabilistic deterioration models

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Abstract: The task of maintaining the huge stock of structures provides both owners and engineers with financial and technical challenges. Building managers are increasingly faced with having to maintain their building assets more efficiently whilst reducing the short and long-term cost of rehabilitation. Several approaches employing a Markovian Model have been adapted to the bridge structure domain; fewer in the domain of concrete buildings. The present paper describes a parallel approach to maintenance management used in bridge structures, but adapted to the maintenance of RC buildings. The maintenance of several components of a concrete structural system is considered in the context of both yearly and longer-term maintenance planning. The significance of different components in relation to others in the system is determined by first conducting a failure mode effect and criticality analysis (FMECA) on all structural/non-structural elements. The FMECA permits developing a component criticality index from which their relative importance is assigned amongst the different building components. An optimization of different possible maintenance actions is considered in relation to the cost of specified actions or replacement of components based on a multi-objective index (MOI). This index provides a means of relating competing maintenance objectives; that of controlling maintenance intervention costs and maintaining component condition ratings. It provides yearly maintenance costs of individual components for a given structural system over a long-term horizon that spans the life of the building.

Keywords: reinforced concrete buildings; building maintenance; component deterioration; failure mode analysis; criticality index; multi-objective index; MOI; condition rating; maintenance; Markovian models; decision making; optimization.

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1 Introduction

Structural engineers are responsible for solving the problems arising from an individual structure, which is defective, deteriorated or damaged. Tasks to be fulfilled can be summarized briefly as: "*to decide what to do about a given structure and how to do it efficiently*". Superficially, such decisions can be easily made on the basis of the condition of the structure and its ability to satisfy various structural and functional requirements, (Abdelalim, 2012a, 2012b, 2014). If the structure is considered inadequate to satisfy the structural requirements, appropriate action, such as major repair can be undertaken. Otherwise, actions such as preventive maintenance may be enough. Unfortunately, it is not an easy task to evaluate accurately the condition of a structure, especially when safety is a problem. Firstly, the assessment of an existing structure, usually suffers from the limited data and imprecise theoretical models. Secondly, any experiment or test on an existing structure needs to be non-destructive. Thirdly, while the causes of defects usually need to be considered in assessing the structure and also in deciding on an appropriate repair method, determining the true causes is rarely a straightforward task. Although there is no up-to- date a widely- agreed evaluation methodology of RC buildings, which can be considered exclusive and exhaustive, the bridge management systems (BMS) realized a noticeable advance in evaluating bridges (AASHTO-LRFD, 2007; Al-Wazeer, 2007). The present research proposes a framework for assessing RC structures depending on integrated probabilistic deterioration models as a tool for building maintenance management systems (BMMS). A review of some achievements in the BMS as an entry to the suggested methodology for RC buildings may be helpful. After then, the adapted methodology and objectives will be elucidated and a road map for investigating the safety of existing RC structures will be introduced. The provision of a systematic approach for engineers considering the diagnoses of existing reinforced concrete structures in a well-structured manner was one of the main aims of the research.

The proposed technique not only applies in evaluating the current condition of RC structures, but also can be used in monitoring RC structures to evaluate their performance and to indicate damage or predict their future performance.

To verify and test the suggested methodology, a real model (case study) was chosen in order to apply the proposed method of diagnosis and maintenance. The model is a housing block consisting of a ground and five typical floors. It exhibits miscellaneous damage aspects. A structural revising committee was formed to assess the structural performance of the building after 12 years of its erection and to decide the appropriate rehabilitation technique. The tests and visual inspection reports of this committee were studied carefully and the proposed method was applied. Developed informative degradation curves of the RC building were constructed, which proved numerically that that periodic monitoring and repairing of RC buildings lead to a better structural performance of building, a delay in deterioration, a reduction in degradation profile and consequently to a prior gain of improvement effects. Finally, conclusions, limitations and recommendation for future work are introduced.

2 Research objectives

- develop a diagnostic procedure which can be used to find out the most likely causes of anomalies in structural behaviour observed in concrete buildings
- develop a framework for BMMS especially for RC buildings
- development of a method to assess the condition of existing concrete buildings, in particular those are defective or damaged
- develop a 'road-map' for diagnosis/prognosis of RC buildings can be used either in evaluation or routine maintenance
- quantify the damage of RC elements using the most deteriorating factors
- applying the proposed technique on an existing RC building and compare outcomes of traditional inspection techniques with the proposed one.

3 Research methodology

To achieve the above-mentioned study objectives, the following procedure was carried out:

- review literature research to examine previous research and identify the gaps in current knowledge in building maintenance systems
- propose a diagnostic/prognostic approach suits the case of RC buildings
- apply the deterioration probabilistic models (Markovian model) in the proposed approach
- develop the framework for assessing RC structures depending on probabilistic deterioration models as a tool for BMMS
- verify and test the suggested methodology in a real model (case study) and construct the degradation profile of building using the proposed method of diagnosis and maintenance.

