Available online at www.sciencedirect.com
ScienceDirect
Composites: Part B 38 (2007) 236–246
composites
Part B: engineering
www.elsevier.com/locate/compositesb

Life-cycle performance model for composites in construction

Deepak Richard [a], Taehoon Hong [b,*], Makarand Hastak [c,1],
Amir Mirmiran [d,2], Ossama Salem [a,3]

[a] Department of Civil and Environmental Engineering, University of Cincinnati, OH 45521-0071, United States
[b] School of Architecture and Architectural Engineering, The University of Seoul, 90 Jeonnog-dong (Siripade-1 gil 12-1), Dongdaemun-gu, Seoul 130-743, South Korea
[c] School of Civil Engineering, Purdue University, West Lafayette, IN 47907-2051, United States
[d] Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33199, United States

Received 11 January 2005; received in revised form 2 April 2006; accepted 2 April 2006

Abstract

Fiber reinforced polymer (FRP) composites have become popular in recent years both in the construction of new facilities and in the renewal of existing structures owing to their technical advantages and economic benefits over traditional materials. However, there is a concern in the civil engineering industry over the lack of information on the long-term durability and life-cycle performance of composite materials used for infrastructure applications.

The model proposed in this paper predicts infrastructure deterioration based on the material degradation by considering the environmental exposure, operation conditions, material durability, and the effect of maintenance actions on the structure over time. The analytical framework is generic and can be used to model the life-cycle performance of different types of structures and is applicable to different material types and exposure conditions. It is proposed as being particularly suitable for composite applications in civil engineering for which historical performance data are not available. A complete description of the modeling framework is presented here along with a hypothetical example case to illustrate the procedure.

Keywords: C. Analytical modelling; C. Damage mechanics; C. Finite element analysis (FEA); C. Statistical methods; B. Damage tolerance

---

1. Introduction

Infrastructure management involves the appropriate allocation of limited financial resources for the maintenance, repair, and rehabilitation (MR&R) of structures to ensure acceptable safety levels and operating conditions. Infrastructure management systems, therefore, require reliable performance prediction methods that can forecast structural performance into the future. Concrete and steel have been the construction materials of choice in the last century due to their easy availability and low cost. In recent years significant deterioration in existing infrastructure facilities both in the United States as well as in other countries has been observed. According to ASCE report card for America's infrastructure, 29% of the nation's bridges were assessed to be structurally deficient as of the year 1998. It was further reported that over $210 million is required over the next 20 years to eliminate all bridge deficiencies [1]. With such large amounts of money involved, infrastructure management and deterioration modeling have received a lot of attention among researchers and the industry in recent years.

The need for efficient repair and rehabilitation of damaged infrastructure facilities has contributed to the increased popularity of composite materials in civil engineering. Fiber reinforced polymer (FRP) composites provide significant

---

[*] Corresponding author. Tel.: +82 2 2210 5730; fax: +82 2 2248 0382.
E-mail addresses: hong7@uos.ac.kr (T. Hong), hastak@ecn.purdue.edu (M. Hastak), mirmiran@fiu.edu (A. Mirmiran), osalem@uc.edu (O. Salem).
[1] Tel.: +1 765 494 0641; fax: +1 765 494 0644.
[2] Tel.: +1 305 348 2314; fax: +1 305 348 2802.
[3] Tel.: +1 513 556 3759; fax: +1 513 556 2599.

1359-8368/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compositesb.2006.04.001

performance enhancements over conventional materials in the construction of new structures as well as in the rehabilitation of existing structures. Critical technical advantages provided by composite materials over traditional construction materials are: (i) high specific strength, (ii) high stiffness, (iii) directional strength, (iv) light weight leading to easy handling and transportation, (v) parts consolidation, and (vi) improved resistance to corrosion and chemicals [2–5]. These advantages result in considerable savings in time and cost when composite materials are used in construction projects. Composite materials have been applied in numerous ways in civil engineering. Some of the more important applications of composites are as follows: (i) FRP composite bridge decks, (ii) prefabricated FRP structural components, (iii) FRP composites used as external reinforcement for steel and concrete components, (iv) FRP rods replacing steel in reinforced concrete, and (v) prestressed FRP cables and rods for reinforcing concrete beams [2,4]. In spite of their advantages and versatility, composite materials have not seen widespread use in civil engineering owing to the lack of knowledge about their long-term behavior and high initial costs involved. Hastak and Halpin [6] have proposed that a life-cycle cost benefit assessment model for composites will enhance the use of composite materials in civil engineering. Such a method will allow decision makers to compare the financial viability of composite options against conventional material options, thereby facilitating the use of composites in infrastructure [6].

Prediction of life-cycle costs for composites would depend on the availability of a practical life-cycle performance model for composite materials in construction. Existing life-cycle performance modeling methods that rely on historical performance records are not useful in the case of composites. Although there is a wealth of information available on the performance of composites in other fields like aerospace, defense, and automobile sectors, such information cannot be used for life-cycle modeling of composites in civil engineering because of critical differences in the environmental exposure, operating conditions, and loading patterns [3]. This research work attempts to satisfy this need by proposing a modeling framework for life-cycle performance assessment of composites based on material degradation characteristics. The model has been developed with a view to assist the management in life-cycle cost estimation and optimizing MR&R actions over time [2].

2. Background

Maintenance of civil infrastructure systems at acceptable performance levels requires timely MR&R actions. Determining when to perform such MR&R actions and the type of MR&R actions is based on the condition of the structure. Generally, MR&R actions in civil infrastructure are reactive rather than proactive. In practice, the condition of a structure or group of structures is monitored at periodic intervals and when significant structural damage is observed appropriate remedial measures are initiated.

Table 1
Categories of life-cycle performance models in civil engineering structures

Deterministic methods	Stochastic and probabilistic methods	Artificial intelligence methods
Statistical techniques	Markov methods	Machine learning methods
Mathematical models	Semi-Markov methods	Genetic algorithms
	Fault-tree analysis	Artificial neural networks
	Bayesian updating	Expert systems
	Simulation using mathematical models	Case-based reasoning

The following are the many available methods in which structural performance is monitored in the field: (i) visual inspection and condition ratings, (ii) health monitoring of structures, (iii) continuous monitoring systems, (iv) periodic monitoring, (v) testing techniques, (vi) non-destructive methods, and (vii) destructive methods.

It is more efficient and less costly to maintain structures that are in good condition than to maintain structures that exhibit significant deterioration. This is the main reason for the importance of life-cycle performance modeling, which allows the user to forecast structural performance into the future and schedule appropriate MR&R actions that are most beneficial and cost efficient over the whole life of the structure [2]. Modeling structural deterioration is more difficult because of the inherent complexity of the process and the multitude of external factors and mechanisms that are responsible for deterioration.

