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Reliability-Based Design of Deteriorating Bridges under Corrosion Effects

Théorie de fiabilité appliquée au dimensionnement des ponts soumis à la corrosion

Einsatz der Zuverlässigkeitstheorie bei der Bemessung korrodierender Brücken

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SUMMARY

Available data suggests that corrosion may have significant effects on the reliability of highways bridges. Therefore, the design requirements for highway bridges must include consideration of corrosion. This paper presents a highway bridge reliability-based design formulation which accounts for corrosion effects on both steel and reinforced concrete bridges. The approach incorporates both time-independent constraints specified in the AASHTO bridge code and time-dependent constraints due to corrosion effects. Numerical examples illustrate the application of the proposed approach.

RÉSUMÉ

Les données actuelles laissent supposer que la corrosion a une influence significative sur la fiabilité des ponts autoroutiers. Raison pour laquelle il faut prendre en compte un tel phénomène destructif dans les exigences de calcul de ces ouvrages. L'article expose une méthode d'étude basée sur la théorie de la fiabilité, qui tient compte des effets corrosifs aussi bien sur les ponts métalliques que sur ceux en béton armé. Ce mode opératoire inclut tant les sollicitations ne dépendant pas du temps et spécifiées par la norme AASHTO applicable aux ponts, que celles dépendant du temps et résultant de l'influence de la corrosion. Des exemples numériques illustrent l'utilisation de la méthode proposée.

ZUSAMMENFASSUNG

Vorhandene Daten deuten auf den grossen Einfluss, den Korrosion auf die Zuverlässigkeit von Autobahnbrücken hat. Deshalb müssen die Bemessungsanforderungen die Berücksichtigung der Korrosion einschliessen. Der Beitrag stellt eine Entwurfsregel für Stahl- wie auch Stahlbetonbrücken auf Grundlage der Zuverlässigkeitstheorie vor. Eingeschlossen sind sowohl zeitunabhängige Nebenbedingungen nach der AASHTO-Brückennorm als auch zeitabhängige infolge Korrosionsauswirkungen. Numerische Beispiele illustrieren die Anwendung des vorgeschlagenen Ansatzes.

1. INTRODUCTION

In the past two decades, deterioration in highway bridges has received increased attention as a cause of strength reduction and possible collapse [1-3]. In fact, several recent bridge failures have been attributed to various material degradation processes. Corrosion in steel and reinforced concrete bridges appears to be one of the most important degradation mechanisms in determining the service life of these structures. As pointed out by Kulicki *et al* [1] "the estimated cost of repairing corrosion-damaged bridges in the United States is staggering". At present, however, there are no established procedures for taking into account corrosion effects in the design of highway bridges. This paper presents a highway bridge design formulation which accounts for corrosion effects in both steel and reinforced concrete bridges. The approach incorporates both time-independent (reserve) constraints specified in the AASHTO bridge code [4] and time-dependent (residual) constraints due to corrosion effects.

2. CORROSION

The effects of corrosion on steel and/or concrete highway bridges can vary dramatically depending on the environment, location, and amount of deterioration.

For steel bridges, Kayser [2] and Kulicki *et al* [1] described various forms of corrosion, including uniform corrosion, pitting, galvanic corrosion, and stress corrosion. In this paper uniform corrosion is considered. On steel bridges this type of corrosion can be identified easily. It consists of many small pits joined together [1]. From the collected data on uniform corrosion penetration in steel coupons in different environments, Townsend and Zocolola [5] fitted time-corrosion penetration curves to a power function

$$C(t) = At^B \tag{1}$$

where C(t) is the average corrosion penetration determined from weight loss, A and B are regression coefficients whose value depend on the type of steel and the type of environment [3], and t is the time in years. A coefficient α may also be introduced to take into account modeling uncertainty [6]. In this case the corrosion penetration is given as

