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Sustainability-informed maintenance optimization of highway bridges considering multi-attribute utility and risk attitude

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ABSTRACT

Throughout their service life, highway bridges deteriorate due to increasing traffic loads and aggressive environmental conditions. Aging of materials can have significant effects on the structural performance of highway bridges. A comprehensive risk assessment procedure is crucial in evaluating and ultimately mitigating detrimental consequences of structural failure to the economy, society, and the environment. The proposed sustainability-based maintenance optimization decision-support framework provides decision makers with optimal life-cycle maintenance actions that balance conflicting objectives. Utility theory is employed herein in order to effectively capture the sustainability performance of highway bridges and impact of the decision maker's risk attitude. The main objective of this framework is to reduce the extent of the consequences of structural failure to the economy, society, and the surrounding environment. The capabilities of the proposed approach are demonstrated on an existing highway bridge.

1. Introduction

Throughout their service life, highway bridges may be exposed to a multitude of stressors, including aggressive chloride environmental conditions, material aging, and increasing loads due to traffic. These stressors cause the structural performance of highway bridges to gradually decrease over time leading ultimately to structural failure. The consequences associated with structural failure due to progressive deterioration can be large and widespread. In order to mitigate the detrimental impacts of structural failure, risk and sustainability indicators are utilized within an efficient life-cycle maintenance optimization procedure to find maintenance strategies that balance cost and performance. The results from this optimization may be employed within a risk-informed decision making process.

The decision-making paradigm associated with the optimal maintenance of civil structures is a fundamental concept studied within the field of life-cycle structural engineering. Generally, five separate stages of decision making may be considered: the pre-analysis, problem set-up, uncertainty quantification, utility assignment, and optimization [1]. First, it is assumed that there is a single decision maker who possesses a predetermined risk attitude with respect to a specific structural system. Next, typically, all possible solution alternatives are identified and the uncertainties corresponding to the decision-making problem are recognized and accounted for using a probabilistic approach. After effectively incorporating the appropriate uncertainties, the decision maker can assign utility values to the consequences associated with each alternative. Lastly, an optimization procedure is carried out in order to find the alternative that maximizes the utility value.

Within the proposed decision support system for life-cycle maintenance planning of highway bridges, several attributes, including economic, societal, and environmental impacts, are considered in quantifying the consequences of structural failure in terms of risk (i.e., probability of failure occurrence multiplied by its associated consequence). Previous research efforts have effectively performed risk analyses in a qualitative [2,3] and quantitative manner [4–9] under a multitude of hazards for various structures. In general, structural components that are under relatively high risk should receive priority for maintenance interventions. Although there have been a wide variety of studies investigating quantitative risk assessment, these studies do not attempt to quantify sustainability. In this paper, risk assessment techniques are combined with multi-attribute utility theory to formulate an appropriate sustainability performance indicator.

Optimal maintenance planning is a widely investigated topic within the field of life-cycle engineering. Studies concerning the optimization of maintenance strategies based on reliability, risk, and/or redundancy have been conducted [8,10–12]. Additionally, lifetime distributions have also been used within maintenance

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optimization applications in [13,14]. In this paper, structural performance is formulated in terms of multi-attribute utility that effectively represents the sustainability indicator. This novel utility-based sustainability metric is utilized as an objective within an optimization procedure that determines the best essential maintenance strategies for highway bridges. Additionally, a second objective that represents life-cycle maintenance costs is integrated within the proposed framework. Therefore, a robust decision support system that simultaneously maximizes performance and minimizes cost is obtained.

The methodology utilized herein quantifies the sustainability of existing highway bridges and employs multi-criteria optimization techniques to find the best maintenance strategies. Within this approach, the desirability of each alternative (i.e., maintenance plan detailing the type and timing of interventions) depends on three risk-attributes (i.e., economic, social, and environmental impacts), measured with different units. Ultimately, there is a need to establish a consistent range of values that each attribute may take so that the attributes are directly comparable to each other. Utility theory is applied in order to normalize each risk-attribute value to a number between 0 and 1. The formulation of the utility function corresponding to each attribute greatly depends on the knowledge and preferential characteristics of the decision maker. Monotonically decreasing functions are employed to effectively depict the relative utility of detrimental consequences of the structural failure of deteriorating highway bridges. A final multi-attribute utility function is developed that considers the weighted relative utility value corresponding to each attribute involved. This function represents a sustainability metric that effectively weighs the contribution of impacts to the economy, society, and the environment.

