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Probabilistic Load Modelling for Bridge Fatigue Studies

Modèle probabiliste de chargement pour l'étude de la fatigue dans les ponts

Probabilistische Belastungsmodelle zur Untersuchung der Ermüdungsfestigkeit von Brücken

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SUMMARY
A reliability (safety index) model is presented to provide consistent levels of fatigue safety for steel girder bridges. An accurate truck loading spectra is required, however, for such probabilistic-based design. A weigh-in-motion system is described using highway girders as equivalent static scales which monitor truck weights without detection. Its implementation at more than fifty sites in the United States demonstrates that accurate truck data for bridge loading spectra and other planning needs is feasible.

RESUME
Un modèle de fiabilité (indice de sécurité) est présenté afin de prévoir les différents niveaux de sécurité à la fatigue des ponts à poutres métalliques. La connaissance précise du spectre des charges de camions est nécessaire pour un tel calcul probabiliste. On décrit un système de mesures utilisant les poutres-maîtresses du tablier comme balance pour le pesage des camions en mouvement. Son utilisation sur plus de cinquante sites aux Etats-Unis a démontré qu'il était possible d'obtenir des données précises relatives aux charges de camions pour les spectres de chargement de ponts ou pour tout autre besoin.

ZUSAMMENFASSUNG
Ein Zuverlässigkeitsmodell (Sicherheitsindex), das entsprechende Sicherheitsniveaus gegen Ermüdungsbruch liefert, wird vorgestellt. Für eine auf der Wahrscheinlichkeitstheorie aufgebaute Berechnung benötigt man aber ein genaues Lastenspektrum. Ein System wird beschrieben, das Lastwagengewichte während der Fahrt unbemerkt überprüft, indem die Brückenträger als Waagen dienen. Dieses System wurde an mehr als 50 Brücken in den USA angewendet und hat gezeigt, dass genaue Lastwagendaten für Brückenbelastungsspektren oder andere Planungszwecke erfasst werden können.

1. INTRODUCTION

An important part of the probabilistic criteria of safety is the loading description. Recent implementation of fatigue specifications for steel highway bridges incorporated load spectra, laboratory data on welded attachments and field observations of stress histories [1]. The influence of fatigue specifications on short and medium span steel bridges is considerable affecting both main girder sizes and attachments used. In the United States the load spectra was based on distributions of truck weights and field measurements of stresses [2]. In particular, the fatigue life distribution is significantly influenced by the extreme tail of the load histogram. Several studies at Case Institute investigated fatigue loading on bridges and probabilistic based design methodology [3,4]. Ten steel bridges were instrumented with over 10,000 truck passages monitored for bridge response including stress ranges at critical locations and truck loading patterns including speed, lane and interval spacing [5]. Because of the importance of the heavy end of the truck weight spectra a weigh-in-motion system was developed and is described herein. The need arises because heavy vehicles exceeding the legal weight laws often avoid permanent and temporary weigh scales. The system obtains accurate and economical weight spectra in an undetected manner [6]. Such information can be incorporated in a probabilistic load model and also in a safety index or reliability formulation of bridge fatigue [7,8]. These approaches are described herein.

2. HIGHWAY BRIDGE FATIGUE MODEL

Using several assumptions a simple bridge fatigue model can be developed. These include: a) each truck passage produces one cycle of stress range amplitude, b) the number of stress cycles is the expected truck volume, c) the relationship between calculated nominal stress from design loads and formulae and the actual nominal stresses at attachments can be estimated from field studies, d) gross vehicle weight distributions can be directly transformed into load effects (moment, shear, etc.) distributions and e) a linear damage sum is applicable to fatigue damage prediction.