The approaches available for modeling life-cycle performance of civil engineering structures are listed in Table 1. The available approaches to model life-cycle performance can also be classified into network level and structure level methods. Network level methods predict the condition deterioration of a group of structures grouped either by locality or type. Markov methods and statistical regression techniques have been widely used in modeling structural deterioration at the network level. Some techniques predict the deterioration of a single structure over its lifetime. Conceptual modeling based on physical principles is one example of such an approach. Most of the existing methods rely on historical performance data from similar structures to predict the future performance of a new structure. Such methods are not suitable for use in the case of modern materials like FRP composites. In such cases, it is essential to rely on methods that are based on knowledge of the physical and chemical processes that are responsible for material deterioration until sufficient historical databases can be built over time [7].

3. Overview of modeling framework

The primary hypothesis in this research work is that decrease in performance during the life cycle of a structure can be modeled on the basis of the properties of the constituent materials, the impact of external factors that impact the materials, and an understanding of the appropriate material deterioration mechanisms [2]. For the purpose of this research, a structure's lifetime is defined as the finite time period during which the structure functions at an acceptable performance level subject to physical deterioration due to external agencies and the effect of MR&R actions. It represents the time period from the completion of construction of the structure to the time when the structure reaches a stage where it is judged necessary to decommission its use due to functional obsolescence, unacceptably high operating costs, or excessive deterioration that cannot be remedied at reasonable expense. In this research, structural performance is assumed to represent the physical integrity or condition of the structure, and not the functional or economic aspects of its performance.

Structural deterioration over time occurs due to the impact of environmental exposure and conditions of usage. A civil engineering structure is a complex assembly of interconnected elements. In modeling performance, it should be realized that each component is designed for a specific structural behavior and is composed of different constituent materials. The deterioration of these materials depends on the local environment, the type and pattern of loads it is subjected to, and the durability characteristics of the material itself. Different components of a structural system experience different deterioration mechanisms and deterioration rates because of their different mechanical characteristics, and the different operational and loading conditions [8]. Consequently, structural performance should be modeled at the component level based on the degradation of the constituent materials.

The modeling procedure should begin with a logical decomposition of the structure into its components. There is no fixed scheme to break down a structure into its components. However, a conceptual decomposition of a structural system into sub-components is a pre-requisite to performance modeling. Bridge structures are commonly divided into four major components: (1) bridge deck, (2) superstructure, (3) substructure, and (4) pavement surface. Each of these components can then be sub-divided into several sub-components as shown in Fig. 1 according to the level of detail required by the user.

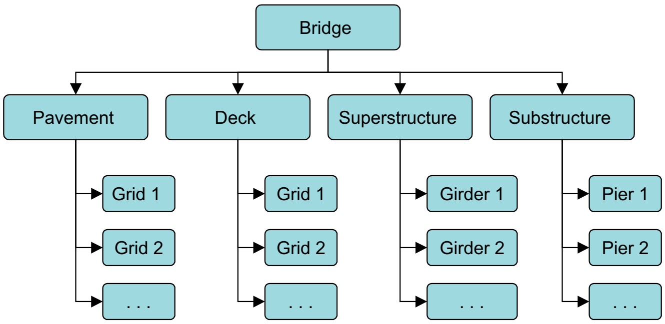

Fig. 1. Conceptual breakdown of a structure into its sub-components.

3.1. Damage modes and external factors

Several researchers have investigated the deterioration of materials under the influence of a single damage mechanism. Though it is recognized that several deterioration mechanisms may be simultaneously active and interaction among them might lead to an increased amount of deterioration, very limited information is available on this aspect. In order to capture the effect of different damage mechanisms and the complex interaction among them the proposed framework incorporates two features called damage modes (DM) and external factors (EF). The two terms are defined as follows.

3.1.1. Damage mode

It is defined as any physical or chemical process acting on a component that can result in damage over time by causing a change in the mechanical properties of the constituent materials, their physical dimensions, or the composite action present between the materials. For instance, corrosion of steel reinforcement is a damage mode leading to progressive loss in the mass of steel reinforcement over time [2]. The presence of a damage mode denotes the existence of certain influencing factors that are responsible for its activity and its severity. When several damage modes are active at the same time, one damage mode can be influenced by some of the other damage modes resulting in an increase in its severity.

3.1.2. External factor

These factors are responsible for the action and the severity of the damage modes. The intensities of the factors usually vary over time and are responsible for the severity of the damage modes. Some examples are moisture, chemicals, load cycles, temperature, etc. [2]. The external factors are defined in the framework to model the effect of the environmental, operational, and loading conditions. Structural deterioration occurs over prolonged time periods and consequently time is a factor in modeling the deterioration process. However, time of exposure is considered implicitly in calculating the severity for all damage modes and is therefore not explicitly shown in the set of external factors for each damage mode. The damage modes are defined to model the underlying physical and chemical mechanisms that cause material and structural deterioration. As shown in Fig. 2 there are four successive stages in modeling the structural performance. External factors that cause material damage should be considered at the first level. These factors are responsible for initiating and maintaining the physical and chemical processes that over the course of time cause the actual material damage. In the second level, these physical and chemical processes should be modeled. The impact of these processes depends on the type of material affected. For example, cement concrete undergoes deterioration due to physical process of freezing and thawing. In the third level, the damage manifested by the impact of these processes should be modeled. For instance,

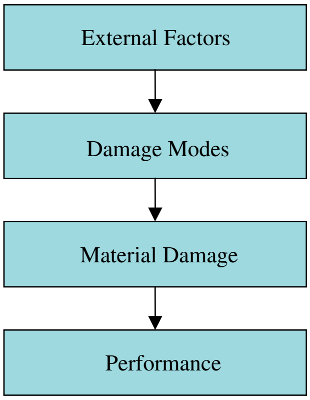

Fig. 2. Estimating structural performance.

repeated freezing and thawing leads concrete damage in the form of cracking and scaling. Finally in the fourth level, the effect of the damage on the performance of the structural member should be assessed.