The multi-attribute utility methodology adopted herein was first suggested in [15] where a sustainability performance indicator including the consequences of structural failure on the economy, society, and the environment was proposed. Besides the work reported in [15], there has been a lack of relevant studies that utilize multi-attribute utility theory within the structural engineering field. Furthermore, little research has been carried out that includes optimization within multi-criteria decision making problems [16]. Among this small pool of studies, Papanikolaou et al. [17] employed multi-objective optimization procedures to facilitate decision making regarding oil tanker design, Grierson [18] developed a multi-criteria decision making strategy that is applied to bridge maintenance-intervention protocol design, and Dabous and Alkass [19] proposed a multi-criteria decision support method for bridge deck management. In this paper, multi-attribute utility theory is employed to effectivity quantify the sustainability of highway bridges and determine optimal lifetime maintenance plans. This sustainability indicator quantifies the detrimental impacts of bridge failure due to increasing live loads and an aggressive corrosive environment, while the sustainability metric proposed in [15] was employed to assess the effects of seismic hazard on a network of multiple highway bridges. Overall, the main novelty of this work is the development of a sustainability performance indicator that has the ability to incorporate a wide variety of risks associated with structural failure of highway bridges. This performance indicator is integrated within a bi-objective optimization that determines optimal maintenance planning while balancing cost and performance.

Additionally, a four-objective optimization procedure is applied in this paper to determine optimal maintenance schedules. The illustrative example contained herein examines the lifetime maintenance optimization problem that simultaneously maximizes utility associated with the maintenance cost and the utilities corresponding to economic, societal, and environmental risks. The results of this four-objective optimization may be utilized in order to determine appropriate values of weighting factors for further use in the multi-attribute utility assignment.

The proposed methodology has the ability to quantify sustainability-based performance in terms of utility and effectively employs multi-criteria optimization procedures in order to determine optimum maintenance strategies that reduce the extent of detrimental consequences to the economy, society, and the surrounding environment, while simultaneously minimizing maintenance costs. The utility values of both the cost and performance corresponding to alternatives are utilized within an optimization procedure that determines optimal maintenance plans for highway bridges. The effects of the risk attitude and preferences of the decision maker, in addition to the number of maintenance interventions on the optimal maintenance strategies, are investigated. Furthermore, optimal maintenance strategies obtained considering the simultaneous maximization of four utility values are investigated as motivation for choosing appropriate weighting factors within the multi-attribute utility assessment. A genetic algorithm (GA) based optimization procedure is utilized to find the optimal maintenance interventions. The proposed approach provides optimal intervention strategies to the decision maker that ultimately allows for risk-informed decision making regarding maintenance of highway bridges. The capabilities of the presented decision support framework are illustrated on an existing highway bridge located in Colorado.

2. Multi-attribute risk assessment of highway bridges under traffic loading

2.1. Vulnerability analysis

The first step in the risk assessment is to evaluate the performance of a bridge considering the hazards that plague it. An increase in live loads associated with the average daily traffic and the effect of chloride contamination are the hazards considered herein for bridge superstructures. The time-variant performance function associated with a reinforced concrete bridge deck in bending g_{deck} is [20]

$$g_{deck}(t) = K_1 A_{sr}(t)\gamma_{mfs}\lambda_{deff} - K_2\frac{A_{sr}(t)^2\gamma_{mfs}f_y^2}{f'_{cs}} - K_3\lambda_a - K_4\lambda_c - K_5\lambda_{trk}(t) \quad (1)$$

The random variables considered in Eq. (1) are: $A_{sr}(t)$ = area of transverse steel reinforcing in the slab at time t (m^2), f_y = yield strength of reinforcing steel in slab (MPa), f'_{cs} = compressive strength of the concrete slab (MPa), γ_{mfs} = modeling uncertainty for flexure in the slab, λ_{deff} = reinforcing depth uncertainty factor, λ_a = asphalt weight uncertainty factor, λ_c = concrete weight uncertainty factor, and $\lambda_{trk}(t)$ = effect of the load. Deterministic quantities, K_1, K_2, K_3, K_4, and K_5, take on specific values depending on bridge type and geometric properties. In addition to flexure in the deck, the most critical mode of failure for the girders is associated with flexure. Thus, the following performance function is assumed to describe the time-variant performance with respect to bending in the steel girders

$$g_{girder}(t) = K_6 F_y S_p(t)\gamma_{mfg} - (K_7 + K_8)\lambda_s - K_9\lambda_c - K_{10}\lambda_a - K_{11} - M_{trk}(t) I_f D_f \quad (2)$$

Random variables in Eq. (2) include: F_y = yield strength of steel girder (MPa), $S_p(t)$ = plastic section modulus at time t (m^3), I_f = impact factor, D_f = the distribution factor, γ_{mfg} = modeling uncertainty for flexure in girder, λ_s = structural steel weight uncertainty factor, and $M_{trk}(t)$ = moment due to truck load (kN m). K_6, K_7, K_8, K_9, K_{10}, and K_{11} are deterministic constants.