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Cost-benefit analysis for the optimal rehabilitation of deteriorating structures

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Abstract

A cost-benefit analysis for planning rehabilitation efforts of deteriorating structures is proposed, which takes into account all life-cycle costs, such as construction, failure, inspection and state-dependent rehabilitation costs, as well as state- or time-dependent benefit rates. Rehabilitations can take place anytime throughout the lifetime and are optimized by maximizing the expected net present benefit rate. This approach not only allows to determine optimal sequence of rehabilitation times and rehabilitation levels, but allows also to determine optimal lifetimes and acceptable failure rates. Numerical examples demonstrate that proper planning of rehabilitations allows to extend the lifetime of a structure – as long as the expected costs for such efforts outweigh the expected future benefit. If this is not the case, then, indeed, the structure is obsolete and alternatives have to be evaluated.

Keywords: Cost-benefit analysis; Deterioration; Rehabilitation; Structural safety; Optimization

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1. Introduction

Civil infrastructure like bridges deteriorate with time due to inherently random factors such as loads and environmental stressors. In fact, in most more economically developed countries an ever growing percentage of existing structures show significant deterioration and, consequently, is threatened by obsolescence in the short- to medium-term. At the same time it is recognized that due to purely economic reasons, this situation cannot be countered by simply re-building everything anew. Hence, to ensure sustained serviceability and safety of these structures, maintenance interventions become mandatory, which allow partial or complete structural rehabilitation. In order to rationalize decisions with respect to maintenance or rehabilitation, bridge management systems have been developed and implemented in North America, Europe and Japan [1–6]. The generic components of these management systems can be coarsely summarized as: (a) assessment of bridge conditions, (b) forecasting of further bridge deterioration, and (c) identification and prioritization of

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maintenance needs and their corresponding financial requirements. However, these systems have been repeatedly criticized for mainly two reasons. The first point of criticism is, that the assessment of bridge conditions is done commonly by so-called condition ratings (verbal descriptors) on structural element level made during routine visual inspections. Therefore, these condition ratings mostly indicate the relative health of structural elements only, but they do not identify the physical or chemical processes that cause the deterioration, nor are they directly related to structural behavior, that is, structural safety and serviceability [5,7]. Structural safety is only indirectly mentioned – as a need for immediate intervention – in the most severe of the typical, say, five to seven condition states.

Whereas more objective and accurate structural condition assessments can be performed by utilizing concepts of structural identification [8], the complex of problems related to structural safety can only be addressed by structural reliability theory. Thus, what is required is a consistent description of the time-variant condition of a structure in terms of both deterioration and ultimate failure states, as done, for example, in [9–14]. A structural state description in terms of only "failure" or "no failure", as proposed, among others, in [15], via so-called reliability profiles, is not sufficient for optimal maintenance planning, since it does not allow to relate (directly or indirectly) observable deterioration states to specific performance conditions – including its effect on the load carrying capacity and the remaining lifetime – as well as rehabilitation actions to be performed, as is mandatory for effective bridge maintenance systems [7,16]. The addition of a separate condition profile in [17] tries to remedy this shortcoming, although it remains unclear why condition and safety should be treated as separate entities. Moreover, the reliability and condition profiles in [15,17] are not calculated with the help of structural reliability theory, but are either directly determined by so-called experts, or estimated from statistical data. However, as shown in [18], time-variant reliability profiles depend on a multitude of factors (structural design, loads, environmental conditions, deterioration mechanisms, etc.) which will be hardly reflected in its entirety in expert knowledge, nor does it seem to be overly realistic to assume, that there will be ever enough data available to directly estimate reliability profiles, that is, without recursion to a physical or chemical model.

Thus, to summarize the first point of criticism, when addressing the problem of optimal maintenance planning, a consistent probabilistic description of the condition of a structure – including not only deterioration states, but also structural collapse – is indispensable. This requires the explicit modeling of structures, deterioration processes, condition assessments and maintenance interventions. For practical applicability, condition states in the probabilistic analysis should be selected compliant with experimental condition assessment techniques. This allows not only to utilize inspection data for modeling purposes, but also to define optimal maintenance actions in terms of experimentally observable – whether directly or indirectly – indicators of structural deterioration. We will show this herein exemplarily for a simple truss-type bridge under fatigue loading, where the overall structural damage state is determined with the help of static load tests.

The second set of criticism of existing bridge management systems is centered around the models utilized for deterioration forecasting. Commonly, discrete-time Markov chains, with time-homogeneous transition probabilities, are employed as a statistical model, based on the above mentioned visual inspection data [1–6]. Due to their sole reliance on inspection data, these Markov chains, evidently, inherit also the above mentioned shortcomings of the subjective nature of condition ratings and their lack of information on structural behavior. But also the data itself is problematic, since most often it does not make reference to differences in the structural characteristics of bridges, environmental conditions, past rehabilitation efforts or even time intervals between inspections, thereby compromising the accuracy of its estimates. Also there is ample theoretical as well as experimental evidence that the transition probabilities are, in general, time-inhomogeneous, that is, that age – the time since construction or rehabilitation – has a significant impact on the deterioration rate [19–21]. However, it should be also mentioned that we do not follow the general rejection of Markov processes as being not able to model such behavior at all, as has been done in [15,17]. Utilizing continuous-time Markov chains, with time-inhomogeneous transition probability rates, indeed allows to model age dependency [21] as well as maintenance effects like delays in deterioration or changes in deterioration rates. For this purpose we propose to utilize the time distributions of reaching defined damage or deterioration states – as determined from a probabilistic analysis – to build up the transition matrix. It should go again without saying, that this requires an explicit modeling of the deterioration process and respective maintenance interventions, that is, it cannot be done by solely utilizing inspection data or expert knowledge.