4 Evaluating deterioration using stochastic models

The use of stochastic models has contributed significantly to the field of modeling infrastructure deterioration because of the high uncertainty and randomness involved in the deterioration process. The most commonly used stochastic technique for infrastructure deterioration is the Markov chain model. This process has been used to develop stochastic deterioration models for different infrastructure facilities. Markovian bridge deterioration models are based on the concept of defining states in terms of bridge condition ratings and obtaining the probabilities of a bridge condition changing from one state to another. The most popular bridge condition rating has been developed by the Federal Highway Administration (US Department of Transportation, FHWA, Technical Reports 1997a, 1997b and 1998). In general, the condition rating can be categorized as bridge ratings and component ratings. Based on the FHWA condition rating for the deterioration in the condition of the Indiana Department of Highway bridges (IDOH), Jiang (1990) and Jiang et al. (1988) have developed a performance prediction model by using the Markov chain,. In this model, a transition probability matrix was developed for three main bridge components: the deck, superstructure, and substructure. The transition probability matrices take into account the type of structure (steel or concrete), and the effect of age (assuming that the rate of deterioration differs with age) (Yoshitaka and Uomoto, 2005). The drawback of this study is that it does not consider other factors affecting the deterioration process such as traffic density and climate.

It should be noted that the transition matrix (and accordingly, the deterioration behaviour) is greatly affected by the service condition (or the environment) to which the bridge element is exposed (Shipra, 2008). In an interesting study by Morcous and Lounis (2006), they attempted to describe clearly the service conditions associated with the four environmental categories: benign (gentle), low, moderate, and severe.

Utilization of Markovian chains in case of RC buildings will be discussed in the application of the proposed procedure in the following sections.

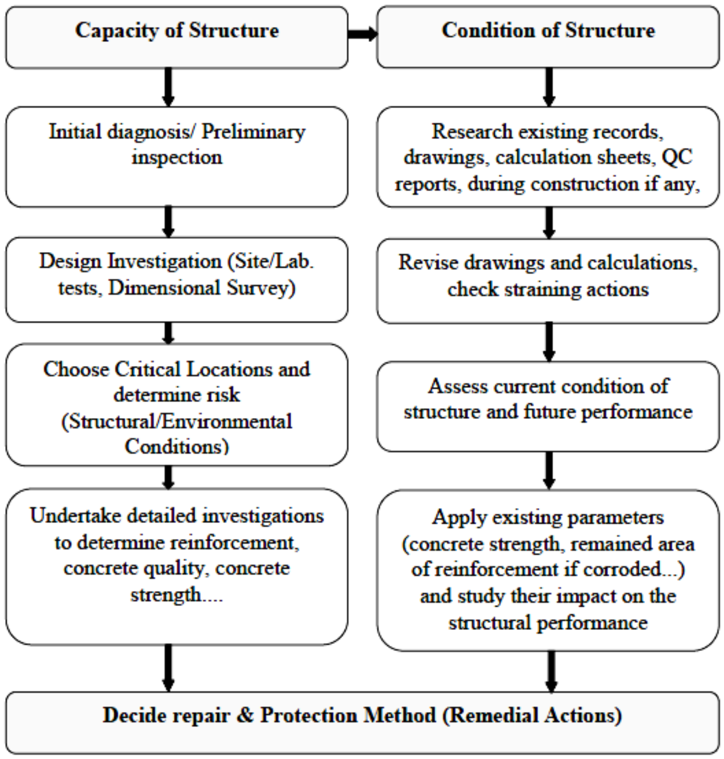
Table 1 Proposed rating of deterioration for buildings (see online version for colours)

Scaling deterioration as per Scaling Deterioration as per FHWA; Federal Highway Administration Report, 2002	
Rating	Description
10-N	Not applicable (just-constructed)
9	Excellent condition, new condition, not worthy deficiency
8	Very good condition, no repair is needed
7	Good condition, some minor problems for minor maintenance
6	Satisfactory condition, some minor deterioration for major maintenance
5	Fair condition, minor section loss, cracking or scouring for minor rehabilitation, minor rehabilitation is needed
4	Poor condition, advanced section loss, deterioration, spalling or scouring for major rehabilitation, major rehabilitation is needed
3	Serious condition, section loss, deterioration, spalling or scouring has seriously affected primary structural components, immediate rehabilitation is needed
2	Critical condition, advanced deterioration of primary structural elements, urgent rehabilitation, the structure may be closed until corrective actions are taken
1	Imminent failure condition, major deterioration or section loss, structure may be closed until corrective actions which may put it back into light service
0	Failed condition, beyond corrective action, out-of service

5 Proposed deterioration rating of concrete buildings

The scale adopted in this research is the FHWA, which modified to suit the case of RC buildings. It categorized damage into ten ratings, each one represents figurative rating accompanied by a description of deterioration (see Table 1). Before applying the suggested diagnosing technique, a subjective assessment of all probable causes of defects is needed (see Figure 1).

