Research framework of life-cycle performance based bridge design method

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ABSTRACT: Based on the principle of life cycle cost (LCC) analysis method, this paper presents conceptual framework of life-cycle performance based bridge design method. Namely, Taking structural reliability analysis as a basis, the design method minimizes present values of life-cycle cost during bridge lifetime as optimal performance objective, and makes use of life-cycle cost analysis method to evaluate bridge design strategy subjected to structural performance constraints whether or not it is an optimum strategy. An approach to study on life-cycle performance based bridge design method is proposed in this paper, including systematic method study and parametric uncertainties analysis and risk evaluation. Optimal algorithm is employed as a search method for the optimal design strategy solutions and Monte Carlo simulation is taken as risk analysis approach to account for the uncertainties. The method presented in this paper stresses on the interaction of lifetime performance prediction, reliability-based life-cycle cost and maintenance/repair interventions, and has many characteristics, such as explicit concept and convenient realization. The relative theories developed in this paper can provide references for bridge design, construction, lifetime maintenance and rehabilitation and retrofit actions.

1 INTRODUCTION

Many researchers have been devoting in research on the deteriorating bridges, and have presented all kinds of repair strategies, which is benefit for bridge maintenance and management. But the retrofit of aging bridges is only a remedial way. Thus a problem is put forward, that is to say, how to evaluate the economy and risk of a design plan. On the other hand, how do estimate bridge maintenance costs and serviceability during bridge service.

Based on related documents in home and abroad, this paper tries to research the life-cycle performance from concept to theory framework, proposes a new bridge design method based on bridge reliability, subjected by serviceability level, taking minimum of life-cycle cost as optimum object. From this point of view, bridge design should not only satisfy bridge safety and durability, but also maintain serviceability level and decreases life-cycle maintenance cost.

2 CONCEPT OF LIFE-CYCLE PERFORMANCE

Reliability index is used to evaluate bridge condition by bridge engineers, mainly includes three aspects: 1) bear all kinds of loadings during construction and service; 2) have good working condition during service; 3) have enough durability. The life-cycle performance object is the minimum of the present values of life cycle cost based on reliability during bridge lifetime. Reliability is an integrated estimation of safety, serviceability, durability and economy. Structural reliability β_{life} is used to evaluate bridge condition during lifetime, and target reliability β_{life}^{*} represents the minimum acceptable level. When $\beta_{life} < \beta_{life}^{*}$, the bridge needs rehabilitation or retrofit.

The life-cycle performance is introduced into bridge design, construction and maintenance, which can improve serviceability level during lifetime and result in rational expenditure during lifetime. This concept will lead to that bridge design and maintenance have more explicit and favorable target.

3 RESEARCH AND APPLICATION OF LIFE-CYCLE PERFORMANCE BASED BRIDGE METHOD: STATE-OF-THE-PRACTICE

This research field integrates the effect of technological, engineering, environmental, economical, mechanical, optimum analysis theory and reliability. In recent ten years, uncertainty parameters research, structural risk evaluation, structural reliability assessment, optimum maintenance strategy decision-making and structure service-life prediction have become international hot issuses.

Frangopol et al. (2000a) presented realistic examples of optimal bridge maintenance planning based on minimum expected LCC criterion. Based on a modified event tree analysis, Kong and Frangopol (2003) computed probabilities of maintenance actions of deteriorating highway bridges and the expected life-cycle maintenance cost. Liu et al. (1997) minimized both life cycle maintenance cost and a normalized weighted average deterioration measure for maintaining bridge decks. Miyamoto et al. (2000) investigated optimal maintenance of existing bridges through minimizing maintenance cost and maximizing bridge load-carrying capacity as well as durability.

From social need, subject development and engineering application as concerned, existing design theory and method need to further be studied. Main problems includes: 1) Using ultimate limit state and serviceability limit state design method, no quantitative durability design and life-cycle design concept is contained; 2) Only paying more attention to initial investment, ignoring maintenance cost and the maintaining of serviceability level; 3) Now, though bridge engineers have devoted to studying structural reliability, maintenance cost and residual lifetime prediction respectively, but have not consider them from design viewpoint.

4 UNCERTAINTY PARAMETERS ANALYSIS

It is a basis that characteristics and action ways of all kinds of stochastic parameters that affect bridge condition are systematically analyzed before bridge performance is studied. As a whole, there are interior, external and economical factors. Bridge life cycle is divided in three phases, including design phase, construction phase and service phase. According to the three phases, stochastic parameters and interactions of them are showed in Fig.1.

