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Reliability-Based Evaluation of Existing Bridges

Appréciation de la fiabilité des ponts existants

Zuverlässigkeitsuntersuchung bestehender Brücken

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SUMMARY

Reliability is considered as a rational measure of the structural performance. The major parameters which require evaluation are random variables, in particular, load components, load distribution factors and resistance. Static and dynamic portions of live load are simulated using the available truck survey data. Resistance is modeled by simulations using the available material data. Reliability indices are calculated for girder bridges. The analysis is performed for steel girders, reinforced concrete T-beams and prestressed concrete girders. Various spans and girder spacings are considered.

RÉSUMÉ

La fiabilité est considérée comme une grandeur rationelle de la qualité structurale. Les paramètres principaux à évaluer comprennent les variables aléatoires, tout particulièrement la nature et la répartition des facteurs de charge, ainsi que la résistance de la structure. Les effets partiels statiques et dynamiques des charges mobiles sont simulés à partir de relevés des données disponibles relatives aux camions, tandis que la résistance est étudiée à partir de ceux des données disponibles relatives aux matériaux. L'auteur en déduit ensuite des indices de fiabilité pour les ponts à poutres, à savoir pour ceux à poutres en acier, en béton armé et en béton précontraint. Dans cette étude, il prend en considération la variation des portées et des entraxes de poutres.

ZUSAMMENFASSUNG

Die Zuverlässigkeit wird als rationales Mass für die Tragwerksgüte angesehen. Ihre auszuwertenden Hauptparameter sind Zufallsvariablen, insbesondere Arten und Verteilung der Einwirkungen sowie der Tragswerkswiderstand. Statische und dynamische Anteile der Verkehrseinwirkungen werden aufgrund verfügbarer Erhebungen von Lastwagendaten simuliert, der Widerstand aufgrund vorhandener Werkstoffdaten. Daraus werden Zuverlässigkeitsindizes für Trägerbrücken ermittelt, und zwar für solche aus Stahl, Stahlbeton und Spannbeton. Unterschiedliche Spannweiten und Trägerabstände werden betrachtet.

1. INTRODUCTION

Bridge evaluation is an increasingly important topic in the effort to deal with the deteriorating infrastructure. There is a need for accurate and inexpensive methods to determine the actual strength of the bridge and the actual load spectrum. The major factors that have contributed to the present situation are: the age, inadequate maintenance, increasing load spectra and environmental contamination [3,7]. The deficient bridges are posted, repaired or replaced. The disposition of bridges involves clear economical and safety implications. To avoid high costs of replacement or repair, the evaluation must accurately reveal the present load carrying capacity of the structure and predict loads.

The major parameters which affect the structural performance are loads and resistance (load carrying capacity). Bridge loads include dead load (own weight of the structural and non structural components), live load (weight of trucks), dynamic load (dynamic effects of moving trucks), environmental loads (wind, earthquake, temperature) and special forces (collisions, emergency braking). Resistance is determined by material properties, dimensions and geometry, and it depends on the method of analysis. Loads and resistance are random in nature. Their variation and uncertainty involved in the analysis can be expressed by statistical parameters. Knowledge of loads, their magnitude and frequency of occurrence, can be gained through surveys, field observations, measurements and statistical analysis. In this study, bridge load and resistance models are reviewed and a procedure is formulated for evaluation existing bridges. Structural performance is measured in terms of the reliability index.

2. BRIDGE LOAD MODEL

The basic load combination for highway bridges is a simultaneous occurrence of dead load, live load and dynamic load. The load models are developed using the available statistical data, surveys and other observations. Load components are treated as random variables. Their variation is described by two parameters: λ = ratio of mean-to-nominal and V = coefficient of variation. Existing bridges are evaluated for various periods of time, e.g. 1, 5 or 75 years. Therefore, the extreme values of loads are extrapolated from the available data base. Nominal values of load components are calculated according to the current AASHTO [1].

Dead load, D, is the gravity load due to the self weight of the structural and non structural elements permanently connected to the bridge. Because of different degrees of variation, it is convenient to consider four components of D, as shown in Table 1.