It is important to recognize that different components or members of a structure undergo different types of damage and deteriorate at different rates. This is due to the following reasons:

1. Each structural component is designed for a specific type of structural behavior. For instance, a beam is designed for flexure whereas a column or pier is designed to withstand compression.
2. Each member is subjected to different operational and loading conditions. In the case of a beam, it is primarily subjected to lateral loads. A column is subjected to mainly axial loads.
3. Different components might be exposed to different local environmental conditions. For instance, because of their location in a bridge structure, a bridge deck and a pier are subjected to different local environments. The deck and superstructure might be exposed to deicing salts periodically in colder regions. The foundation and substructure, on the other hand, might be submerged in water or exposed to sulfates and other chemicals present in the surrounding soil.
4. The material composition is different for different structural members. For instance, a bridge deck might be fabricated using FRP composite materials while the foundation and substructure might be constructed from reinforced concrete. Moreover, in the case of a composite member, one material might be protected from the deleterious effect of the environment by the surrounding material as in instance of steel reinforcing rods encased in concrete.

From the above discussion, it is obvious that the structural deterioration should be modeled at the component level. The deterioration of a structural component is governed by the deterioration of its constituent materials under the impact of several parameters and it should be modeled on the basis of the following:

- Knowledge of the structural properties of each material.
- Knowledge of the durability characteristics of each material.
- Knowledge of the physical and chemical mechanisms that cause the deterioration of each material with time.
- Understanding of the interactions that might be present among different deterioration mechanisms that are active during the same time period.
- Knowledge of the manifestation of the damage caused by the deterioration mechanisms on the material(s) themselves and/or the component as a whole.

Supposing it is possible to model the damage modes and the values of the external factors then material damage over time can be predicted. Structural performance at different stages in the structure's life cycle can be modeled based on the amount of undamaged material left at that time. In this work, it is assumed that existing and future research work can provide suitable material deterioration models that can be used to represent the damage modes. The external factors can be modeled using appropriate historical data or experimental observations. The accuracy of

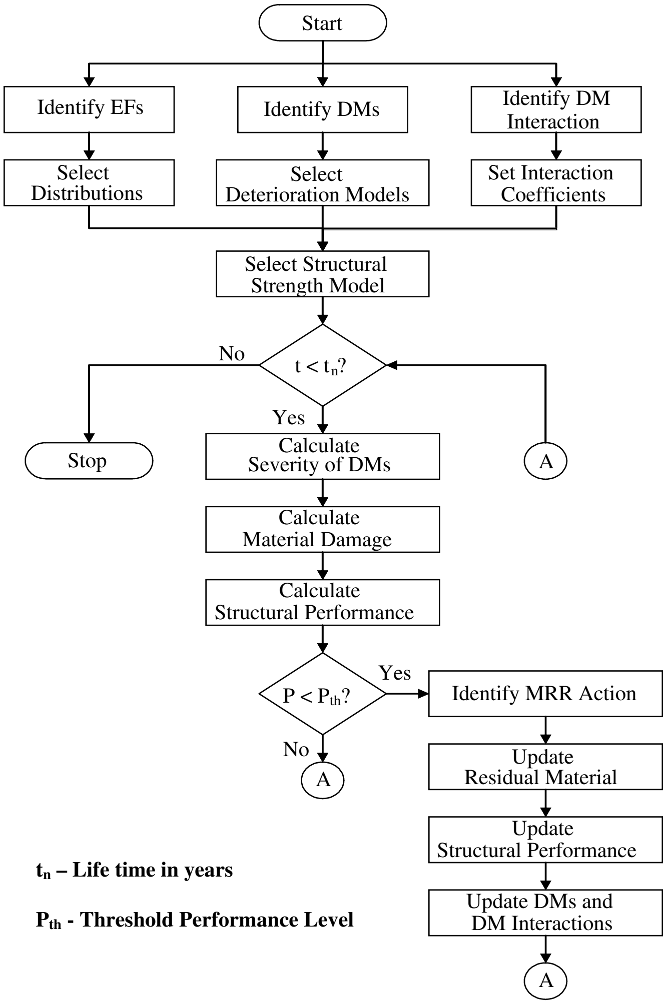

Fig. 3. Flowchart of life-cycle performance modeling.

the model depends on the deterioration models selected to represent the damage modes and the probability distributions defined for the external factors. The method proposed in this paper has been explained by assuming hypothetical relations between the parameters involved. When suitable models are made available they can be used in the model with greater success. The complete modeling procedure is illustrated in Fig. 3 and the different portions are explained in the subsequent sections of the paper.

4. Material deterioration

Mechanisms leading to deterioration of the materials used in infrastructure applications have not been completely understood at present. This is true not only in the case of composite materials but also for conventional materials [9]. Moreover, existing historical data do not completely capture the influence of all the factors that are responsible for material and structural deterioration over time [7]. Due to such limitations in the existing knowledge base, it is necessary to make assumptions in order to develop a realistic and practical model for predicting life-cycle performance. Another difficulty in modeling material deterioration is that damage mechanisms do not act in isolation and several damage mechanisms might interact and lead to aggravated damage. Although this fact has been recognized in existing research work little progress has been achieved in measuring this synergistic effect among the deterioration mechanisms. In the proposed model, the material damage occurring over time is directly attributed to the prolonged effect of certain damage modes. The extent of material damage during a given period of time depends on the severity of the corresponding damage mode(s) during that period. The severity of the damage mode is assumed to be dependent on the intensity of the external factors and the severity of other damage modes. The following assumptions are made to model the relationship among the factors and damage modes (refer to Fig. 5a).

1. External factors influence the damage modes.
2. A damage mode can be influenced by other damage modes.
3. The influence of an external factor a_1 on a damage mode d_1 is independent of the influence of a_1 on other damage modes, the influence of other external factors on d_1, and the influence of other damage modes on d_1.
4. The damage modes can influence one another. The influence of one damage mode d_1 on another damage mode d_2 is independent of the influence of d_1 on other damage modes, the influence of other damage modes on d_2, and the influence of factors on d_1.

Apart from the above assumptions that are necessary to capture the nature of the influence pattern that exists among the damage modes and external factors, few more assumptions to model the material damage are necessary. These assumptions are listed below:

5. It is assumed that each damage mode can be represented using a specific material deterioration model. It is assumed that such models can be obtained from existing sources or through future research in structural and materials engineering.
6. The severity of a damage mode for any finite time period is assumed to give a measure of the amount of material damage that is caused by that damage mode in the same period.
7. The severity of a damage mode d_1 is assumed to be aggravated by the influence of certain other damage modes. It is assumed that such effects can be quantified using available data, and through future studies. In the absence of such information, it is assumed that they can be reliably estimated using subjective input from experts.

