III

On Fatigue Damage Estimation of Railway Bridge Members Through Actual Train Loading

Sur l'estimation des dommages causés aux éléments de ponts-rails par la fatigue due aux essieux

Über die Schätzung von Ermüdungsschäden an Eisenbahnbrücken-Teilen durch Zuglasten

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INTRODUCTION

The major load acting on railway bridges is the train load which makes a short-term variation. Its amplitude of variation is considerably wide, therefore in discussing the safety of railway bridge members it is important to consider not simply the maximum value of load but also the decline of strength due to repeated loading, i.e., the fatigue damage. It is for this reason that in many countries the specifications or codes for designing the railway bridges set an allowable unit stress for fatigue in bridge members, and information on how to decide the safe limit of fatigue strength is being eagerly sought by engineers.

Fatigue life depends on the number of repeated stress cycles as well as on the maximum value of stress. Therefore the thing to be known is not only what is the maximum value of stress developed under passage of a train but also to what number of stress cycles with an amplitude of the maximum stress in that condition corresponds the fatigue damage occurring in bridge members under passage of that train.

According to Prof. Pelikan, who investigated German trains, the number of repeated stress cycles mentioned above depends on the span length of a railway bridge. This trend must be the same with the Japanese railways, too. JNR has constructed Tokaido SHIN KANSEN as a line devoted to the operation of multiple-unit electric railcar trains. On this line, the train load is uniformly distributed but with a larger wheel base than in locomotives, the number of repeated loadings tends to be large. In case of bridges on SHIN KANSEN, with the above fact taken into account, the designing was so made as to let the bridge bear a larger load than really encountered but the difference due to bridge span length was ignored.

The purpose of this paper is to investigate the situation in more detail. The points to be elucidated are: How best to analyze the stress-time relation; how best to utilize the results of this analysis for estimation of fatigue life; how to relate these results to train category or span length of a bridge; or what are the best statistical quantities for checking the safety. The present paper sums up what has so far been achieved on this problem by the author in his own way which is even short of the statistical approach.

STRESS-TIME RELATION UNDER TRAIN LOAD

The stress-time relation developing in bridge members under train passage has different features from those of airplane wings in turbulent air or of axles in running cars. The stress in a wheel axle varies randomly on both sides of the mean level which is virtually constant, with no definite correlation existing between maximum and minimum.

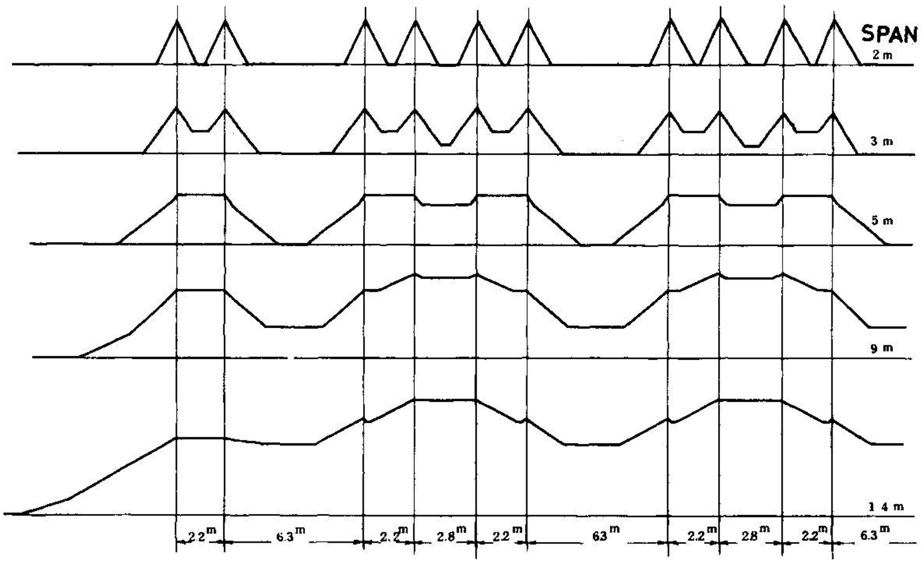

Fig. 1 Theoretical stress-time relations under Tokaido SHIN KANSEN N-load train.