Table 2-1. Statistical Parameters of Dead Load

Component	λ	V
Factory-made members	1.03	0.08
Cast-in-place members	1.05	0.10
Asphalt (mean thickness)	90mm*	0.25
Miscellaneous	1.03-1.05	0.08-0.10

The need for a reliable truck weight data has been recognized by many bridge authorities. In this study, the load spectra are determined on the basis of truck survey data, truck counts and weigh-in-motion measurements. The data includes truck weights, axle spacings and axle loads. Multiple truck occurrence (more than one truck on the bridge simultaneously) is determined by special truck counts. Bridge performance is affected by moments and shears rather than gross vehicle weights. Therefore, the surveyed trucks were run over the influence lines to determine the moments and shears.

The development of live load model for highway bridges is described by Nowak and Hong [6] and Nowak [5]. The expected maximum live load moments and shears are evaluated for various time periods. Life time is 75 years for newly designed bridges, but 1 to 5 years for evaluation of existing structures. The measured trucks represent a statistical sample of the total number of trucks which cross a bridge in 1, 5 or 75 years. Therefore, calculation of the maximum moment (shear) for longer periods involves extrapolation of the obtained results.

The maximum effect is calculated by simulation of the actual traffic. For multiple occurrence, various truck configurations are considered: in lane and side-by-side. The analysis indicates that a lane load is governed by a single truck up to about 30-36m span. For longer spans two fully correlated trucks govern. For two lanes, the live load is governed by two fully correlated trucks (side-by-side), each being about 85% of the mean maximum 75 year truck. The actual values of the mean maximum moments and shears for various time periods also depend on traffic volume.

The statistical parameters of live load moment for various spans and for time periods 1, 5 and 75 years are presented in Table 2. The nominal value is calculated as a design moment specified by AASHTO [1], as shown in Fig. 1.

Table 2 Statistical Parameters of Live Load Moment

	Time Period					
	1 year		5 years		75 years	
Span (m)	λ	V	λ	V	λ	V
3	1.37	0.15	1.46	0.15	1.65	0.14
12	1.58	0.13	1.64	0.12	1.74	0.11
36	1.90	0.135	1.97	0.12	2.08	0.11
60	1.78	0.14	1.85	0.125	1.96	0.11

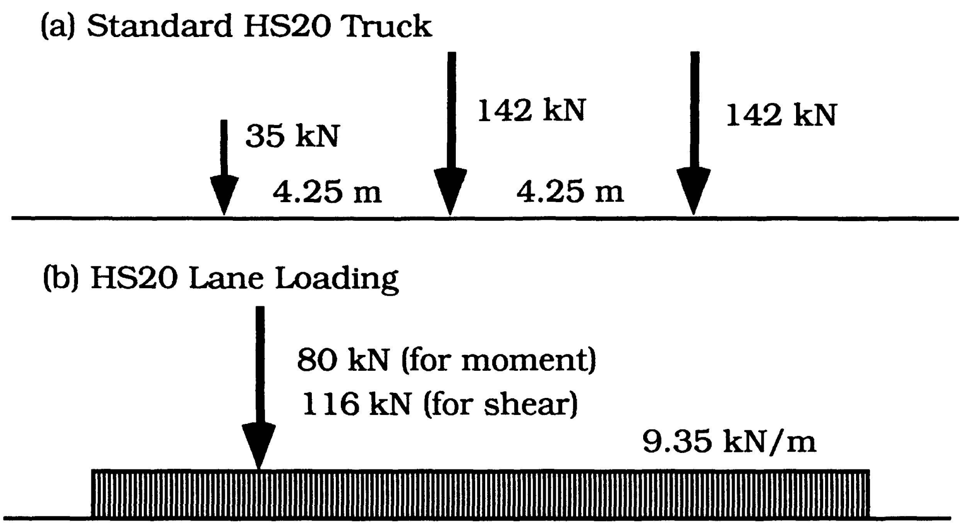

Fig. 1 AASHTO Standard Truck and Lane Loading [1].