A commonly used probabilistic safety formulation is to assign random variables to resistance, R, and loading, S, and express the reliability measure as a safety index, β, in terms of means ($\bar{R}$ and $\bar{S}$) and coefficients of variation (V_R and V_S). In the present model the load (S) uncertainties are the bending moment due to a single vehicle (M), load amplifications due to closely spaced vehicles (h), analysis uncertainty (g), impact (I) and section property (S_x). The loading, S, may be conveniently expressed as:

$$S = \frac{MghI}{S_x} \tag{1}$$

The equivalent resistance may be obtained by setting the expected fatigue damage sum D equal to 1.0 where the damage may be expressed from the stress range spectra as:

$$D = \frac{V}{A} \Sigma S_i^3 \ f(S_i) \tag{2}$$

where V is the lifetime truck volume or number of cycles, $f(S_i)$ is the frequency of occurence of stress range S_i and A is the fatigue life intercept of the particular weld attachment. Since stress is assumed proportional to vehicle weight we can substitute for the weight distribution $f(W_i)$ from:

$$S_i = W_i \frac{R}{W_n} \qquad (3)$$

where R is the design resistance corresponding to the nominal design vehicle W_n (or its equivalent if using distributed uniform loading models rather than the vehicle loading typical in North American practice [9]).

Expressing the vehicle weight distribution by a single equivalent fatigue loading value, L, as:

$$L = \Sigma \left[\frac{W_i}{W_n}\right]^3 f(W_i) \qquad (4)$$

a loading average with a cubic (fatigue slope) weighting function. Substituting Equations (3) and (4) into Equation (2) with damage, D = 1 gives:

$$R = \left[\frac{A}{LV}\right]^{1/3} \qquad (5)$$

The resistance, R, in Equation 5 is the stress which gives an expected damage D = 1 with the load spectral distribution L, truck volume V and fatigue attachment constant A. L, V and A are the random variables associated with resistance R and M, g, h, I and S_x are random variables of loading S. Other arrangements of the variables are possible and should give similar reliability conclusions especially if advanced level II calculations are performed. For convenience the safety index can be defined from a typical lognormal format as:

$$\beta = \frac{\mathrm{Ln}\,\frac{\bar{R}}{\bar{S}}}{\sqrt{V_R^2 + V_S^2}} \qquad (6)$$

The means and coefficients of R and S may be derived from Equation 1-5 [4]. Data for the random variables are available from field measurements, traffic studies and laboratory tests. A previous study by the author and his collegues showed that AASHTO based designs have typical safety indices in the range of 1.5 to 3.0 for redundant components and 50 year lives [4,8]. Higher β's occur for nonredundant components for which AASHTO permits lower stress ranges [9]. The study showed that with some revisions a consistent array of β's for different component designs could be achieved. For example, the allowable stress range should be made a continuous function of truck volume instead of discrete volume categories as presently in some codes such as AASHTO. Further, the nominal loading should coincide with a representative vehicle with expected dimensions and axle load percentages instead of a variable wheel base vehicle. Safety indices for nonredundant structures should be based on risk models which integrate load probability occurrences over a range of damage initiating from component failure to complete collapse [7].

3. WEIGH IN MOTION STUDIES

An important consideration in bridge and pavement design affecting strength and fatigue is the extreme vehicle loadings. The load distribution variable

L in Equation 4 is strongly affected by the heavy tail portion of the vehicle weights. In developing the AASHTO load specification data was used from typical traffic survey studies [2]. Heavy trucks, however, will try and avoid such scales because of the legal penalties assigned to overweight vehicles. By-pass roads and CB radios make such avoidance relatively easy in most situations.

In recent years a number of research organizations all over the world have participated in developing pavement scales for weigh-in-motion operations. This involves setting a small scale or plate even with the pavement whose response to passing tires could be monitored and calibrated with static axle weights. The author and his collegues reviewed such operations and concluded that the dynamic impact is the major limitation of pavement scales. [10]. The typical scale "sees" an instantaneous axle load for only several milliseconds while it is fully supported on the scale. This time represents only a small portion of the tire force oscillation period. Due to normal pavement roughness and possibly a "bump" caused by the scale itself the force oscillation could easily be 30-40% of the static value and introduce erroneous predictions. One solution attempted is multiple scales in series and averaged, but this increases the chances for equipment malfunction. If properly resurfaced the pavement scales may be adequate for general statistical trends, but mostly they have been installed at busy loadometer stations where truck speeds can be controlled. However, the problem of avoidance remains.