Figure 1 Principal stages of investigating RC structures



Given that building, managers do not necessarily dispose of unlimited budgets for maintenance actions, only the most critical set of components is further analyzed by simulation of the deterioration process. These simulations reflect the change in condition state of building components and thus the degree of overall deterioration over time. The different condition states are necessarily defined thereby ensuring that it is possible to observe symptoms of these conditions during an inspection. The condition state vector (D_t), given in Figure 2, provides information on the current condition; each element in this vector having '*S*' condition states, represents the estimated percentage of all like components in a particular condition state after time '*t*', for which '*t*', is expressed in transition periods, or e.g., Periods between inspection. The likelihood of a component remaining or changing state at given inspection intervals provides the transition probabilities (Pi,j), that is, probability of changing (or not) condition from state 'i' to a lower state 'j', and for which the corresponding transition probability matrix (P) is obtained. Thus, the matrix (S × S) permits estimating the service life of components through an analysis using the Markovian model, as shown in Figure 3. Given the present condition vector of a component (D_t), the future condition vector (D_{t+n}) can be obtained as: $D_{t+n} = D_t \times P_n$, where n, is the number transition periods in the future. The rehabilitation of deteriorated concrete structures requires an assessment of the remaining life to justify a particular course of action. Many methods that have been used for predicting the service life of construction materials include: estimates based on experiences (subjective), deductions from similar materials, accelerated testing techniques, mathematical modeling based on chemistry and physics of degradation process, and application of reliability and stochastic concepts; stochastic approaches like reliability method and combination of statistical and deterministic methods can be used in life prediction of RC structures, the last method was adopted in the current research work.

Figure 2 Description of performance analysis and development of Markov condition state matrices for service life estimation

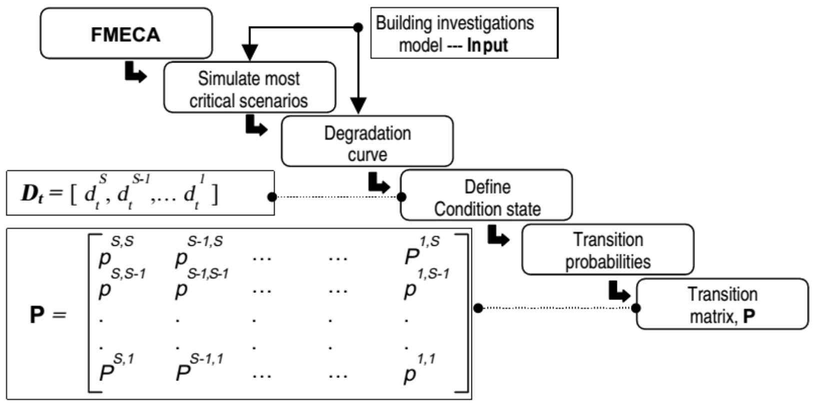
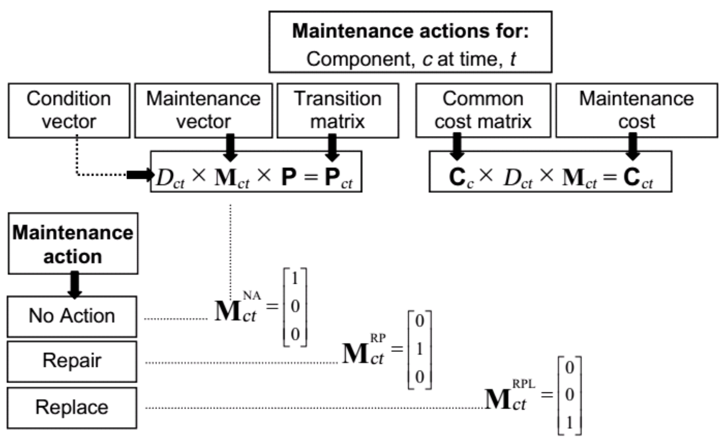


Figure 3 Description of maintenance analysis – possible choice of maintenance actions, associated maintenance vector, transition matrix and cost matrix



6 Management of component condition state using a Markovian method

There are different maintenance actions that maintenance managers can take over the course of managing the building component condition state. For example, the component might be repaired such that its condition can be maintained or it might be completely replaced. If repaired, consideration should be given to how amenable to repair the component. Can the component be repaired more than once? Then again, can the component be repaired indefinitely? Provided a component is readily accessible then repair is likely possible. However, it is unlikely that any building component can be repaired indefinitely, so then repairs should be considered as actions capable of retarding the degradation process, but ultimately not preventing the need for replacement at some time in the future. Hence a repair action undertaken on a component typically would not renew the component to its original condition state, but the action would improve its condition to a stated higher level.

If, however, the component were replaced then its condition state would be renewed to that of a new component. A typical example of components in a building more likely replaced as opposed to repaired would be the non-structural components; walls, floorings, plastering… etc. Moreover, it may be decided that no maintenance action be taken, in which case the loss in performance over time would continue at the rate prescribed by the deterioration process.

For each of these actions (described as a maintenance vector, M_{ct}), including the no maintenance action, there exist transition matrices that reflect the action taken (i.e., P_{ct}) and associated with each of these at cost for repair or replacement, and in some cases, a cost for no action as well (C_{ct}). The general stages in the maintenance action approach are provided schematically in Figure 3. Once the consequences of maintenance actions are established, one can then consider optimization of maintenance actions.