Based on the above assumptions, the material damage occurring over time can be modeled according to the procedure described below. Consider a damage mode d_j that is influenced by the factors $a_1, a_2, a_3, \ldots, a_m$, and by the damage modes $d_1, d_2, d_3, \ldots, d_i$. The severity of the damage mode d_j at time t due to the influence of factors only can be expressed using the relation

$$d_j = f(a_1, a_2, a_3, \ldots, a_m) \tag{1}$$

In Eq. (1) $a_1, a_2, a_3, \ldots, a_m$ represent the intensities of the corresponding factors during the considered time interval. Depending on the availability of suitable material deterioration models, the severities of the damage modes and the intensities of the factors used in Eq. (1) can be expressed in terms of their actual physical units. Alternatively, the equation can be kept generic by expressing all the values on a scale of 0 to 1, with 0 representing the minimum possible value and 1 representing the maximum possible value. The influence of other damage modes $d_1, d_2, d_3, \ldots, d_i$ on d_j leads to an increase in the severity of target damage mode d_j given by Eq. (1). The combined effect of all the damage modes that affect the target damage mode d_j can be modeled using a multiplying coefficient k_j that represents the total percentage increase in the severity of d_j as estimated in Eq. (1) on the basis of the corresponding set of external factors alone. So, the resulting severity of the damage mode d_j can now be expressed as

$$d_j = k_j * f(a_1, a_2, a_3, \ldots, a_m) \tag{2}$$

The value of the coefficient k_j can be calculated by a summation of the contributions from each damage mode to the aggravation in the severity of the target d_j. The influence of a damage mode d_i on a damage mode d_j is dependent on the severity of d_i itself. If c_{ij} is a multiplicative factor representing the contribution of a damage mode d_i to the increase in severity of d_j, then the coefficient k_j can be expressed as

$$k_j = 1 + c_{1j} * d_1 + c_{2j} * d_2 + \cdots + c_{ij} * d_i \tag{3}$$

The coefficient c_{ij} in Eq. (3) stands for a percentage increase in the severity of d_j due to the influence of d_i alone. Eq. (3)

allows the user to quantify the impact of several damage modes on a target damage mode. As mentioned in the list of assumptions above, in case there is a lack of available information on the synergistic action among different damage modes, it can be left to the users to model the contributions of the different damage modes using expert opinion. From Eq. (2), the severity of the damage mode d_j at time instant t can be calculated. This value gives a measure of the material damage caused by d_j alone at time t. The total damage to a material at time t can be obtained by summing up the material damage caused by all the damage modes that impact the concerned material.

5. Structural performance

Existing structural deterioration modeling methods quantify structural performance using different measures such as reliability index, soundness index, condition rating, etc. Each member of a structure is designed for a specific structural behavior. In this research structural performance of a member is quantified in terms of its structural behavior. The structural behavior may be expressed in terms of the strength of the component, its stiffness, etc. The structural behavior of a component depends on the properties of the constituent materials, their physical dimensions, and the composite action among the different materials. As an example, we might consider a reinforced concrete beam that is designed for flexural strength. The parameters involved are the physical dimensions such as cross-sectional areas of the two materials, properties like the elastic modulus of the materials and composite action such as the bond between the two materials. The changes in these quantities over time can be estimated using material degradation model described above. The formula initially used for the design of the structural component can then be used to calculate the structural behavior of the component based on the undamaged or residual material at any time t. If $m_1, m_2, m_3, \ldots, m_k$ are the physical quantities of the materials used, $p_1, p_2, p_3, \ldots, p_k$ are the properties of the corresponding materials, and $c_1, c_2, c_3, \ldots, c_l$ represent the composite actions between the materials involved, then the structural behavior of the component s_x can be expressed as follows:

$$s_x = g(m_1, m_2, m_3, \ldots, m_k, p_1, p_2, p_3, \ldots, p_k, c_1, c_2, c_3, \ldots, c_l) \tag{4}$$

Eq. (4) defines the relation between the structural performance and material deterioration. In Eq. (4), s_x can represent structural behavior of a member such as structural strength, stiffness, etc. The value of the structural performance can be expressed using the actual units as in the design formula or it can be converted to a scale of 1 to 0, with 1 representing the design performance level and 0 representing structural failure. This allows the user to determine the deterioration of the structure in different respects. At the beginning of the structure's life cycle there is no material damage and the structural component is intact. In terms of the structural strength of the member, it is assumed to have its full design strength at time t_0. At time t_1, after an interval of time has elapsed, material degradation has occurred leading to a change in structural behavior. Using the original design formula, as given by Eq. (4), the new structural strength is calculated for time t_1. The procedure can be carried out for different periods of time and the structural performance over the whole life of the structure can be established in the form of a performance curve. The estimated structural performance curves provide an important tool to schedule maintenance activities on the structure. A threshold performance level established by the user can be used to determine the appropriate times when major repair and rehabilitation measures need to be taken. When the predicted performance level falls to the threshold level, the predicted material damage curves can be used to assess material damage and appropriate remedial measures can be taken to restore the component strength.

6. Uncertainty and Monte Carlo simulation

There is considerable uncertainty and variation present in any structural deterioration model. There are many sources that contribute to the uncertainty in the model, which include differences in material characteristics, environmental factors, construction quality, human errors, etc. Consequently, structural deterioration is modeled as a stochastic process. The external factors in the model can assume a wide range of values that also vary over time. The material deterioration models used to represent the damage modes also involve uncertainty that comes from insufficient understanding of the actual physical and chemical processes and the inability to accurately capture all the effects of environmental factors through empirical methods. Uncertainty is also present in modeling the interaction among different damage modes. Therefore, Monte Carlo simulation (MCS) is used to account for the uncertainty and variation present in the model.

The MCS is a mathematical technique used for probabilistic risk assessments. In order to perform a MCS a valid mathematical model should be developed to represent the system or process under consideration. Probability distributions are then defined for each input variable in order to model the uncertainty and variation present in it. A MCS works through random sampling of the input distributions and a distribution of the potential output values is generated [5]. In the proposed framework input probability distributions are defined to represent the range of possible values that can be assumed by each external factor in the model. The distributions can be defined based on historical information, physical observations of the factor values, or expert judgment. Probability distributions are also defined for the coefficients used to model the influence of a damage mode on another. Finally, a Monte Carlo simulation of the model results in time-dependent performance curves. These curves show the spread of potential performance values at different times during the life of the structure.

7. Effects of maintenance actions

Maintenance, repair and rehabilitation (MR&R) actions are performed on a structure at various points in its life cycle to ensure adequate structural performance and service levels throughout its life. There are several types of MR&R actions that can be classified into the following categories. There are many types of infrastructure maintenance strategies that include the following: (1) preventive maintenance, (2) corrective maintenance, (3) routine maintenance, (4) hard-time replacement, (5) on-condition maintenance, and (6) critical maintenance [10]. MR&R actions generally result in the following two effects on the performance of a structure both of which are depicted in Fig. 4(a): (i) reduction in the rate of deterioration of the performance and (ii) a sharp increase in the current performance level of the structure.

