Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 13 (1973)

Artikel: Structural safety of steel highway bridges subjected to repeated vehicle loads

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DOI: https://doi.org/10.5169/seals-13784

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Structural Safety of Steel Highway Bridges subjected to Repeated Vehicle Loads

Sécurité des pont-routes en acier soumis à des charges de trafic répétées

Tragwerksicherheit von Stahl-Autobahnbrücken unter wiederholter Fahrzeugbelastung

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1. Introduction

Recently, several probabilistic studies on stresses at main girders of highway bridge subjected to repeated moving loads, have been published. The present study is based on a different concept from past studies, and is intended to estimate the distribution of peak stress frequency at a main girder, taking into account statistic factors on traffic flow. Numerical examples for model bridges demonstrate practicability of the proposed analysis for static and fatigue failurs.

2. Estimation of Working Stresses

It is assumed that an effect of the high frequency components of a stress wave is covered by an impact coefficient and that local minimum stresses can be disregarded. When a sequence of concentrated loads , $P_1, \cdots\cdots, P_N$, moves at a uniform speed, V , on a simple beam as shown in Fig. 1, a bending moment, $Y(t)$, at the span center, A , and at a time, t , is presented by an influence line shown in the figure, as follows:

$$Y(t) = \sum_{i=1}^{N} (P_i \cdot a_i) \qquad (1)$$

If a load P_J is at the span center as shown in Fig. 1, the occurrence of peak value will be given on the following condition:

$$\left| \sum_{i=1}^{I} P_i - \sum_{i=K}^{N} P_i \right| < P_J \qquad (2)$$

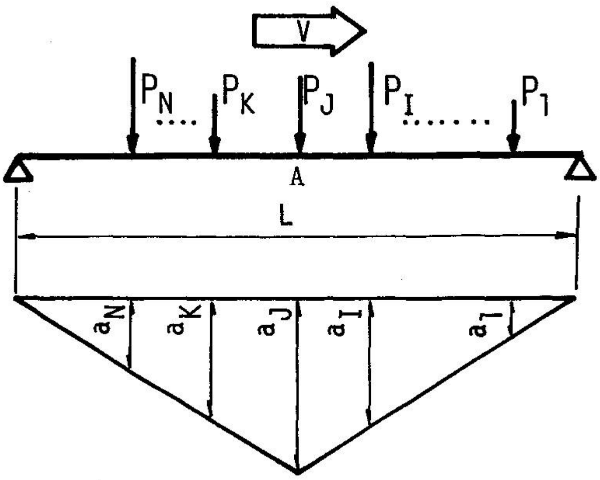

Fig. 1 A Sequence of Moving Loads and Influence Line

Then, the following mathematical amounts should be computed for distribution of peak stress: the probability density function of P_J, $P_J \cdot a_J$ and $\sum_{i=1}^{N}(P_i \cdot a_i)$; the joint probability density function of $\sum_{i=1}^{I} P_i$ and $\sum_{i=1}^{I}(P_i \cdot a_i)$, $\sum_{i=K}^{N} P_i$ and $\sum_{i=K}^{N}(P_i \cdot a_i)$, and $\left| \sum_{i=1}^{I} P_i - \sum_{i=K}^{N} P_i \right|$ and $\sum_{i=1}^{I}(P_i \cdot a_i) + \sum_{i=K}^{N}(P_i \cdot a_i)$.

3. Models of Traffic Flow and Models of Highway Bridges

(1) Traffic flow: Actual measurements of wheel loads of a vehicle have been reported, but are a few ones published on the measurements of total weight of vehicles. Fig. 2 shows one of them[1] in Japan. It is assumed that the distribution of vehicle total weight can be expressed by the superposition of the three kinds of normal distribution corresponding to each vehicle group. The combination ratio and distribution pattern illustrated in Table 1, as a standard example, are selected so that the excesses probability may have an inclination to coincide generally with, and to be somewhat larger than, the actual measurements shown in Fig. 2. The Probability, $p(i)$, that the number of moving vehicles covering the length of $L/2$ is i , is expressed by the following equation, on the assumption that the probability density function of headway follows the exponential function of $\mu=0.02i$:

$$p(i)=(\mu L/2)^{i}\, e^{-\mu L/2} / i! \quad (3)$$

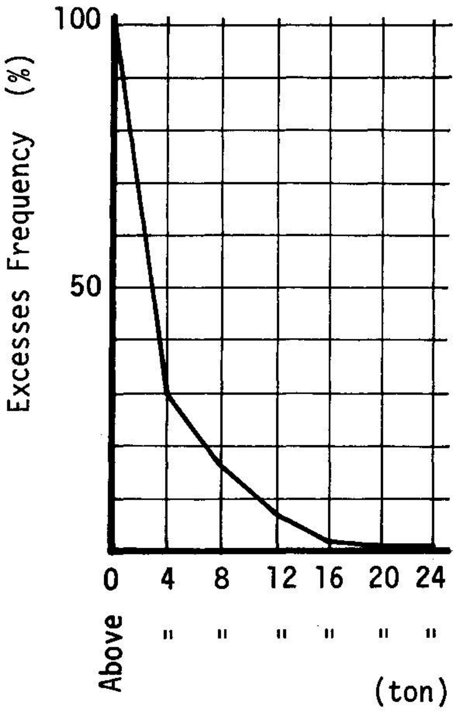

Fig. 2 Excesses Frequency of Vehicle Total Weight

Table 1. Standard Examples for Distribution of Vehicle Total Weight

Vehicle	Average Weight (tons)	Standard Deviation of Weight (tons)	Combination Ratio
Heavy Trucks	20	6.0	0.02
Light Trucks	10	4.0	0.23
Passenger Cars	2	1.2	0.75

(2) Highway bridge models illustrated for study are the standard composite girder bridges in Japan as shown in Table 2. Stress calculations are made for a lower flange at the span center as a representative member. The 1st class bridge is designed for 20-tons trucks, and the 2nd class is for 14-tons trucks. The assumption is made that simultaneously loaded vehicles are 5 numbers for 40 m span and 3 for

24 m with the occupying length of 8.0 m, and are concentrated loads independent from each another.

Table 2. Models of Highway Bridge

Notation	Class	Width (m)	Span Length (m)	Girder	Dead Load Stress (kg/cm2)
ST-1	1st	6.0	40.0	Outside	1108
ST-2	1st	6.0	40.0	Inside	1045
ST-3	1st	6.0	24.0	Outside	888
ST-4	1st	6.0	24.0	Inside	840
ST-5	2nd	6.0	24.0	Outside	1122

4. Material Properties

The static strength[2] of the steel SM50 for representative members of the model bridge is expressed by its yielding stress, the distribution pattern of which is represented by the lognormal distribution, and the mean value is 3750 kg/cm^2 and the coefficient of variation of which is 0.08. The fatigue strength[3] of the steel SM50 is expressed by the time strength, the distribution of which is of the lognormal one, the median value of which at 2×10^6 numbers of loading cycles is 1500 kg/cm^2. An inclination of the *S-N* curve for the material is deterministic and its mean value is 6.0, and the standard deviation of logarithmic fatigue life is 0.25 .

5. Calculation Results for Distribution of Peak Stress

Results of the calculations of excesses probability of the stress due to live load and impact at the model bridges ST-1∼5 are summarized in Fig. 3 .

In the calculation, the excesses probability is taken one for outside girders when a vehicle passes through the span center on the lane right above the girders, and it is taken one for inside girders when a vehicle passes through the span center on either lane.