7 Applying the proposed methodology on real model

To verify and test the suggested methodology, a real model (case study) was chosen in order to apply the proposed method of diagnosis and maintenance. The model is a housing block consisting of a ground and five typical floors. It exhibits miscellaneous damage aspects. A structural revising committee was formed to assess the structural performance of the building after 12 years of its erection and to decide the appropriate rehabilitation technique. The tests and visual inspection reports of this committee were studied carefully and the proposed method was applied. A ‘road-map’ is described in the Table 2 for running a diagnostic/prognostic evaluation of reinforced concrete structures as below. The adopted FHWA scale based on detailed visual inspection gives an evaluation of the building ranges between 4 and 5, referring to Table 1.

Based on the diagnosis of the building condition; decision will be one of the following:

1 do nothing

2 do nothing for specified period

3 re-analyze, possibly downgrade the use of structure

4 prevent or reduce future deterioration

5 repair, protect, and strengthen part/all of structure

6 demolish part of the structure

7 reconstruct part of structure/all.

Table 2 Applying the proposed method on RC structures

Step 1	*Categorizing the structural elements of the model and preparing inventory* (colour-coded); No. of columns, beams, slabs, shear walls, footings, walls, E/M, non-structural elements, etc.
Step 2	*Initial inspection phase, visual inspection.* This step aims at primarily inspect the building unifying the same elements; Slabs of 1st floor, 2nd floor, etc. It includes questionnaires and sketches of apparent symptoms of distress (cracking, rust of reinforcement, and spelling, sagging...) and simple rating of apparent defects.
Step 3	*Desk study of gathered data/setting up hypothesis set (causes/attributes).* This step aims at studying data gathered from initial visual inspection in addition to the available heuristic information (history of the structure), setting up the hypothesis set according to the decimal scale used to describe damage.
Step 4	*Classifying defects/ambient conditions (promoters).* This step aims at categorizing defects, in order to enhance attributes (increasing the confidence level of causes expected). This could be done through further cycles of inspection.
Step 5	*Detailed inspection plan (sampling, mapping, in-situ/lab. tests, and desk study).* This step aims at deciding the appropriate investigations and tests required to quantify the damage of RC elements.
Step 6	*Structural assessment of RC elements (based on the derived results of compressive strength).* This step aims at evaluating the structural performance and to quantify the damage of RC elements.
Step 7	*Predicting surface condition and future behaviour of concrete based on performance indices.* This step aims at Using the available data in prediction of future behaviour of RC elements using Monte-Carlo-Markovian-Chains and damage indices like Chloride content, Carbonation Depth.
Step 8	*Derivation of damage indices for each category (slabs of all floors, columns of all floors, beams..,).* This step aims at using the available test results and active excel sheets containing design equations to calculate damage indices of RC elements.
Step 9	*Ranking elements and calculating overall damage index.* This step aims at applying the proposed ranking of elements; primary (columns, shear-walls), (beams), (slabs), secondary (walls, joints…).
Step 10	*Designing remedial actions based on cost, duration, efficiency, and the urgency of most deteriorated areas.*

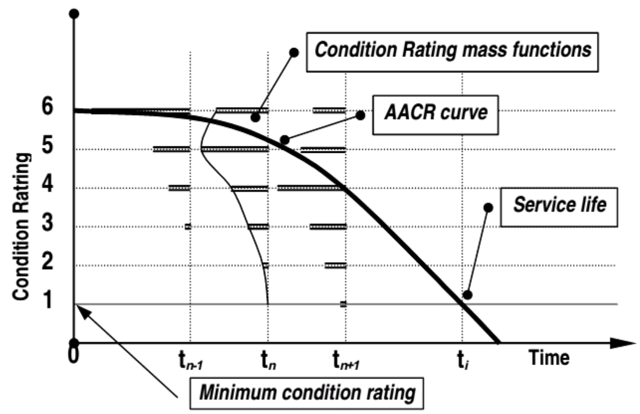
8 Optimization of maintenance actions

An optimization of different possible maintenance actions considers three scenarios that relate aggregated component condition rating (ACCR) to a desired or available maintenance budget. These scenarios include:

- maximization of component condition rating for a given annual maintenance budget
- minimizing the maintenance budget for a targeted conditioned state (aggregated condition state of all components)
- use of multi-objective index (MOI) when the budget is neither defined nor is the expected condition state – a compromise solution between maximization of the budget and minimization of the condition state over time.

The AACR is derived from the a knowledge of the number of ‘sections’ in any given condition state at a given time, a section being defined as a measurable part or portion of the entire set of sections that together form the representative ‘mass’ for a given component type. As illustrated in Figure 4, at any given time, ‘*t*’, component sections will be in their respective conditions state.

Figure 4 Condition state mass functions that define the AACR



The MOI, obtained from Morcous and Lounis (2006), with evaluation criteria, i, a set of criteria, m, and assuming the solution metric with p = 1, is given as follows:

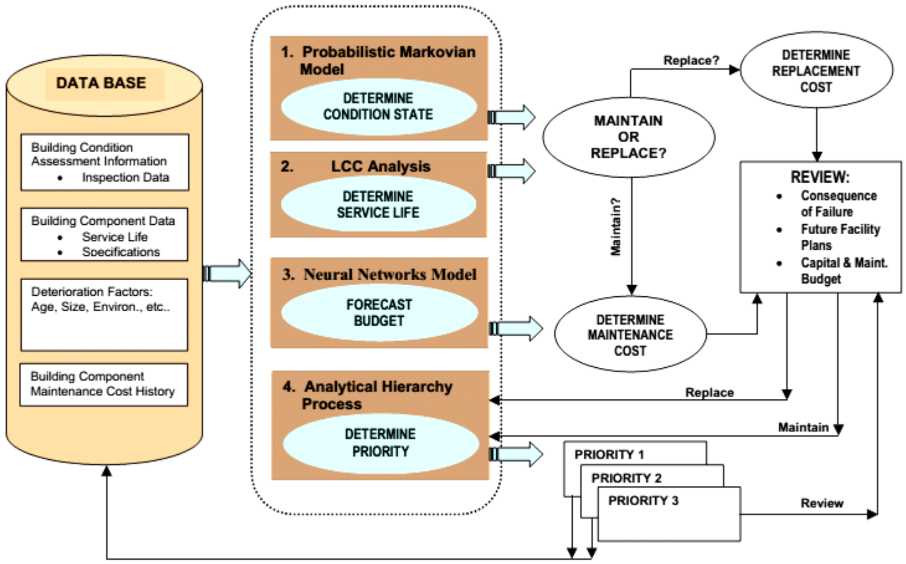
$$MOI(x) = \left[\sum_{i=1}^{m} w_i \bullet \left| \frac{f_i(x) - \min\ f_i(x)}{\max\ f_i(x) - \min\ f_i(x)} \right| \right] \tag{1}$$

where W_i is the weight given to criteria *i*, $f_i\ (x)$ the value of the objective function, and *max* $f_i(x)$ and *min* $f_i(x)$ are the maximum and minimum values of the same function respectively. The choice of (*p*) indicates all deviations from the ideal solution are considered in direct proportion to their magnitudes (Lounis and Vanier, 2000). If it is assumed that the competing objectives are budgeted maintenance cost and AACR, then this index provides a means of relating competing maintenance objectives; that of controlling maintenance intervention costs and maintaining component condition ratings.

If a building maintenance manager is aware of the expected annual budget or has made the necessary provision for acquiring the requisite funds to conduct a proper maintenance program. Then in this case, the maintenance strategy is to maximize the overall component condition rating. Essentially, the manager has interest to maximize the gains afforded by a given annual maintenance budget allocation.

Another scenario is when the building manager may know the overall component condition rating to attain, or maintain, but wishes to minimize the budgetary requirements. Whereas a more likely scenario, as in the third case, is one in which the manager may not as yet have defined budgetary requirements and as well, is not aware of the average aggregate condition state under which he should be operating the facility beyond minimum acceptable levels. Indeed, the building manager may require some insight into the most cost effective maintenance he can expect over a long-term horizon and still operate the facility above a minimum acceptable condition state (see Figure 5).

Figure 5 Condition rating vs. maintenance choices and prioritizing work (see online version for colours)

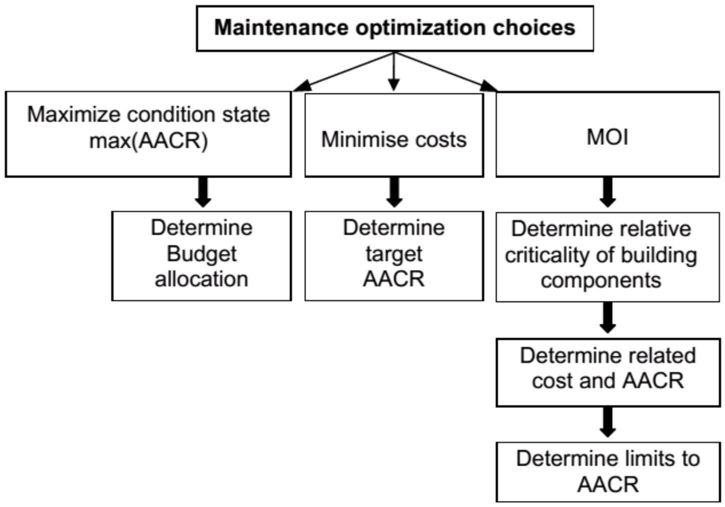


This is a case where a compromise is to be reached between two competing objectives: maintaining a minimum acceptable AACR in relation to the yearly maintenance budget. The intent is to determine the highest achievable AACR for any given year maintenance budget. As such, a MOI approach is used that is based on the: degree of criticality of amongst components; number of components being considered; condition state vector; relative importance brought to the budget in relation to the building condition state; and the AACR, and limiting values for ACCR (i.e., $ACCR_{min}$ and $ACCR_{max}$).

With respect to the limiting values for AACR, these values are selected by the building manager to better manage the maintenance process. Hence, the manager can set limits on minimum and maximum values of ACCR for each building component. For example, the building manager can determine that if the AACR of the components lies between ‘new condition’ (which equals 8 on *an FHWA – scale*) and an ‘average’ condition, then no action to consider replacing the unit should be taken. Whereas a repair could be requisitioned should the components be considered in the poor, urgent of critical states (e.g., condition states 3, 2, 1 reps.). The determination of such limits, thus permits the building manager to establish a policy of when actions should be taken and indeed the system could be used to determine how such policies might affect overall maintenance costs.