Traditionally, the dynamic load is considered as an equivalent static load. Many codes, including AASHTO [1], specify the dynamic load as the function of span length only. However, it has been observed that the dynamic load depends on dynamic properties of the vehicle, dynamic properties of the bridge, and pavement roughness. A procedure was developed by Hwang and Nowak [2] to model the dynamic behavior of girder bridges including the three factors (pavement roughness, bridge and vehicle). The procedure was used for extensive simulations. The major parameters considered include the degree of road roughness, truck type and weight, speed, and structural type of bridge. The results indicate that the absolute value of the dynamic load component is almost constant (measured in terms of deflection). Static deflection increases with truck weight and therefore the dynamic load, as a percent of static live load, decreases for heavier trucks.

Simulations were carried out for the cases of one truck and two trucks side-by-side. The results indicate that, on average, dynamic loads do not exceed 15% of live load for a single truck and 10% for two trucks. The coefficient of variation of dynamic load is about 0.80.

3. RESISTANCE MODELS

The capacity of a bridge depends on the resistance of its components and connections. The component resistance, R, is determined mostly by material strength and dimensions. R is a random variable. The causes of uncertainty can be put into three categories:

- material; strength of material, modulus of elasticity, cracking stress, and chemical composition.
- fabrication; geometry, dimensions, and section modulus.
- analysis; approximate method of analysis, idealized stress and strain distribution model.

The resulting variation of resistance has been modeled by tests, observations of existing structures and by engineering judgment. The information is available for the basic structural materials and components. However, bridge members are often made of several materials (composite members) which require special methods of analysis. Verification of the analytical model may be very expensive because of the large size of bridge members. Therefore, the resistance models are developed using the available material test data and by numerical simulations.

In this study, R is considered as a product of the nominal resistance, R_n and three parameters: strength of material, M, fabrication (dimensions) factor, F, and analysis (professional) factor, P,

$$R = R_n \, M \, F \, P \tag{1}$$

The mean value of R, m_R, is

$$m_R = R_n \, m_M \, m_F \, m_P \tag{2}$$

and the coefficient of variation, V_R, is,

$$V_R = (V_M{}^2 + V_F{}^2 + V_P{}^2)^{1/2} \tag{3}$$

where, m_M, m_F, and m_P are the means of M, F, and P, and V_M, V_F, and V_P are the coefficients of variation of M, F, and P, respectively.

The statistical parameters are developed for steel girders, reinforced concrete T-beams, and prestressed concrete AASHTO-type girders. The results are presented in Table 3.

Table 3 Statistical Parameters of Resistance

Type of Structure	F M		P		R	
	λ	V	λ	V	λ	V
Non-composite steel girders						
Moment	1.095	0.075	1.02	0.06	1.12	0.10
Shear	1.12	0.08	1.02	0.07	1.14	0.105
Composite steel girders						
Moment	1.07	0.08	1.05	0.06	1.12	0.10
Shear	1.12	0.08	1.02	0.07	1.14	0.105
Reinforced concrete						
Moment	1.12	0.12	1.02	0.06	1.14	0.13
Shear	1.13	0.12	1.075	0.10	1.20	0.155
Prestressed concrete						
Moment	1.04	0.045	1.01	0.06	1.05	0.075
Shear	1.07	0.10	1.075	0.10	1.15	0.14

4. RELIABILITY ANALYSIS

The available reliability methods are presented in several publications e.g. [4, 8]. In this study the reliability analysis is performed using Rackwitz and Fiessler procedure. The reliability index, β, is defined as a function of P_F,

$$\beta = - \Phi^{-1}(P_F) \qquad (4)$$

where Φ^{-1} = inverse standard normal distribution function.

There are various procedures available for calculation of β. These procedures vary with regard to accuracy, required input data and computing costs. The simplest case involves a linear limit state function. If both R and Q are independent (in the statistical sense), normal random variables, then the reliability index is,

$$\beta = (m_R - m_Q)/(\sigma_R^2 + \sigma_Q^2)^{1/2} \qquad (5)$$

where m_R = mean of R, m_Q = mean of Q, σ_R = standard deviation of R and σ_Q = standard deviation of Q.