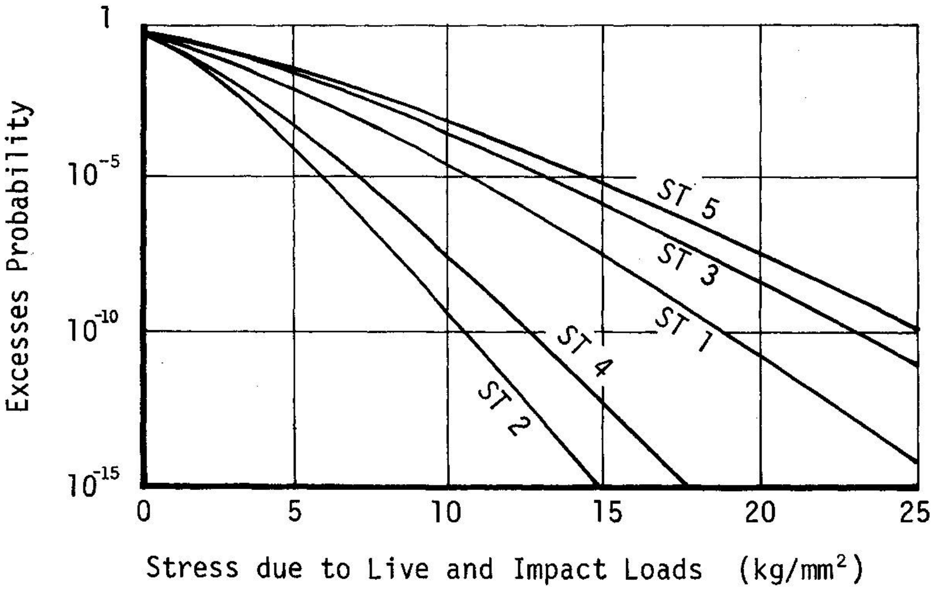

Fig. 3 Calculation Summary for Peak Stress Distribution

6. Equation for Probability of Static Failure

When loads are applied either in equal intervals or at prescribed time instants so that the life of the structure can be measured in terms of the number,

n, of load application, and if the resistance, R, is a random variable, the case considered in which the distribution functions $F_S(y)$ of applied load S, and $F_R(x)$ of R, are time invariant, implying that all the loads, S, applied in sequence belong to one and the same distribution and the material and structure suffer no deterioration. Then, the probability of failure of a structure, p_{fn}, resulting from a series of n load applications, is expressed as, with the density function, $f_R(x)$, of R :

$$p_{fn} = \int_0^\infty f_R(x)\{1 - (F_S(x))^n\}\,dx . \tag{4}$$

7. Equation for Probability of Fatigue Failure

(1) Rule of fatigue damage accumulation : The most widely known and used procedure for cumulative fatigue damage is the linear damage rule commonly referred to as the Miner rule. Also, various methods have been proposed[4)] as alternative to the linear damage rule. Since the proportion of too small stresses to the total actual stress is large, instead of the standard S-N relationship, the modified linear damage rule be applied to the present situation.

(2) Assumption for calculation: The S-N curve reaches the fatigue limit at $2\text{x}10^6$ cycles of loading and it takes a horizontal line for $N > 2\text{x}10^6$ numbers of cycle. Scattering of the fatigue limit will be expressed in terms of the scattering of time strength or fatigue life. The slope, θ, of a sloping portion of the S-N curve may be taken deterministic. The minimum stress due to dead load may be assumed to be deterministic and its correction may be made in the modified Goodman diagram.

(3) Equation for the probability for fatigue failure is, then , obtained as follows:

$$p_f = P_r\left(\sum_{i=1}^{n} \frac{S_i^\theta}{N_0 S_0^\theta} > 1\right) , \tag{5}$$

where S_i = a stress due to i-th loading, N_0 = a fatigue life expectancy to the stress S_0, and θ = a slope of the S-N curve. Eq. (5) presupposes that the S-N curves are presented as straight lines on a log-log plot, and that the modified linear damage rule is valid. The number N of cycle of loading can be treated as deterministic, because, as the result of great number of repetition of measurement for traffic volume per day, the distribution of day traffic volume will be given. Since the number of loading on a highway bridge during its useful life is very large, randomness of $\sum_{i=1}^{n} S_i^\theta$ is not taken into account. With the above discussion, Eq. (5) will be transformed into

$$p_f = P_r\left(\frac{N}{N_0 S_0^\theta}\int_0^\infty S^\theta f(S)\,dS > 1\right) , \tag{6}$$

where N_0 = the number of repetition to failure due to independent loading of a stress level S_0 (probabilistic), S_0 = the standard stress level (probabilistic), S = a stress level due to live load and impact (probabilistic), $f(S)$ = the probability density function of S .

Then, the further transformation will give $p_f = \int_0^C f_{N_0}(x)\,dx$, (7)

where f_{N_0} = the probability density function of fatigue life between zero to tension, $0 \sim S_0$, and $C = \frac{N}{S_0^\theta} \int_0^\infty S^\theta f(S)\,dS$.

8. Presentation of Calculation Results

With the numerical values for strength factor given at the Chapter 3, the probability of failure, p_f , for static failure and fatigue failure can be calculated by Eqs. (4) and (7), respectively. The calculation results of p_f are summarized in Fig. 4, with chainlines for the static failure and full lines for the fatigue failure.