In the proposed modeling framework, only three basic types of MR&R actions are considered in order to model their effects on the predicted structural performance. These are described as follows:

(1) *Routine maintenance*: Routine preventive maintenance actions are performed, on a frequent basis, to prevent or reduce the rate of long-term damage to a structural component or system. These actions do not include major repair actions that involve significant costs and increases in performance. The routine maintenance costs are usually uniform yearly expenses. The only effect of such measures is to reduce the rate of material deterioration and the decrease in the performance of a structural member.
(2) *Strengthening measures*: These are major structural repairs that are performed to restore the structural strength of a component that has undergone significant damage that may be severe enough to compromise the safety of the structure. These are the MR&R actions that the user deems necessary based on the current performance level of the component. For instance, increasing the cross-sectional area of a member, addition of external reinforcement, prestressing, etc., are major strengthening measures that result in a marked increase in the current structural performance of a member. They involve considerable costs that contribute to the total life-cycle costs.
(3) *Replacement actions*: These are major rehabilitation actions that involve the complete replacement of a structural component when it has been damaged beyond repair i.e., after the component has reached the end of its service life. Component replacement involves significant expenditure that contributes to the total life-cycle cost of a structure. Replacement of a structural member implies that the structural performance is restored to the initial design value.

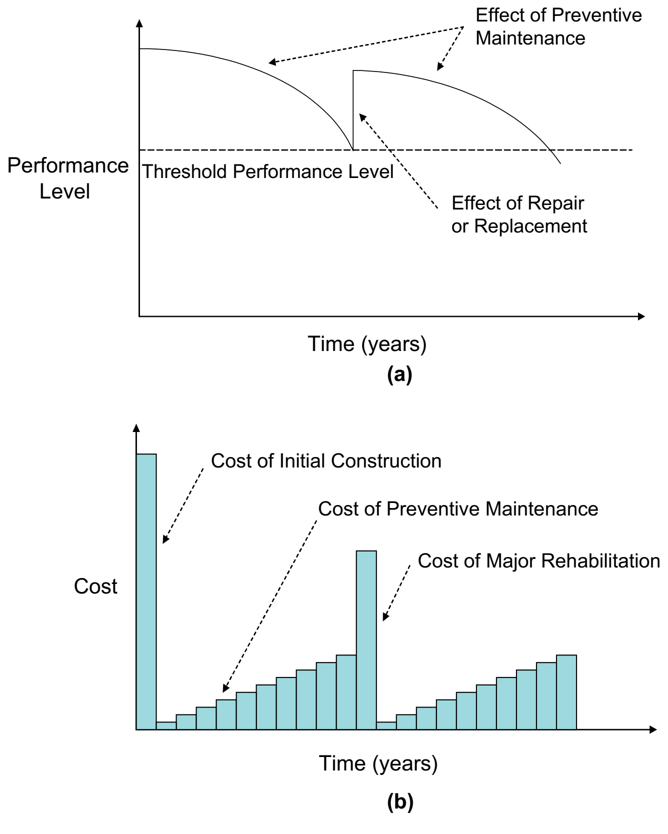

Fig. 4. MR&R actions and corresponding life-cycle costs: (a) effect of MR&R measures on life-cycle performance and (b) accumulating MR&R costs over life cycle.

Routine preventive maintenance results in mitigating the material damage resulting from the effect of the different deterioration mechanisms. Therefore, the effect of routine maintenance can be incorporated into the model by multiplying the severity of a damage mode, calculated using Eq. (2), with a reduction factor that lowers the calculated severity value. The severity of a damage mode d_j on which preventive maintenance has an effect can be expressed by including the coefficient r_j in Eq. (2) as follows:

$$d_j = r_j * k_j * f(a_1, a_2, a_3, \ldots, a_m) \tag{5}$$

The coefficient r_j in Eq. (5) is represented as a percentage decrease in the value of the severity d_j calculated in Eq. (4). In the case of strengthening actions, new material is added to the damaged component leading to a change in the material parameters as well as the component's structural strength. The user has to explicitly model the effect of such actions by updating the material parameters and the structural strength in the deterioration models. In the case of replacement, the material properties and performance level are restored to their initial design values. From the performance curves generated by the model, the user can find out the time when the material damage or component performance reaches a pre-determined threshold level and schedule timely and appropriate MR&R activity. Thus the user is allowed to model the effect of different maintenance actions on the predicted performance. The resulting increase in structural performance will be reflected in the performance curve as a sharp increase in the performance level at the time when the MR&R action has taken place. After each MR&R action, the material damage again starts accruing and the performance level decreases with time. When the performance again decreases to the threshold level, the next MR&R action needs to be scheduled. If the costs of each scheduled MR&R action are known, the total life-cycle costs can be estimated. In this way the user can study the effects of different MR&R strategies on the life-cycle performance and estimate the corresponding life-cycle costs before selecting the optimal strategy to be implemented. The effects of routine preventive maintenance and major rehabilitation involving strengthening or replacement on the performance of a component and the corresponding life-cycle costs are shown schematically in Fig. 4.

8. Illustrative example model

8.1. Description of the model

The proposed modeling framework is explained by applying it to the case of a hypothetical example involving a component composed of two materials m_1 and m_2. Three damage modes are considered: d_1 affecting m_1, and d_2 and d_3 affecting m_2. Six external factors, $a_1, a_2, a_3, \ldots, a_6$ are identified. The hypothetical case is developed as an analogy to a reinforced concrete beam (refer to Fig. 5). Several physical and chemical processes are responsible for the deterioration of reinforced concrete. Some examples are corrosion of steel, scaling of concrete under frost attack, chemical attacks like sulfate attack, alkali aggregate reactions, and fatigue. The deterioration of a reinforced concrete member with age can be modeled on the basis of accruing damage in steel and concrete. In the example case, the deterioration of a reinforced concrete component is modeled in a limited way by considering the impact of three damage modes: (i) corrosion of steel, (ii) frost attack on concrete, and (iii) sulfate attack on concrete. The damage modes are influenced by six factors which are (i) moisture, (ii) temperature, (iii) chloride, (iv) total deicing salt content, (v) freeze–thaw cycles, and (vi) sulfate content.