By contrast, the stresses in bridge members are, though short in duration, characterized by mean stress variation which has a stress-time relation depending on train category, span length of the bridge and functions of members, and a relatively small oscillation added around this stress. Figure 1 illustrates the theoretical wave form appearing Tokaido SHIN KANSEN passes over simple supported girders of several different span lengths, the wave form is broadly similar to the above-mentioned mean stress variation. From this it is realized how influential is the span length.

STATISTICAL COUNTING METHODS FOR ANALYZING LOAD-TIME HISTORIES TO BE APPLIED FOR ESTIMATION OF FATIGUE LIFE

In the discussion of fatigue life, it is not enough to find simply the magnitude of maximum stress intensity and its probability of occurrence. Because the fatigue strength is not associated with the magnitude and frequence of maximum stress intensity only, but, more important, with those of stress amplitude. Thus, the counting method for this purpose must be one that can permit conversion to the magnitude and frequence of stress amplitude so that the counted stress waves appearing in railway bridge members may be related to the fatigue strength. If several such methods are available, the most reasonable and most practicable one must be selected from among them.

The author checked the following nine as such counting methods:
a) Peak Count Method.
b) Mean-Crossing Peak Count Method.
c) Level-Crossing Count Method.
d) Fatigue Meter Count Method.
e) Range Count Method.
f) Range-Mean Count Method.
g) Modified Range Count Method.
h) Range-Pair Count Method.
i) Modified Range-Pair Count Method.

Out of these nine, the four (a)-(d) are rejected for the present purpose because they cannot give stress amplitude from counted result on stress-time relations such as developed in railway bridges. The methods (e) and followings, which deal with stress amplitude from the first, are satisfactory in this respect, but the other three except (h) and (i) have the drawback that not only the results vary depending on the position and number of artificially selected counting levels, but also a major amplitude is apt to be overlooked as the result of minor vibration components, if any, being counted. Since it is undesirable to adopt for the solution of a scientific problem a method whose data depend on something artificial, the author thinks it advisable to refrain from use of such methods.

The remaining two methods (h) and (i) produce absolutely the same results. The instruments available for Range-Pair Count Method have a slow response, and to count the stress so rapidly changing as those in railway bridge the instrument becomes too large to be fit for field use. Thus, Modified Range-Pair Count Method has been found best for this purpose.

This is a method devised by Shiraishi; in this method the maximum and minimum values in stress-time relation are arranged in the order of their occurrence and they as reduced to a pulsating load are counted. Shiraishi performed the reduction graphically, but the author changed the procedure to do it numerically with no resort to the counting level. Measured stress-time relations are recorded on magnetic tape and, after reduced by the data processor to a series of extreme values, are fed to the electronic computer for necessary conversion.

METHOD TO BE USED FOR ESTIMATION OF FATIGUE LIFE

Numerous studies have been made to search for a damage law that can predict the number of repeated cycles to failure of members subjected to variable load such as to be able to agree with experimental results, but there is yet no theory established about which of these studies can give the most re liable results.

Here the author is going to discuss not in terms of determining which of these studies is generally the most accurate but in those of finding which of them will be the most convenient for the practical purpose. In this line of thinking certain errors would be tolerated.

From this standpoint the so-called Miner's method or its improvement, for instance, method of Corten & Dolan seems to be the most preferable one. As steel, when corroded, has its endurance limit reduced, here for the purpose of simplifying the calculation, the endurance limit of steel is to be disregarded.