$$C(t) = \alpha At^B \tag{2}$$

For concrete bridges, corrosion of the reinforcement due to carbonation and chloride is considered herein. Once corrosion of reinforcement is initiated it is assumed to be propagated as uniform corrosion (i.e., all bars are assumed to become corroded with the same penetration rate at the same time) [7,8]. The total flexural reinforcement area in a cross section of a reinforced concrete beam as a function of time is

$$A_s(t) = \begin{cases} n\pi d^2/4 & \text{for} \quad t \le t_0 \\ n\pi[d - 2\nu(t - t_0)]^2/4 & \text{for} \quad t > t_0 \end{cases} \tag{3}$$

where d is the diameter of a single bar, n is the number of reinforcement bars (i.e., all bars are assumed to have the same diameter), t_0 is the time of corrosion initiation, and ν is the rate of corrosion. The shear reinforcement area in a cross-section of a reinforced concrete beam placed in a corrosive environment can be also defined as a function of time [9].

3. RELIABILITY-BASED DESIGN INCLUDING CORROSION

For composite steel bridges, corrosion will cause a reduction in the cross-sectional area of the lower flange and the web and a reduction in the geometric bending properties of the section. This reduction will decrease the tensile capacity of the lower flange and reduce the ultimate moment capacities of the section. Similarly, for concrete bridges corrosion of reinforcement will reduce both the bending and shear capacities.

Under corrosion, the formulation of the design problem in a reliability-based design format is almost identical to that of the time invariant model [10]. In order to include the corrosion effects in the formulation, the two additional regression coefficients A and B in Eq.(1) should be considered to describe the corrosion model for a given environment. Using the time-variant reliability-based context, the design formulation of steel and/or concrete bridges under corrosion is as follows:

Minimize $\quad C(\mathbf{X}, \mathbf{Y}, \mathbf{Z}, t) \qquad (4)$

such that :

$$\beta_i(t) \geq \beta_i^*(t) \qquad i = 1, 2, \ldots, m \qquad (5)$$
$$g_j(t) \leq 0 \qquad j = 1, 2, \ldots, n \qquad (6)$$
$$\beta_{system,k}(t) \geq \beta^*_{system,k}(t) \qquad k = 1, 2, \ldots, s \qquad (7)$$

where C = cost function, $\mathbf{X}$ = vector of design variables, $\mathbf{Y}$ = vector of design parameters, $\mathbf{Z}$ = vector of parameters defining the corrosion process, t = time, $\beta_i(t)$ = reliability index with respect to limit state i, $\beta_i^*(t)$ = allowable value of β_i, $g_j(t)$ = performance function such that $g_j(t) \leq 0$ is the safe state, $\beta_{system,k}(t)$ = system reliability index, and $\beta^*_{system,k}(t)$ = allowable value of $\beta_{system,k}(t)$.

The reliability-based design formulation (4)-(7) is general and allows flexibility in choosing the cost function C, the design variables $\mathbf{X}$, the reliability-based constraints (5) and (7), and the performance constraints (6). The nonlinear programming problem (4)-(7) is solved by linking the general purpose deterministic optimization software ADS [11] with the structural reliability analysis software RELTRAN [12]. The time-dependent reliability indices $\beta_i(t)$ and $\beta_{system}(t)$ are defined as:

$$\beta_i(t) = -\Phi^{-1}(P_{f_i}(t)) \qquad (8)$$
$$\beta_{system}(t) = -\Phi^{-1}(P_{f_{system}}(t)) \qquad (9)$$

where $P_{f_i}(t)$ = probability of occurrence of limit state i at time t, and $P_{f_{system}}(t)$ = system failure probability at time t. $P_{f_{system}}(t)$ is computed considering all limit states as a series system as the average of Ditlevsen's bounds [13] at time t.

4. RESULTS

To illustrate the applications of the proposed reliability-based design approach to steel and reinforced concrete bridges under corrosion effects, two numerical examples are considered herein.