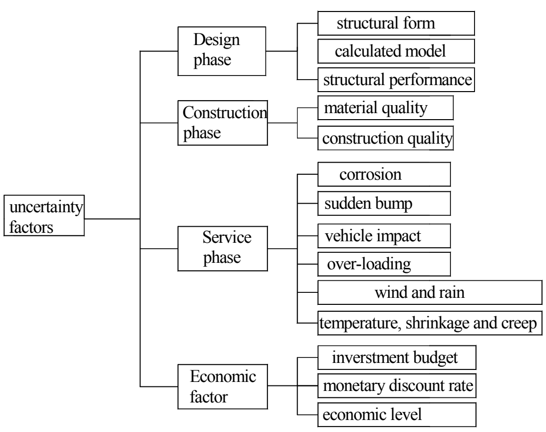

Fig.1 Uncertainty parameters

These uncertainty parameters have many characteristics, as follows:

1) Different factors interact and unite each other, and bridge performance maintenance should have all-round systematic perspective.

2) Bridge performance exists in every phase of lifetime, and bridge design should have life-cycle perspective.

3) Uncertainty parameters analysis should be included in bridge life-cycle performance and lifetime reliability estimation.

Based on stochastic parameters analysis, structural reliability index is calculated during lifetime, and bridge condition is estimated under different aggressive environment. By ascertaining bridge life probability distributed function, the bridge residual life can be forecasted.

5 BASIC RESEARCH FRAMEWORK OF LIFE-CYCLE PERFORMANCE BASED BRIDGE DESIGN METHOD

By analyzing uncertainty factors effect to bridge life-cycle performance, life-cycle performance based bridge design method research should consist the following contents: systematic research on life-cycle performance; bridge life-cycle performance evaluation; bridge life cycle cost analysis method; interaction research on life-cycle performance, life cycle cost and maintenance strategies, lifetime optimum design based on life cycle cost.

5.1 *Systematic research on life-cycle performance*

From systematic sight, bridge performance research should include bridge structural performance research, bridge aggressive environmental research and economics research.

Bridge structural performance research mainly analyzes interior uncertainty factors, such as the elastic modulus of concrete and steel, respectively, etc. Bridge aggressive environmental research mainly discusses durability of deteriorating structures under concrete carbonation or chlorine icon corrosion. Economics research mainly investigates effect of discount rate. Thus, bridge life-cycle performance can be assessed and predicted scientifically and quantitatively.

5.2 *Bridge life cycle cost analysis method*

Life cycle cost analysis (LCCA) method is the most renowned evaluation tool for transportation infrastructure management and decision-making support during the project-level analysis. Federal Highway Administration (FHWA) and State Highway Agencies of USA are interested in promoting its application as evaluation tool capable of achieving higher policy objectives. Paterson recorded the acknowledgment of LCCA in the nineteenth century (Paterson 1985). A significant manuscript published by the FHWA(2002) titled "*Life Cycle Cost Analysis in Pavement Design- In Search of Better Investment*". This manuscript is by far the most referenced document in LCCA nowadays. Its importance lies in the fact that it provided an easy-to-follow step-by-step process on how to conduct LCCA including numerical examples. Life cycle cost composed of agency cost, user cost and society cost. Agency cost consists of the costs of initial construction, rehabilitation and upgrading, periodic maintenance, engineering, and agency overhead. User cost is the costs encountered by the project's users, and are estimated differently during the normal operation of the facility and during work-zone operation. Social cost is the costs of accidents and the costs of environmental impacts, etc.

The complementary wide-ranging model for LCCA method can be presented as follows (Jaward 2003):

$$NPV = \sum_{t=0}^{T} \frac{\left[\sum_{k \in K} \sum_{j \in J} cost(k, j, t) \right]}{\left(1 + r_t\right)^t} \cdot p_c\left(k, j, t\right) \qquad (1)$$

where: $NPV =$ net present value of the total economical worth of a project in monetary units; $K =$ set of costs classified on the basis of bearing entity, including agency cost, user cost and social cost; $J =$ set of costs incurred by each entity in K and classified by their nature (ie, Agency cost can consist of costs of material, labor, overhead, engineering); $t =$ Year at which the cost is incurred;

$T =$ analysis period (years); $\gamma =$ Discount rate (%) at t year; and, $P_c =$ probability that the cost is incurred at t year.

5.3 *Comprehensive interaction study on life-cycle performance, life cycle Cost and maintenance strategies*

Frangopol research group(1997, 1998, 2004 (4)) researched time-variant reliability of reinforced concrete bridges under aggressive environment, and used Monte Carlo simulation to calculate accumulated failure probability and evaluated risk of strategies by analyzing time-varying loads and resistance effect. By reliability index calculation of deteriorating structures, service life assessment and prediction, and maintenance strategy decision analysis, the optimum repair actions are proposed based on the minimum LCC expected value. Thus, a life-cycle design strategy should not only have bearing capacity limit state design, durability of normal usage limit state design, but have predictive service level and maintenance planning.