A summary of the three different maintenance scenarios is given in Figure 6. In essence, the BMM system provides yearly maintenance costs of individual components for a given building system over a long-term horizon that spans the service life of the building.

Figure 6 Maintenance optimization choices: maximize condition rating; minimize maintenance budget



9 Applying the proposed technique on the model case

Applying the proposed methodology on a current reinforced concrete structure with an overall condition rating between 4 and 5 on an FHWA scale over 12 years of service. And if it is decided to take an immediate repairing/strengthening action on main elements. The outcome will be improving the current condition of the building as the overall damage index of these elements is reduced. This will enhance the structural performance of building and modify the degradation curve sequentially. Figures 7 and 8 illustrate the improvement of the building's condition by enhancing performance with repairing action at age (t = 12 yrs). Assuming the available fund of repair allows upgrading the condition rating to *7.5* on the proposed FHWA-scale. Then, the MCMC model should be divided into two separate time intervals; before repairing took place and after it. Determining degradation curve using the updated MCMC results in new curve, almost exhibiting a similar trend; logarithmic. The new curve is better idealized, and then fitted to estimate the area under the degradation curve. This area, which is explained as the performance of building with time progress, will be interpreted here as the performance of building when a repairing action is introduced at mid-period. Therefore, the increment of this area reflects the ratio of improvement resulted from improving the condition of the building at the time (t = 12 years).

In case of applying the repairing action after another five years, there will be three time intervals; [3.76, 12] with no repair, [12, 17] and [17, 28]. The improvement of the building's condition by enhancing performance with repairing actions at age (t = 12 yrs., and t = 17 years) is illustrated in Figure 9.

In case of applying the repairing action before five years, there will be four time intervals; [3.76, 8] with no repair, [8, 12], [12, 17] and [17, 28]. The improvement of the building's condition by enhancing performance with repairing actions at age (t = 8 yrs., t = 12, and t = 17 years) is illustrated in Figure 10.

Figure 7 Original degradation curve in case of taking no action over the years at period [3, 28], with curve fitted trends (see online version for colours)

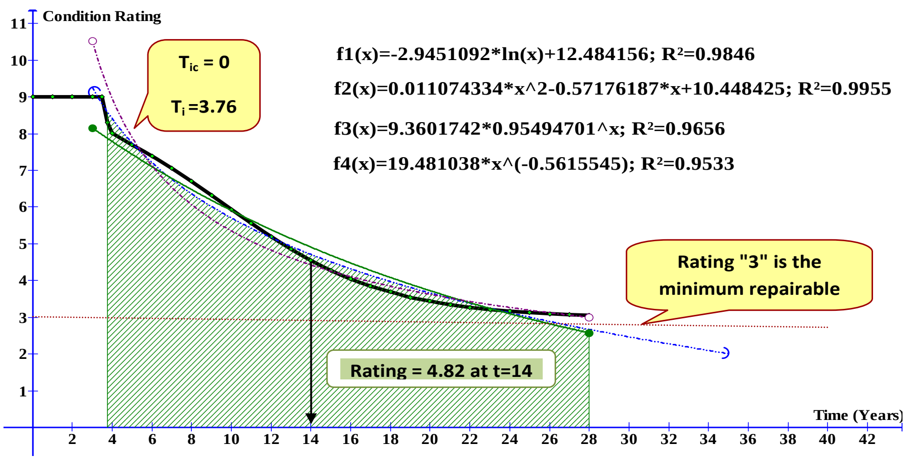


Figure 8 Modified degradation curve at periods [3.76, 12], and [12, 28] due to improving the condition of the building, with curve fitted trends (see online version for colours)

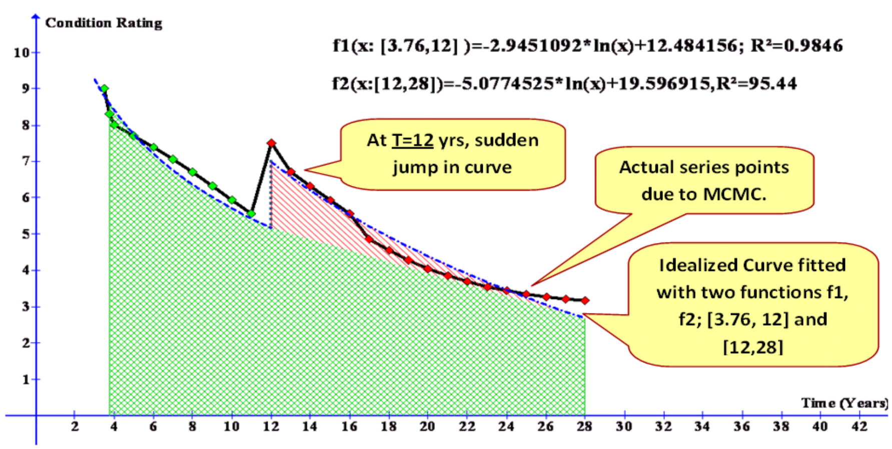


Figure 9 Modified degradation curve at periods [3.76, 12], [12, 17], and [17, 28] due to improving the condition of the building, with curve fitted trends (see online version for colours)