Then putting the stress in a material as σ_i, its number of cycles to failure at this stress level as N_i and k as a constant, it is assumed that the following holds:

$$\sigma_i N_i^k = \sigma_j N_j^k .$$

Under this assumption a fatigue failure occurs when the following holds:

$$\sum_i \left(\frac{n_i}{N_i}\right) = 1.0 .$$

If the number of stress amplitudes σ_i appearing under passage of one train as live load is n_i', the number of trains, N_t, to a fatigue failure will be:

$$\frac{N_t}{N_1} \sum_{i=1}^{m} n_i' \left(\frac{\sigma_i}{\sigma_1}\right)^{1/k} = 1.0 .$$

Therefore, if

$$N_{e1} = \sum_{i=1}^{m} n_i' \left(\frac{\sigma_i}{\sigma_1}\right)^{1/k} ,$$

N_t will be given as the ratio of repeated numbers N_1 and N_{e1} to the representative stress σ_1. If the maximum stress due to a train load is taken as representative stress σ_1 and if the values of a different reference stress σ^* and the repeated number N^* corresponding to this stress are known, N_t will be given by

$$N_t = \frac{N^*}{N_{e1}} \left(\frac{\sigma^*}{\sigma_1}\right)^{1/k} .$$

If the number of trains in category j passing over the bridge in one year is n_{tj}, σ_1 for jth train category is σ_j, etc., and the number of train categories are s, the serviceable number of years T for the bridge will be given by

$$T = \frac{N^*}{\sum_{j=1}^{s} n_{tj} N_{ej} \left(\frac{\sigma_j}{\sigma^*}\right)^{1/k}} ,$$

or finding the equiva lent maximum stress intensity for each train, i.e., $\sigma_t = \sigma_1 N_{e1}^k$, T will be given by

$$T = \frac{N^*}{\sum_{j=1}^{s} n_{tj} \left(\frac{\sigma_{tj}}{\sigma^*}\right)^{1/k}} .$$

If σ_t follows a logarithmic normal distribution with σ_m as median, putting the total number of trains in a year as N_0 and using the standard deviation S_o of log σ_t the following is calculated:

$$N_{eq} = N_o \exp\left[\frac{S_o}{2k^2}\right],$$

and accordingly will be found as

$$T = \frac{N^*}{N_{eq}} \left(\frac{\sigma^*}{\sigma_m}\right)^{1/k}.$$

ESTIMATION BY STATICAL CALCULATION

As mentioned above, the fatigue damage under train passage depends on the equivalent repeated cycles N_{e1} as well as on the magnitude of maximum stress. Much attention has been paid to the maximum stress, but N_{e1} is an entirely novel conception and the following discussion will center around N_{e1}.

(1) Bridge Span vs. Train Categories.

Calculations were made with four categories of train and the relations between the number of trains in each category that can be passed until failure of bridge members and the span length of bridge was established as in Fig. 2. The categories of trains adopted for calculation and their symbols were as follows:

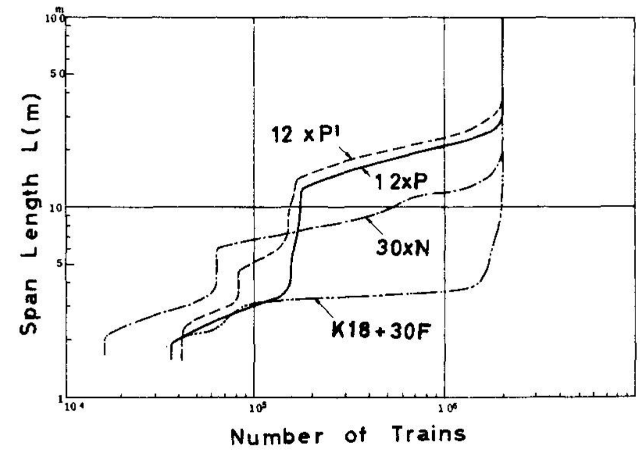

Fig. 2. Span-life relations by statical calculation.

a. 30 x N; Standard freight electric railcar train for designing Tokaido SHIN KANSEN, composed of 30 cars.
b. 12 x P; Standard passenger electric railcar train for designing Tokaido SHIN KANSEN, composed of 12 cars.
c. 12 x P'; Revenue passenger electric railcar train operated on Tokaido SHIN KANSEN, composed of 12 cars.
d. K18 + 30F; A locomotive of K18 standard construction load in Japan hauling 30 four-axle freight cars 10m long with 15 ton axle weight.