Mori and Ellingwood(1993,1994(2)) evaluated deteriorating structural condition based on reliability method, and optimized maintenance interventions based on the minimum of LCC expected value.

The Comprehensive relationship among life-cycle performance, maintenance interventions and life cycle cost is illustrated in Fig.2.

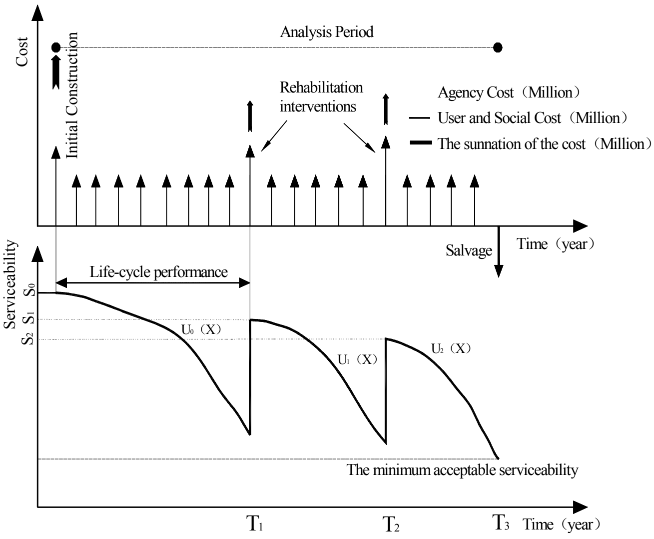

Fig.2 Comprehensive relationship among life-cycle performance, maintenance strategy and cost

It is easy to know that the interactions among life-cycle performance, maintenance interventions decision and life cycle cost are complex.

5.4 *Optimization analysis based on life-cycle cost*

Today, transportation infrastructures construct and develop rapidly in China. How to use tighten capital to build safe, durable and economical bridge is concerned issue for each bridge engineer and investment decision-maker.

As for many design strategies, a design strategy is an investment action. Every strategy has a related life-cycle cost function. How to decide the optimization design strategy among them is the most interesting title for transportation infrastructure management agency. Every design strategy constructs life cycle cost optimization model, and establishes an objective function, and ascertain subject equation $\beta_{life} > \beta_{life}^{*}$. After constructing life cycle cost optimization model, the choice of optimization algorithms is very key problem. Bridge maintenance and rehabilitation interventions are not static procedure, so optimization model of transportation infrastructure should take probability as a tool for predicting structural future condition. The key challenge is that this optimized route is a realistic state of life cycle of factual infrastructures, and optimization formulations have nonlinear characteristics, and have multi-objective decision procedure in life-cycle management at the same time.

6 RESEARCH FLOWCHART OF LIFE-CYCLE PERFOEMANCE BASED BRIDGE DESIGN METHOD

There are two tasks to bridge design. One is that structure is reliable; the other is that life-cycle cost is economical and rational. An excellent design should satisfy above two aspects.

In summary, life-cycle performance based bridge design method combines reliability theory with optimization analysis procedure, and decides the optimum design strategy based on LCC expected value. The basic flowchart of this method is illustrated as Fig.3.

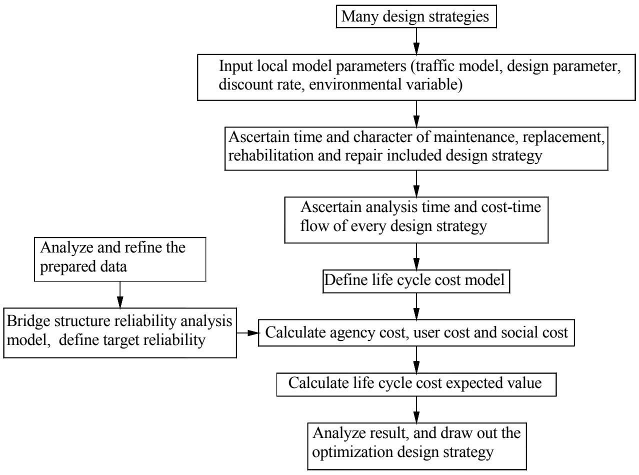

Fig.3 Flowchart of design strategy optimization

The key challenge is how to construct life cycle optimization model based on bridge reliability, and the sensitivity analysis and risk assessment of design strategy and research on optimization algorithm under subject equation.

7 CONCLUSIONS

Life-cycle performance based bridge design method is an innovative design concept, presented in the latest twentieth century. This design method takes the minimum of LCC present values as objective subjected to serviceability level, and seeks predictive serviceability and maintenance cost during bridge lifetime. In China, research on this design method is in phase of initial development. It is very valuable for the development of bridge design method to systematically research life-cycle performance based bridge design method.

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