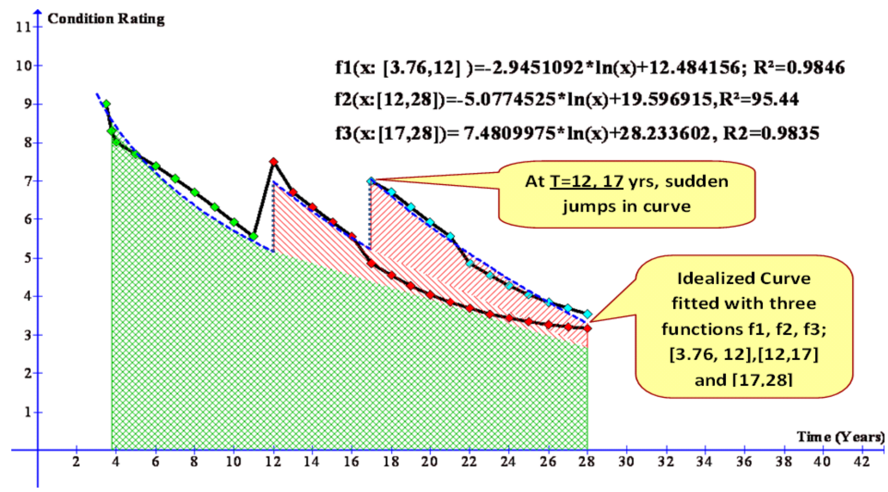
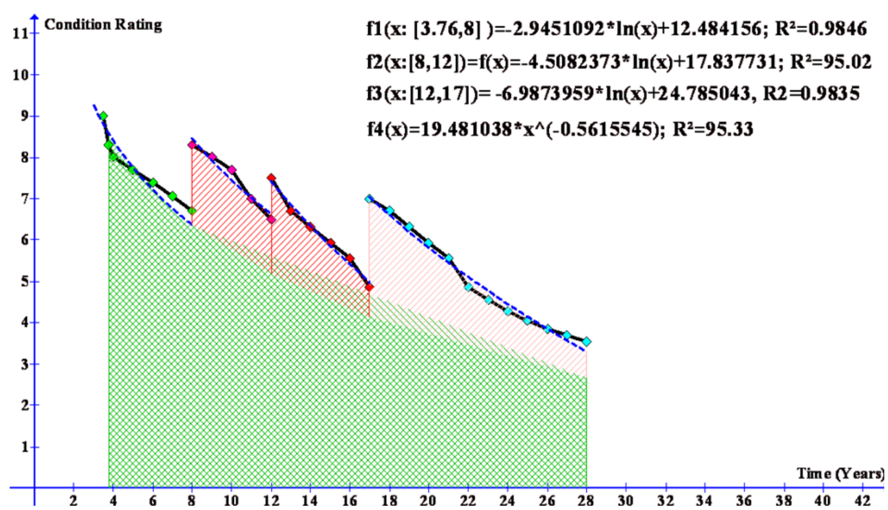


Figure 10 Modified degradation curve at periods [3.76, 8], [8, 12], and [12, 17], and [17, 28] due to improving the condition of the building, with curve fitted trends (see online version for colours)



It can be seen that periodic monitoring and repairing, if any, of RC building results in better structural performance of building, delay in deterioration, reduction in degradation profile, and sequentially prior gain of improvement effects. Therefore, it is highly recommended to update condition rating of buildings periodically, Figure 11 and Figure 12 summaries the process of evaluating the condition of RC buildings either for rehabilitation of defective structures or rating and damage assessment of existing structures. It can be elucidated through sequent processes; diagnosis, prognosis…., as seen in Figure 11, or detailed phases as seen in Figure 12.