Bridge members considered in this calculation were cord members at span center or flange with k = 0.20 taken on assumption that they were designed to be able to stand just 2 million loadings at maximum stress.

From these calculations it may be concluded:

a) N_{e1} of a girder with shorter span length than the shortest wheel base is practically equal to the number of axles and constant regardless of span length.
b) For a train hauled by a heavy locomotive, practically N_{e1} = 1.0 will hold, if the span length of the bridge is longer than 4m.
c) For an electric railcar train, too, $N_{e1} \fallingdotseq 1.0$ will hold, if the bridge span length is more than 1.3 ~ 1.5 times the car length.
d) Under an electric railcar train, N_{e1} is approximately equal to the number of car couplings on a girder with a span longer than the wheel-base at the coupling and shorter than the wheel-base between the second and the third axles of a car.

(2) Difference Depending on Position of Section Under Consideration.

So far as the bending moment is concerned, the value depends little on the position of the member considered in the axial direction of bridge. The results of calculations about 7 sections in a span under passage of JNR series 181 10-units electric car train fitted all into the shaded region in Fig. 3.

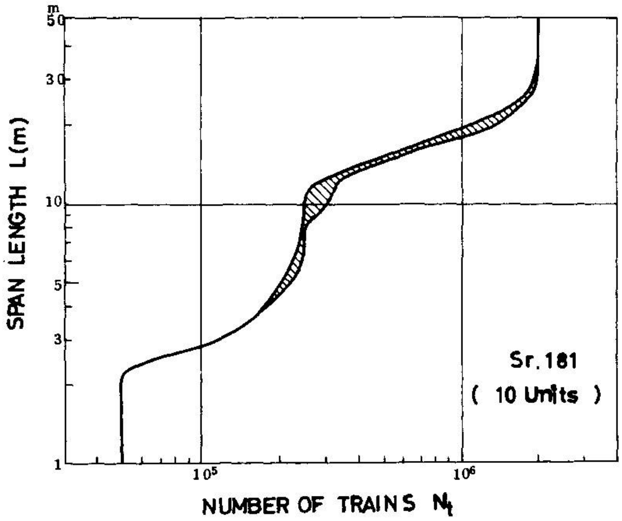

Fig. 3. L - N_t curve of simple girder under 10 units car train (Series 181).

(3) Load-Spreading Effect of Rails.

In JNR, there has never been a single case of even a short-span bridge developing a fatigue failure in its members. This may raise a doubt about the reliability of the above theory.

If the bridge is supposed to have been designed to have a strength that can stand for 2 million repetitions of loading in accordance with the castomary practice and the axle weight is assumed to be spread actually as Fig. 4 on account of rail- and sleeper rigidity, the calculation about the same train as in Fig. 2 produces the results as indicated in Fig. 5.

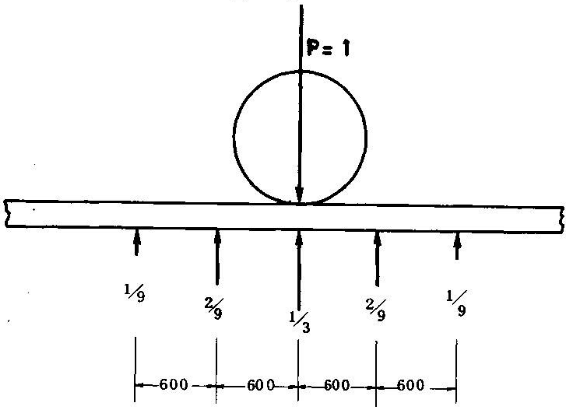

Fig. 4. Assumed distribution of load under sleepers.