First, a simply supported 24.40 m, composite, welded, hybrid, stiffened plate girder of a multi-girder bridge exposed to corrosion is designed according to AASHTO [4]. There are 22 design variables, X_1 to X_{22}, 13 design parameters, Y_1 to Y_{13}, and two parameters defining the corrosion process [10],[14]. Nine deterministic design variables are considered independent (see Fig. 1), and eight design parameters and two parameters A and B defining the corrosion process (see Fig. 2,[2]) are considered random variables [10]. The time-dependent reliability-based design problem (4)-(7) is solved considering the steel weight as the objective to be minimized. Fig. 3 shows results of time-dependent reliability-based design. The least-weight required to maintain the same target reliability level increases with both time of exposure to corrosion and required reliability level. Fig. 4 shows the effects of the number of girders on the time-dependent

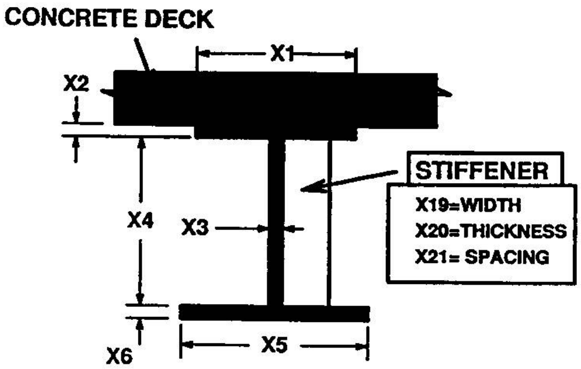

Fig. 1 Independent design variables of a steel plate girder

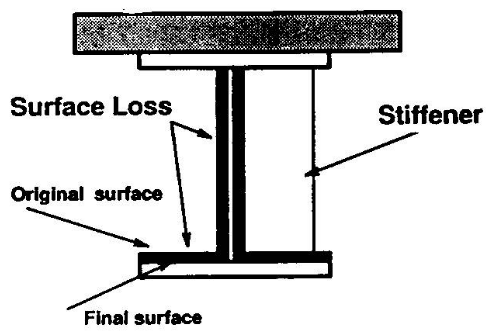

Fig. 2 Surface loss due to corrosion [2]

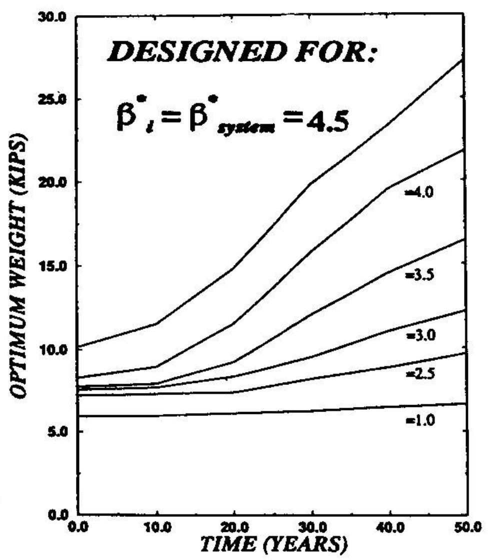

Fig. 3 Optimum girder weight vs. time; 1 kip = 4.45 kN

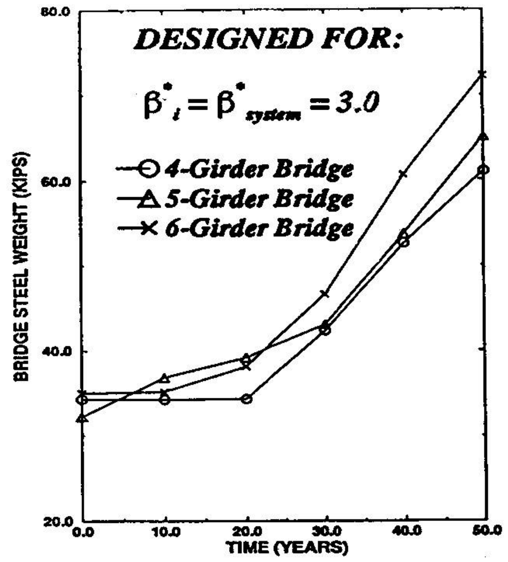

Fig. 4 Optimum bridge weight vs. time; effect of number of girders

reliability-based design of a 24.40-m span bridge. It is interesting to observe that the five-girder bridge (girder spacing = S= 2.45 m) is the best solution for the first four years, and after that the four-girder bridge (S= 3.05 m) becomes the least-weight design. The six-girder bridge (S=1.85 m) is never the optimum solution.