If both R and Q are lognormal random variables, then b can be approximated by

$$\beta = \ln (m_R/m_Q)/(V_R^2 + V_Q^2)^{1/2} \qquad (6)$$

where V_R = coefficient of variation of R and V_Q = coefficient of variation of Q. A different formula is needed for larger coefficients of variation.

If the parameters R an Q are not both normal or lognormal, then the formulas give only an approximate value of β. In such a case, the reliability index can be calculated using Rackwitz and Fiessler procedure, sampling techniques or by Monte Carlo simulations. Rackwitz and Fiessler [4, 8] developed an iterative procedure based on normal approximations to non-normal distributions at the so called design point. The design point is the point of maximum probability on the failure boundary (limit state function). The procedure has been programmed and calculations are carried out by the computer.

5. RELIABILITY INDICES FOR SELECTED BRIDGES

The calculations are performed for a selected set of girder bridges. The selection was based on material, span, number of girders and girder spacing. For the selected bridges, moments and shears are calculated due to dead load components, live load and dynamic load. Nominal (design) values are calculated using AASHTO [1]. The mean maximum values of live load are obtained using the statistical parameters given in Table 1 and 2. Resistance is calculated in terms of the moment carrying capacity. For each case, two values of the nominal resistance are considered: R_{actual}, the actual as-built load carrying capacity and R_{min}, the minimum required resistance which satisfies the AASHTO [1]. In general, R_{actual} is larger than R_{min}. The basic design requirement is expressed in terms of moments as follows [1],

$$1.3\, D + 2.17\, (L + I) < \phi R \qquad (7)$$

where D, L and I are moments due to dead load, live load and impact, R is the moment carrying capacity, and ϕ is the resistance factor, ϕ = 1.00 for steel and prestressed concrete girders, and 0.90 for reinforced concrete T-beams. The ratio of R_{actual} / R_{min} is an indication of overdesign and it is about 1.5 for steel girders and about 1.1 for prestressed concrete girders.

The selected bridges do not cover a full range of spans and other parameters. Therefore, additional bridges are designed as a part of this study. The analysis is focused on girder bridges with spans from 9 to 60 m. Five girder spacings are considered: 1.2, 1.8, 2.4, 3.0 and 3.6 m. Typical cross sections are assumed. In all considered cases, the actual resistance, R_{actual}, is made equal exactly to R_{min} (the sections are neither overdesigned nor underdesigned).

The reliability indices are calculated for girder bridges described by the representative load components and resistance. The results are presented in Fig. 2-4 for steel girders, reinforced concrete T-beams and prestressed concrete girders.

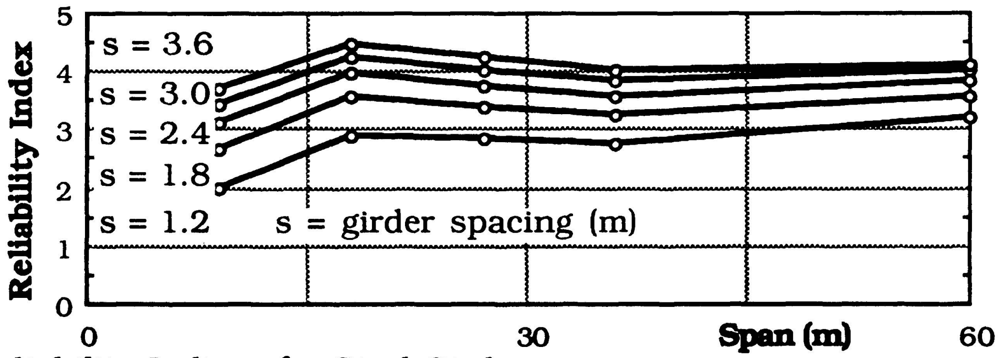

Fig. 2 Reliability Indices for Steel Girders.