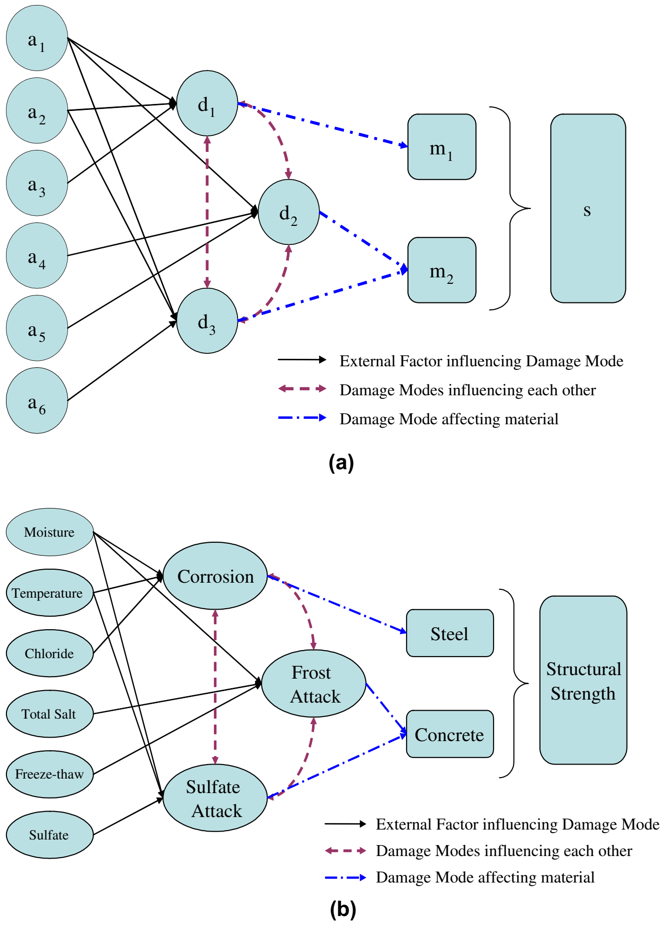

Fig. 5. Illustrative example and analogous real case: (a) influence pattern for illustrative example case and (b) influence pattern for reinforced concrete component.

Corrosion of reinforcing steel is the major cause for the deterioration of reinforced concrete bridges. Corrosion of steel is a chemical process that can be modeled on the basis of moisture content, temperature, and chloride concentration. Corrosion in steel results in the formation of rust and the reduction in the mass of steel. Frost attack is experienced in very cold weather when concrete is subjected to cycles of freezing and thawing. It is influenced by the presence of moisture and dissolved salts in the solution. Frost attack causes damage in concrete, which can be represented as a reduction in the cross-sectional area of concrete. Sulfate attack is a chemical process that results in damage to concrete due to the formation of expansive products which cause cracking. The resulting cracking of concrete can be modeled as a reduction in the cross-sectional area of concrete. Sulfate attack is influenced by the presence of sulfate, moisture, and temperature. Thus the hypothetical example described in this paper can be compared with a real instance of structural deterioration. Deterioration of reinforced concrete under the effect of corrosion, frost attack, and chemical attack can be found in existing literature. However, for the purpose of illustration in this paper no specific deterioration model has been adopted for the damage modes described. Instead a completely hypothetical relationship is established between the factors, damage modes and material damage.

In the example case, hypothetical polynomial functions have been assumed to model the three damage modes d_1, d_2, and d_3. The severity of a damage mode is assumed to be proportionate to the intensities of the factors influencing the damage mode. The material damage is calculated as the sum of the severities of the corresponding damage modes for each time period. Similarly, an arbitrary function was assumed in place of the design formula to express the structural performance 's' in terms of the material values m_1 and m_2. Hypothetical probability distributions have been defined for the external factors in terms of the mean factor intensities per year. The multiplying coefficients to model the interaction among damage modes are specified by the user as distributions based on expert judgment or available information. In the example case, each of the three damage modes is assumed to have an influence on the other two (refer to Fig. 5). Arbitrary triangular probability distributions with minimum, most likely, and maximum values have been assumed for the six coefficients representing the interaction among the three damage modes.

8.2. Simulation and interpretation of model outputs

A simulation study was conducted for the hypothetical model and the results are described in this section. The mathematical model was implemented in Microsoft Excel and the simulation study was carried out using Crystal Ball, a software add-in for Microsoft Excel. A model implemented in Microsoft Excel is deterministic and the Crystal Ball software allows the user to define the uncertain variables as probability distributions, and to perform a simulation. The simulation study was done in time steps of 10 years and residual material curves for m_1 and m_2 as well as performance curves for residual component structural strength '*s*' were produced. In the example, the amount of residual material is expressed on a scale of 0 to 1, where 1 represents the initial undamaged state when the physical dimensions of the material as well as its structural properties like the strength are equal to the values assumed at the design stage and 0 represents the complete loss of the material as well as the structural properties. Similarly, structural performance is also represented on a scale of 0 to 1, with 1 being the member's design performance level and 0 representing structural failure. The MCS takes random samples from the distributions defined for the factors and coefficients and calculates the resulting material damage and structural strength. This produces a distribution of possible values for the residual material damage and structural strength after each time interval. For the purpose of illustrating the effects of different maintenance scenarios, in the example model, two different MR&R strategies are considered as follows:

Case 1: It is assumed that minor routine maintenance is performed on the structure throughout its lifetime. No other MR&R action is performed on the structure during its life.

Case 2: Minor routine maintenance is assumed for the entire lifetime of the structure. In addition to this, a major rehabilitation involving complete replacement of the component is assumed to be performed after a period of 30 years.

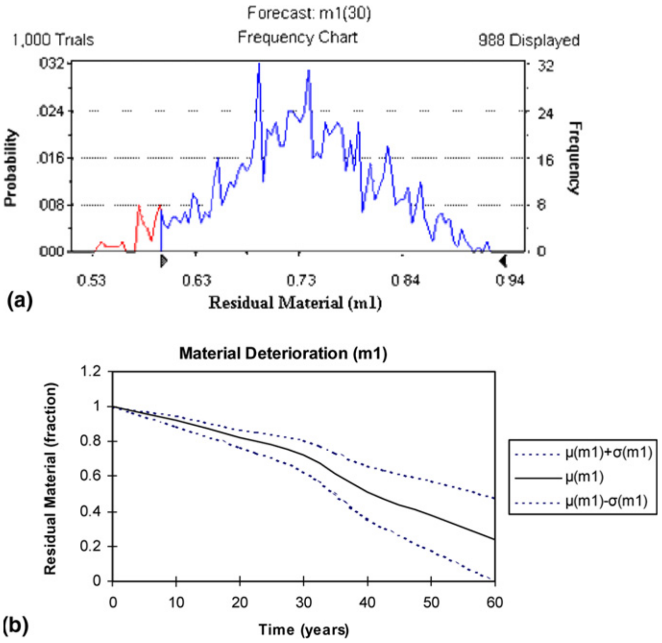

Fig. 6. Material deterioration (m1): (a) Monte Carlo simulation result for distribution of material damage (m1) at time $t = 30$ years and (b) deterioration of material (m1) over time.