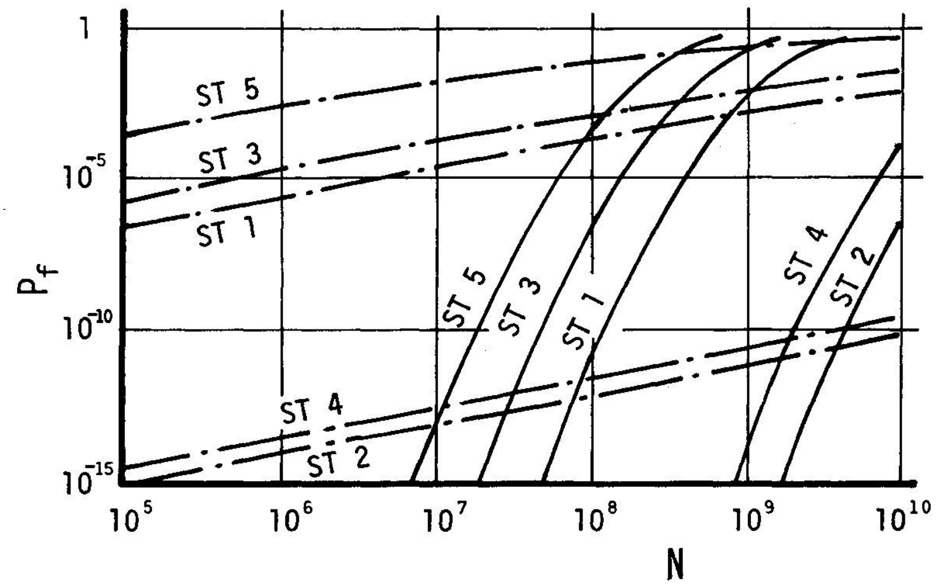

Fig. 4 Probability of Failure of Main Girders

Among the models, the case of ST-5 indicates the largest values for the both of the failures, and ST-3, ST-1, ST-4 and ST-2 show smaller values in this order, corresponding to the amount of the excesses probability of peak stress. It is known that, at the case of ST-5, the static failure is governing for the number of loading less than 6×10^8 and the fatigue failure has a priority for the number larger than that. Such a feature can be seen also at the rest cases, but the case of ST-1 will be governed practically by the static failure.

9. Conclusions

At the present study, a method of stress estimation for the safety of main girders of a highway bridge, is proposed, and its fundamental concept is discussed and the calculation method is given. Also it is pointed out that application of the stress estimation method to actual highway bridges can reflect the actual condition fairly well. Taking into consideration the traffic flow factors such as vehicle weight distribution and vehicle headway distribution, the probability of static failure and fatigue failure of main girders at five simple-supported composite beam highway bridges, is calculated for illustration. As a result, it is known that the static failure governs the safety of illustrated girder models under the condition of the traffic volume of, for example, about 10,000 vehicles per day and of the useful life of about 50 years, rather than the fatigue failure.

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SUMMARY

In order to appraise the structural safety of a main girder of a steel highway bridge subjected to a great number of repetition of variable vehicle loads under a service condition, a probabilistic method for estimating working girder stresses is proposed, together with a basic safety concept and numerical examples. The method makes it possible to estimate the frequency distribution of peak stresses working at main girders, taking into consideration statistical factors on traffic flow, in addition to probabilistic variation of material properties.

RESUME

On présente dans ce travail une méthode probabiliste pour estimer les contraintes à la fatigue dans les poutres maîtresses, associée à un concept de base de la sécurité et à des exemples numériques pour déterminer la sécurité structurale d'une poutre maîtresse d'un pont-route en acier soumis à un grand nombre de charges variables répétées. Cette méthode permet d'estimer la distribution de la fréquence des pointes de tensions dans les poutres maîtresses, en considérant des facteurs statistiques sur le flux de trafic et une variation probable des propriétés du matériau.

ZUSAMMENFASSUNG

Um die Tragwerksicherheit eines Hauptträgers einer Autobahnbrücke aus Stahl bei vielen Wiederholungen von verschiedenen Fahrzeugbelastungen unter Betriebsbedingungen abzuschätzen, wird eine wahrscheinlichkeitstheoretische Methode zur Schätzung der Betriebsbeanspruchungen in den Trägern, zusammen mit einem grundlegenden Sicherheitskonzept und numerischen Beispielen vorgeschlagen. Die Methode ermöglicht die Abschätzung der Frequenzverteilung der Spitzenspannungen in den Hauptträgern unter Berücksichtigung statistischer Faktoren des Verkehrsflusses, zusätzlich zu der wahrscheinlichkeitsbedingten Variation der Materialeigenschaften.