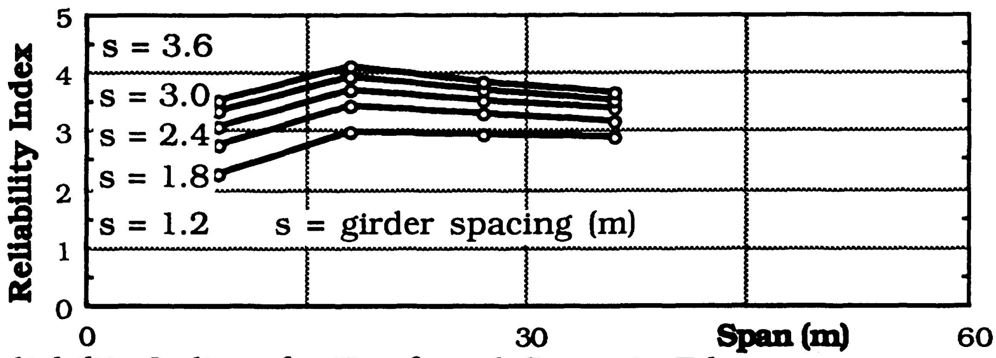

Fig. 3 Reliability Indices for Reinforced Concrete T-beams.

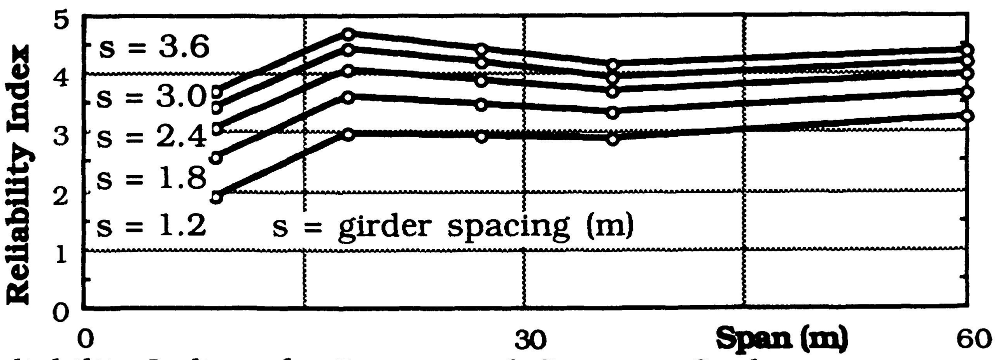

Fig. 4 Reliability Indices for Prestressed Concrete Girders.

6. CONCLUSIONS

The reliability index can be used as an objective measure of structural performance of an existing bridge. The calculation requires the knowledge of site-specific load and resistance parameters. Load parameters can be determined by truck surveys. Resistance depends on the degree of deterioration (e.g. corrosion). The statistical parameters for a general case are presented in Tables 1-3.

Reliability indices are calculated for typical girder bridges, designed using AASHTO [1]. The results show a considerable degree of variation depending on girder spacing, material and span length. This is a clear indication that the current design provides a higher safety reserve for larger girder spacings and spans about 20 m.

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REFERENCES

1. AASHTO, "Standard Specifications for Highway Bridges" American Association of State Highway and Transportation Officials, Washington, D.C., 1989.

2. HWANG, E.S. and NOWAK, A.S., "Simulation of Dynamic Load for Bridges", ASCE Journal of Structural Eng., Vol. 117, No. 5, May 1991, pp. 1413-1434.

3. KONIG, G. and NOWAK, A.S., ed., "Bridge Rehabilitation", Ernst & Sohn, Berlin, Germany, 1992.

4. MELCHERS, R., "Structural Reliability, Analysis and Prediction", Ellis Horwood Limited, Chichester, 1987.

5. NOWAK, A.S., "Calibration of LRFD Bridge Design Code", Report, Department of Civil and Env. Eng., University of Michigan, Ann Arbor, Mi, May 1992.

6. NOWAK, A.S. and HONG, Y.K., "Bridge Live Load Models", ASCE Journal of Structural Engineering, Vol. 117, No. 9, September 1991, pp. 2757-2767.

7. NOWAK, A.S., ed., "Bridge Evaluation, Repair and Rehabilitation", Kluwer Academic Publishers, Vol. 187, Dordrecht, Netherlands, 1990.

8. THOFT-CHRISTENSEN, P. and BAKER, M.J., "Structural Reliability Theory and Its Applications", Springer-Verlag, New York 1982.