In the first case, the effect of routine preventive maintenance is modeled by defining three coefficients r_1, r_2, and r_3 that reduce the severity of each of the three damage modes d_1, d_2, and d_3 respectively. The values for the three coefficients are input by the user for each time interval. After a period of 30 years, the frequency distribution of the values of residual or undamaged material in the case of m_1 and m_2 respectively are shown in Figs. 6(a) and 7(a). Similarly, the frequency distribution of the structural performance level after 30 years is shown in Fig. 8(a). From the simulation results the mean and standard deviation of the values after

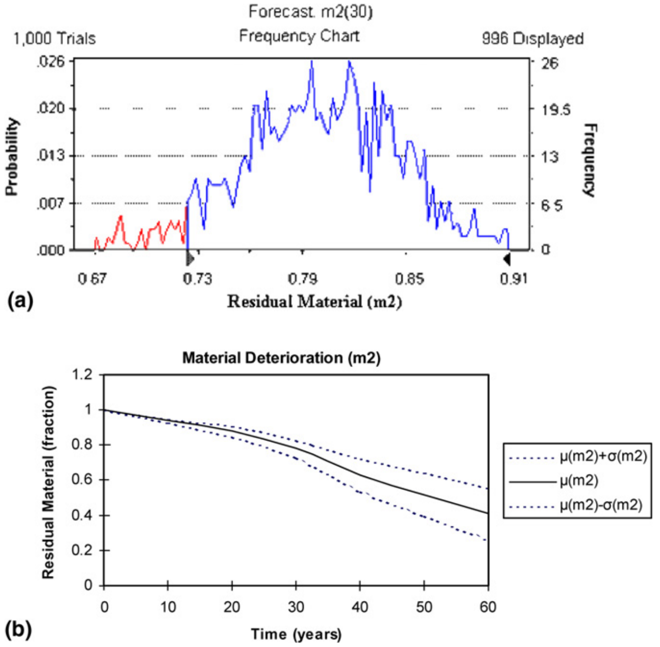

Fig. 7. Material deterioration (m2): (a) Monte Carlo simulation result for distribution of material damage (m2) at time $t = 30$ years and (b) deterioration of material (m2) over time.

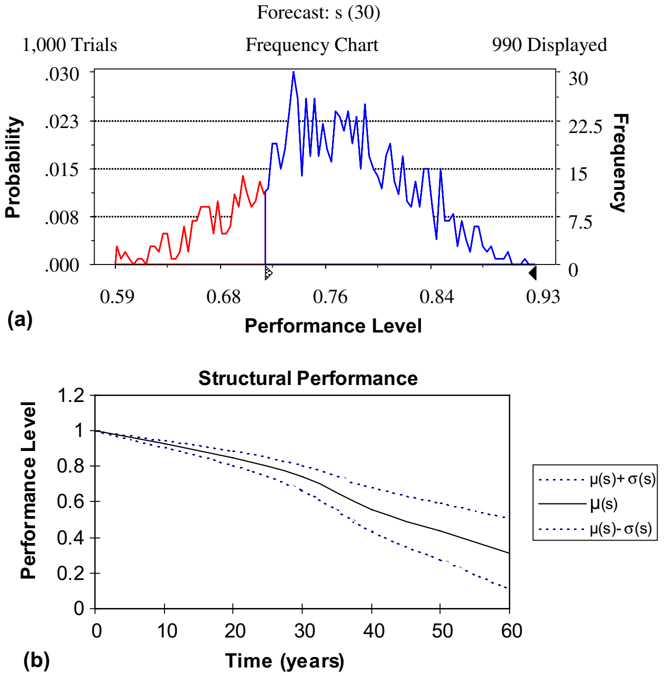

Fig. 8. Structural performance of the component: (a) Monte Carlo simulation result for distribution of structural performance at time $t = 30$ years and (b) structural performance over time.

each time interval can be determined. The mean and standard deviation of the values for residual material and structural performance over a 60-year period at intervals of 10 years is then plotted against time to get the material and structural deterioration curves. Figs. 6(b) and 7(b) show the deterioration of materials m_1 and m_2 from their initial design values over a period of 60 years. Fig. 8(b) shows the variation of structural performance over the same time period. The solid line in these figures shows the mean value of the residual material(s) and structural performance. The variation and uncertainty in the calculated values is shown by the dotted lines that represent the spread in the potential values of the structural performance and residual material in terms of the standard deviation.

In the second case, in addition to routine MR&R action, component replacement occurs after 30 years. In this case, the routine maintenance is modeled in the same way as in the first case. There is no change in the simulation results for the first 30 years. Therefore, the material deterioration and performance curves for the first 30 years remain the same as before as shown in Figs. 9 and 10. However, the effect of the component replacement at $t = 30$ years is modeled by the user through resetting values of the residual material(s) and structural performance to the initial design values. This results in a jump in performance curve at time $t = 30$ years as shown in Fig. 9. Similarly, the residual material curves for m_1 and m_2 also depict a jump to the initial design values for the same time instant as shown in Fig. 10. Performing the simulation for successive time periods again results in corresponding accumulation of material damage and structural deterioration after the MR&R action. This is shown by the decreasing residual material and structural performance level curves from the maximum design values at $t = 30$ years as shown in Figs. 9 and 10. Figs. 8(b) and 9 show the life-cycle performance of the structural component under two different MR&R strategies. In this way, the user can perform a comparative study of the effects of several MR&R strategies on a structure and select the best option. These results can be used for selection and optimization of available MR&R strategies and life-cycle costs for civil infrastructure facilities.

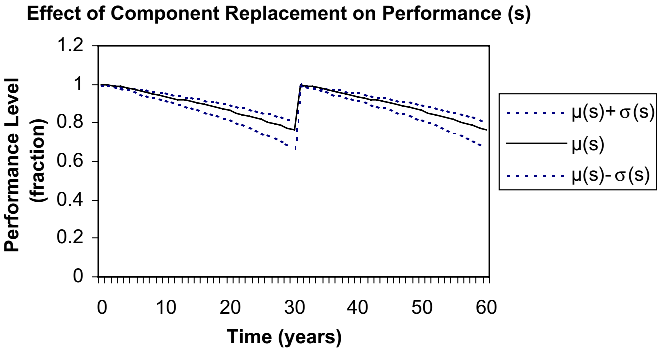

Fig. 9. Component performance with MR&R action at time $t = 30$ years.