As a consequence of such difficulties with pavement scales the author and his collegues extended the bridge stress measurement field program to encompass weight calculations [10,11]. The system developed has reached the stage of relatively routine application by the Ohio Department of Transportation and the Federal Highway Administration to obtain accurate truck weight spectra [6,12]. It has been used thus far to monitor truck weights at more than 50 sites.

3.1 A Highway Bridge "Scale"

The weigh-in-motion system being described utilizes existing highway bridges to serve as equivalent static scales. Trucks move at normal speeds and are unaware of the weighing operation. Traffic tapeswitch detectors (narrow strips) are bonded to the pavement and provide the vehicle's velocity and axle dimensions (also, the vehicle spacings if needed for a bridge loading study). Strain gages contained within reuseable transducers are clamped at bridge midspans to steel flanges or bolted to concrete girders to provide strain response during a vehicle passage across the bridge. By matching the strain response with predictions based on the vehicle's axle spacing and speed, the axle weights of the truck can be found [13]. In fact, a 40-80 HZ strain sampling rate is used and a least square algorithm has been derived to more accurately calculate the axle weights. It applies an inverse-type analyses in which the structure response (strain record) is known and the loads (truck axle weights) are computed. To establish an accurate relationship between strains and truck weights a calibration vehicle of known weight is used. All monitoring instrumentation and portable electric power is contained in an instrument van parked discretely underneath or some distance away from the bridge.

3.2 Accuracy

To date, more than 50 sites have been monitored including simple span and continuous steel girder bridges (40-120' typical) and reinforced and prestressed concrete girders in all parts of the United States. Because of the small girder strains normally encountered the reuseable strain transducers described above were designed to mechanically magnify the strain [14].

The system accuracy has been verified in several ways:
a). Repeatability - By repeated weighing of the calibration truck a measure of the system performance can be achieved. The standard errors in such tests is usually less than 3%. In some instances the scatter with weigh in motion has been smaller than with repeated weighings at fixed static scales.
b). One to One Comparison with Static Scales - In several tests the weigh-in-motion has been set-up near existing static scales. Such monitoring has enabled direct comparisons for relatively large number of vehicles. The results show very good agreement for gross weights with standard errors less than 10%, though as indicated above the source of the differences is sometimes questionable, whether it is in the static or weigh-in-motion values. The observed differences for individual axle weights is larger than for gross weight as would be expected since the bridge behavior acts as a filter responding to the gross truck weight more greatly than individual axles. Nevertheless, by properly choosing bridge dimensions good agreement with static axle weights has been achieved.

The predictions are also unbiased which means that for fatigue calculations it provides a very accurate prediction of the load spectra.

3.3 Future Tests

With the verification of the weighing concept a new tool is available to accurately determine an unbiased histogram of vehicle weights for fatigue analysis. The system is easily installed and the generally large number of available test bridges means that bridge engineers can inexpensively and quickly determine a full range of truck movements. With some modifications the system may also aid enforcement planning since recent software changes reported by Moses and Ghosn [14] permit real-time calculation and display of the truck weights.

At present, the system monitors a single lane or two lanes independently. Tests planned will also involve multilane measurements to specifically monitor closely spaced vehicle combinations. Although, these events may be unimportant for fatigue or some planning studies they are important for developingprobabilistic models of ultimate load conditions. This information could be in corporated in reliability evaluation of ultimate strength criteria [15].