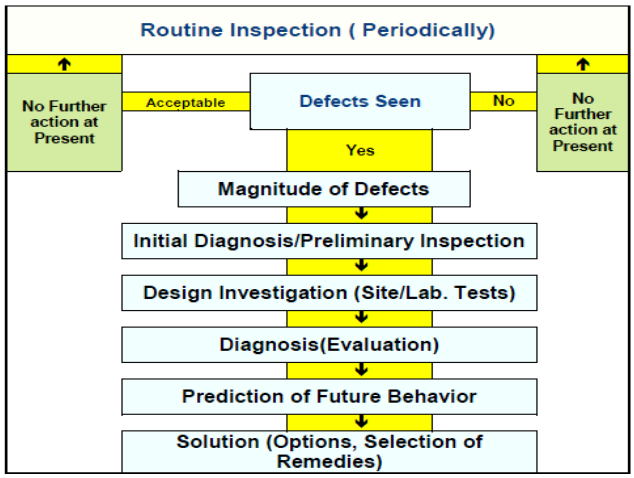


Figure 11 Applying the proposed program on investigation of RC buildings

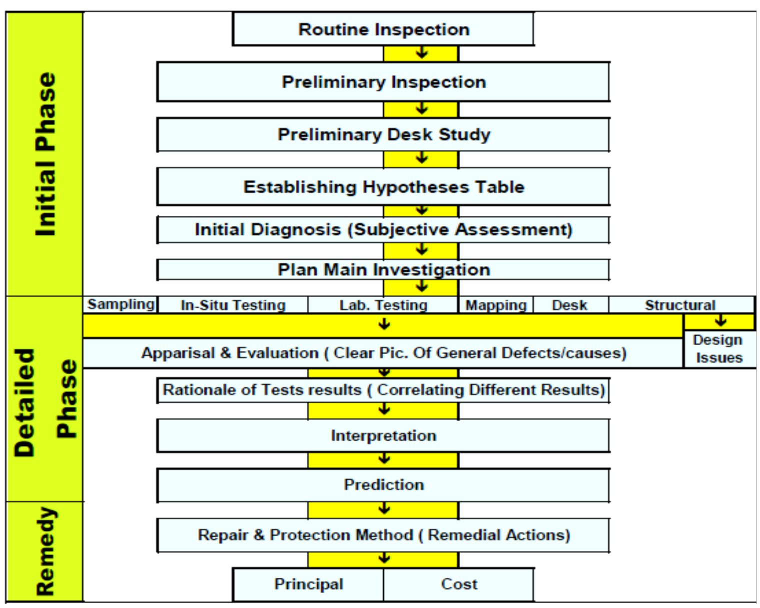


Figure 12 Phases of the program of investigating RC buildings (see online version for colours)

10 Conclusions

- Detailed methodology for diagnosis, condition evaluation and decision-making has been developed. A comprehensive process of integrating these procedures in a methodical way is essential for the treatment of existing defective concrete structures.
- Diagnosing anomalies in defective RC structures is the most important step in assessment process; therefore a compromise is made between subjective assessment and quantification of damage to well-diagnose deficiency and proper-prognosis of remedial actions.
- Stochastic approaches like Markovian chains deterioration models (MCMC) are used in life prediction of RC structures. Not only this, but also extrapolating previous history of deficiencies. The recent progress in managing defective bridges can be utilized in the case of defective RC buildings.
- A BMMS is proposed that considers the effect of different maintenance options on the overall cost of maintenance over a year and longer time scale. Performance predictions in respect to component condition state are based on a one-step Markovian model. An optimization of different possible maintenance actions is considered in relation to the cost of specified actions to, or replacement of, components based on a MOI. This index provides a means of relating competing maintenance objectives; that of controlling maintenance intervention costs and maintaining component condition ratings.

10.1 Limitation of model and recommendation for future work

The model has mainly designated for RC buildings and composite structures, applying the proposed methodology on different structural systems and structures in addition to involving building information modeling technique will be investigated in future research work.

References

AASHTO-LRFD (2007) *Bridge Design Specifications*, 4th ed., SI Units, the American Association of State Highway and Transportation Officials, ISBN: 1-56051-355-1.

Abdelalim, A.M. (2012a) 'A new approach to interpret disintegration, compressive strength and water absorption of concrete under the application of admixtures', *ICCAE-9 Conference*, 29–31 May.

Abdelalim, A.M. (2012b) 'Quantitive assessment of deteriorated RC structures due to reinforcing steel corrosion', *ICCAE-9 Conference*, 29–31 May.

Abdelalim, A.M. (2014) 'Optimization of the building maintenance management process using Markov model', *Al Azhar Scientific Magazine*, Vol. 36, No. 3, Faculty of Engineering.

Al-Wazeer, A.A. (2007) *Risk-Based Bridge Maintenance Strategies*, PhD thesis, University of Maryland, College Park, USA.

Federal Highway Administration (FHWA) (1997) *Highway Statistics 1997*, Technical Report, U.S. Department of Transportation, Washington, D.C.

Federal Highway Administration (FHWA) (1997) *Life Cycle Cost Analysis in Pavement Design*, Draft Report, Pavement Division, Technical Bulletin, U.S. Department of Transportation, Washington, D.C.

Federal Highway Administration (FHWA) (2002) *Life Cycle Cost Analysis Primer*, August, Report, U.S. Department of Transportation, Office of Asset Management.

Jiang, Y. (1990) *The Development of Performance Prediction and Optimization Models for Bridge Management Systems*, PhD thesis, Purdue University, USA.

Jiang, Y., Saito, M. and Sinha, K. (1988) 'Bridge performance prediction model using Markov chain', *Transportation Research Record*, pp.25–32, National Research Council, 1180, Washington, DC.

Lounis and Vanier (2000) 'A multi-objective and stochastic system for building maintenance management', *Computer-Aided Civil and Infrastructure Engineering*, Vol. 15, No. 5, pp.320–329.

Morcous, G. and Lounis, Z. (2006) 'Integration of stochastic deterioration models with multi-criteria decision theory for optimizing maintenance of bridge decks', *Can. J. Civ. Engrg.*, Vol. 33, No. 6, pp.756–765.

Shipra, S.A. (2008) *A Framework for Efficient Condition Assessment of the Building Infrastructure*, PhD thesis, Waterloo, Ontario, Canada.

Van Winden, C. and Dekker, R. (1998) 'Rationalization of building maintenance by Markov decision models: a pilot case study', *J. Operations Research Society*, Vol. 49, No. 9, pp.928–935.

Yoshitaka, K. and Uomoto, T. (2005) 'Proposal for quantitive evaluation methodology of inspection value in maintenance of concrete structures based on repair-risk', *Journal of Advanced Concrete Technology*, October, Vol. 3, No. 3, pp.363–370, Japan Concrete Institute.