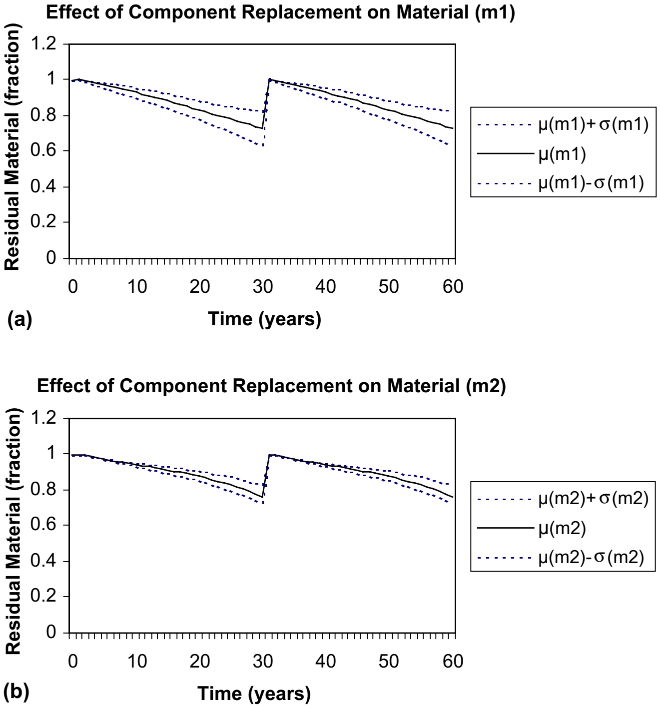

Fig. 10. Material deterioration with MR&R action at time $t = 30$ year: (a) material (m1) deterioration curve and (b) material (m2) deterioration curve.

8.3. Advantages of the model

The proposed framework satisfies the need for a practical method to model life-cycle performance of composite materials.

- The framework provides a way to incorporate existing and future research in material deterioration into life-cycle performance modeling.
- The model does not rely entirely on historical data though historical data can be used when available.
- The framework provides a way to model the time-dependent interaction among different damage modes.
- The proposed approach accounts for the uncertainty in deterioration modeling and the variability in the factors by modeling life-cycle performance as a stochastic process.
- The model allows the user to forecast the long-term effects of different MR&R strategies on the life-cycle performance of the structure, thus facilitating the selection of the optimal strategy and the estimation of life-cycle costs.
- By modeling deterioration at the material level and component level, the framework makes the selection of appropriate maintenance measures easier.
- The framework allows modeling the structural deterioration in terms of different structural properties like the strength and stiffness of the same member. This is very important in certain cases, for instance, if the stiffness degrades faster than the strength.
- The framework is completely general and applicable to different types of structures, involving different materials and different exposure conditions.

8.4. Limitations of the model

The main limitation of the proposed approach is the lack of sufficiently robust material deterioration models and information on the interaction between damage modes. However, such information can be expected to be available in the near future from structures and materials research. Moreover, the framework can be used with available information, mathematical models, and models based on expert judgment until more realistic material deterioration models are made available.

Applying the model to a particular structure requires a considerable amount of preparatory work in identifying the appropriate damage modes, and factors and finding the appropriate deterioration models and distributions respectively. But the complex nature of the deterioration process and the uniqueness of each individual structure make this step unavoidable.

In the proposed framework the performance of a structural component is modeled but not the performance of the entire structure. There are two reasons for this: (1) a performance level for an entire structure like a bridge has little informative value in selecting MR&R actions, and (2) if required the framework can be extended to estimate the overall structural performance by using available techniques like the fault-tree approach proposed by Sianipar and Adams [4].

9. Conclusion

A conceptual framework for modeling the life-cycle performance of civil infrastructure facilities was presented. The model is generic and applicable to structures involving conventional or composite materials. In the proposed approach, life-cycle performance was based on material degradation under the effects of environmental exposure and operational conditions. MCS was used to account for the uncertainty involved in the model. The model is suitable for applications where little or no historical data can be obtained and conventional methods cannot be used. The procedure depends on the availability of appropriate material deterioration models and its success is contingent on the accuracy of the obtained material deterioration models. The model has not yet been verified with case studies due to the non-availability of the appropriate material deterioration models. However, the logical correctness and the computational feasibility of the framework were verified using a hypothetical situation presented in this paper. Successful application of the model in practice can only be achieved when sophisticated material deterioration models are available from future research. The modeling framework presented in this paper can have practical significance as a tool for the selection of optimal MR&R actions, for estimating the life-cycle costs of the structure, and for the comparison of composite and conventional material alternatives in civil infrastructure systems. The authors are currently working on developing the model further by removing some of the modeling assumptions and building a more robust model.

References

[1] ASCE. Report card for America's infrastructure. 2001. Available from: <http://www.asce.org/reportcard/> (November 6, 2003).

[2] Mishalini RG, Madanat S. Computation of infrastructure transition probabilities using stochastic duration models. J Infrastruct Syst, ASCE 2002;8(4):139–48.

[3] Nystrom HE, Watkins SE, Nanni A, Murray S. Financial viability of fiber-reinforced polymer (FRP) bridges. J Manage Eng, ASCE 2003;19(1):2–8.

[4] Sianipar PRM, Adams TM. Fault-tree model of bridge element deterioration due to interaction. J Infrastruct Syst, ASCE 1997;3(3):103–10.

[5] Vose D. How Monte Carlo Simulation works. Risk analysis: a quantitative guide. 2nd ed. New York: Wiley; 2000, p. 57–66.

[6] Hastak M, Halpin DW. Assessment of life-cycle benefit–cost of composites in construction. J Compos Constr, ASCE 2002;4(3): 103–11.

[7] Richard Deepak. Life-cycle performance model for composites in civil infrastructure. MS thesis. University of Cincinnati (OH), 2003.

[8] Aktan E, Chase S, Inman D, Pines D. Monitoring and managing the health of infrastructure system. In: Proceedings of SPIE, vol. 4337. Newport Beach (CA): International Society for Optical Engineering, Society of Photo-Optical Instrumentation Engineers. 2001, p. xi–xxi.

[9] Hjelmstad KD, Lange DA, Parsons ID, Lawrence FV. Framework for modeling durability cost of structural systems. J Infrastruct Syst, ASCE 1998;4(3):126–33.

[10] Hudson W, Haas R, Uddin W. Infrastructure management: integrating design, construction, maintenance, rehabilitation and renovation. New York (NY): McGraw Hill; 1997.