Second, a reinforced concrete T beam of 18.30 m span, simply supported multi-girder bridge is design according to AASHTO [4]. In this case, there are 21 design variables, X_1 to X_{21}, 12 design parameters, Y_1 to Y_{12}, and one deterministic parameter ν defining the corrosion process [9]. Nine deterministic design variables are considered independent (see Fig. 5), and eight design parameters are considered random. The time-dependent reliability-based design problem is solved considering the minimum cost as the objective. The cost is taken as $C = C_{con} + C_{st}$, where C_{st}= cost of steel and C_{con} = cost of concrete. Fig. 6 plots the optimum cost of an individual reinforced concrete T beam of the bridge versus time of exposure to corrosion for different corrosion rates. In this figure, the corrosion initiation time is t_0=3 years, the assumed ratio between the unit cost of steel to concrete is 50 (i.e., C_S/C_C=50), and the allowable reliability indices are $\beta_i^*=\beta_{system}^*$=3.0. The optimum beam cost required to maintain an imposed target reliability level increases with both exposure time and corrosion rate.

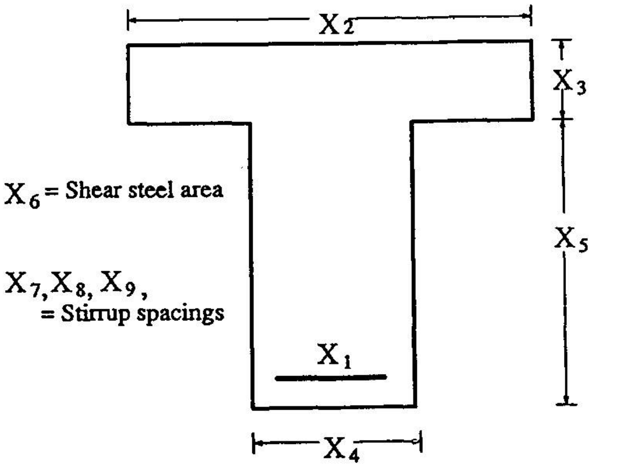

Fig. 5 Independent design variables of a reinforced concrete T beam

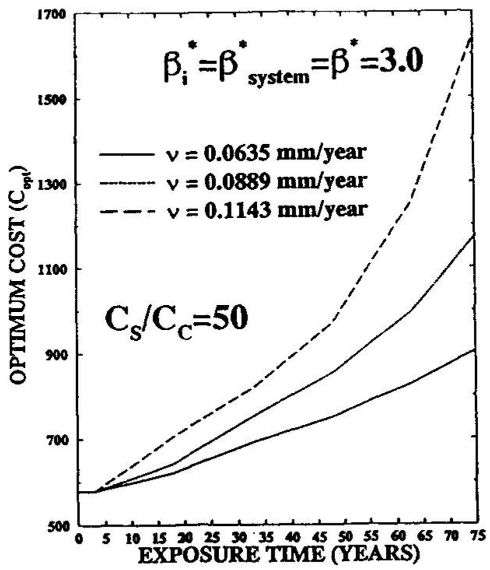

Fig. 6 Optimum beam cost vs. time for different corrosion rates

5. CONCLUSIONS

The proposed reliability-based design model capable of including deterioration constraints has permitted a reexamination of performance requirements of steel and reinforced concrete bridges. The limit state functions considered in the proposed reliability-based design approach are time-dependent. They consider explicitly the environmental effects due to corrosion. Other time-dependent effects, such as fatigue, and accidents, such as collision, need to be incorporated in reliability-based design of highway bridges. More research in this area is needed.

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