The instrumentation described herein may also be used to correlate the truck loads with bridge stresses at fatigue sensitive attachment locations. Such strain history records of in-field behavior could subsequently become the input to laboratory testing programs for bridge components. By correlating truck weights and traffic to the measured stresses a convenient method of extrapolating field data to a variety of site conditions can be achieved. Further, some of the assumptions and results of the fatigue reliability model can be verified.

4. CONCLUSIONS

- 1. Fatigue predictions based on probabilistic analysis require accurate models of load spectra. Frequency of occurence of heavy vehicle loads and vehicle combinations (headway) are needed in reliability prediction models. Partial safety factors can then be derived to obtain consistent reliabilities for different weld attachments and expected truck weights and traffic volumes.

System models should also be derived to produce consistent factors for redundant and nonredundant behavior.

- 2. Current truck weight statistics may not be accurate because of avoidance of public scales by overweight vehicles. A weigh-in-motion system has been described which is now being implemented. It utilizes highway bridges as equivalent scales and can monitor heavy trucks without detection. Its use in the United States at more than 50 sites demonstrates that accurate weight data can be obtained.

- 3. Reliable truck weight data should be assembled and put into a loading model applicable to repeated loadings (fatigue) and maximum lifetime load (limit state design). The observed loadings should be related to legal, permit and rating loads to obtain consistent reliability levels for each application.

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6. REFERENCES

1. FISHER, J.W., "Bridge Fatigue Guide", American Institute of Steel Construction, 1977.

2. GALAMBOS, C.F., "Highway Bridge Loadings", Public Roads, Vol. 43, No. 2, September, 1979.

3. MOSES, F., and GOBLE, G.G. and PAVIA, A., "Applications of a Bridge Measurement System", Transportation Research Record 579, 1976, Washington, D.C.

4. MOSES, F. "Bridge Loading Spectra and Fatigue Design", ASCE National Meeting, New Orleans, April, 1975.

5. GOBLE, G.G., MOSES, F., and PAVIA, A., "Field Measurements and Laboratory Testing of Bridge Components", Report No. Ohio-DOT-08-74, Dept. of Civil Engineering, Case Institute, Cleveland, Ohio, January, 1974.

6. MOSES, F., "Weighing Trucks-In-Motion Using Instrumented Highway Bridges", Proceedings 1980 Ohio Transportation Engineering Conf., Columbus, Ohio, April, 1980.

7. MOSES, F., "Reliability Analysis of Highway Bridge Vehicle Loadings", ASCE National Convention, Portland, April, 1980.

8. MOSES, F. "Probabilistic Approaches to Bridge Design-Loads", Transportation Research Record 711, 1979, Washington, D.C.

9. AASHTO, "Standard Specifications for Highway Bridges", American Association of State Highway Officials, 1977.

10. MOSES, F. and GOBLE, G.G., "Feasibility of Utilizing Highway Bridges to Weigh Vehicles in Motion", Federal Highway Administration, FHWA-RD-75-33, Nov. 1974, Washington, D.C.

11. MOSES, F. and KRISS, M. "Weigh-In-Motion Instrumentation" Federal Highway Administration, FHWA-RD-78-81, June, 1978. Washington, D.C.

12. LIKINS, G. et.al, "Loading Spectrum Experienced by Bridge Structures in the United States", Report in progress, Bridge Weighing Systems, Cleveland, Ohio, 1982.

13. MOSES, F. "Weigh-In-Motion System Using Instrumented Bridges", Journ. of the Transportation Division ASCE, Vol. 105 TE3, April, 1979.

14. MOSES, F. and GHOSN, M., "Weighing Trucks-In-Motion Using Instrumented Highway Bridges", Report to Ohio Department of Transportation, Dept. of Civil Engineering, Case Institute, Cleveland, Ohio, 1981.

15. MOSES, F. and GHOSN, M., "Requirements for a Reliability-Based Bridge Code", ASCE National Meeting, October, 1981, St. Louis.

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