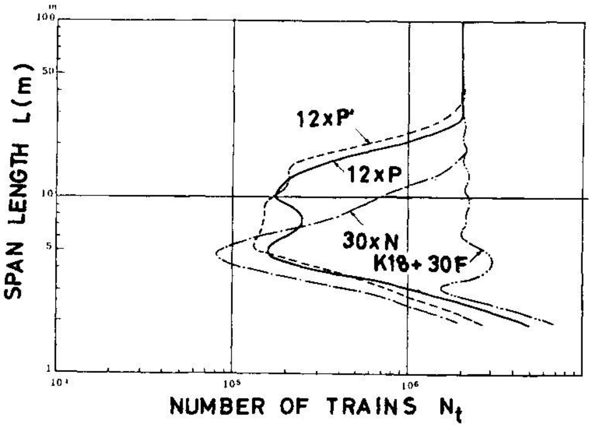

Fig. 5. L - N_t curve under effect of rail and sleeper rigidity.

Namely, so long as the bridge has been customarily designed and the rails supported by the sleepers, the hazard of fatigue failure in a span shorter than 4 m may be rather discounted. Thus, it may be practically presumed that a train hauled by a heavy locomotive necessarily developes a maximum stress intensity only once in its passage. Concerning the electric railcar trains, bridges calling for the most elaborate checking exist in the range of span lengths between 4 m and 20 m.

ANALYSIS USING MEASURED WAVE FORM

Real stress waveforms emerging in bridges are not always in agreement with the results of customary calculations. As well known, all stress-time relations make a smooth charge with no inflections such as observed on calculated curves. Meanwhile, an increased train speed is accompanied with a vibration which is not susceptible of routine calculation. Thus it becomes necessary to ascertain to what extent the above-mentioned calculation is applicable to the real waveforms. Here are to be cited a few examples in recent times.

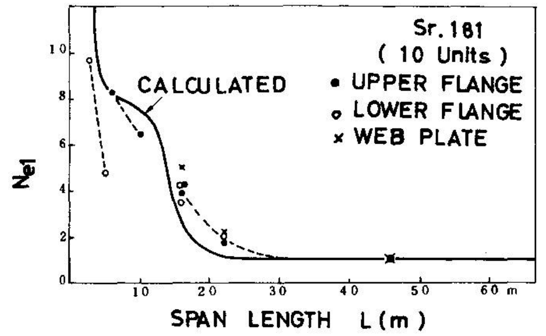

Fig. 6. L ~ N_{e1} relation by electric railcar train (Series 181, 10 units).

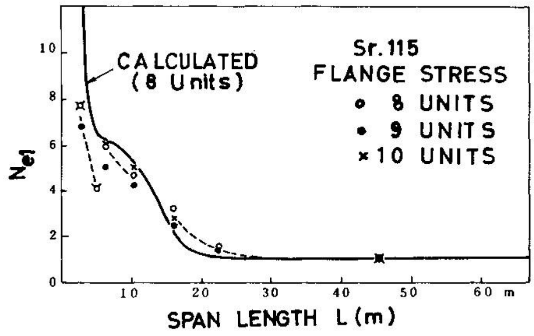

Fig. 7. L ~ N_{e1} relation by electric railcar train (Series 115) measured on flanges of girder.

Fig. 6 and Fig. 7 illustrate the L ~ N_{e1} relations as obtained from a similar analysis to the above of measured stresses in three plate girders, respectively with span lengths of 16.0m, 22.3m and 45.5m, in these figures, in addition to the data on the main girders, data using the measured stresses in 3.2m and 5.1m stringers as well as cross beams 6.4m and 10.2m long in the influence line are entered. Cross beam may be equated to main girder, but the curve for stringer characterized by continuity cannot agree with the curves plotting the results about main girders or cross beams.

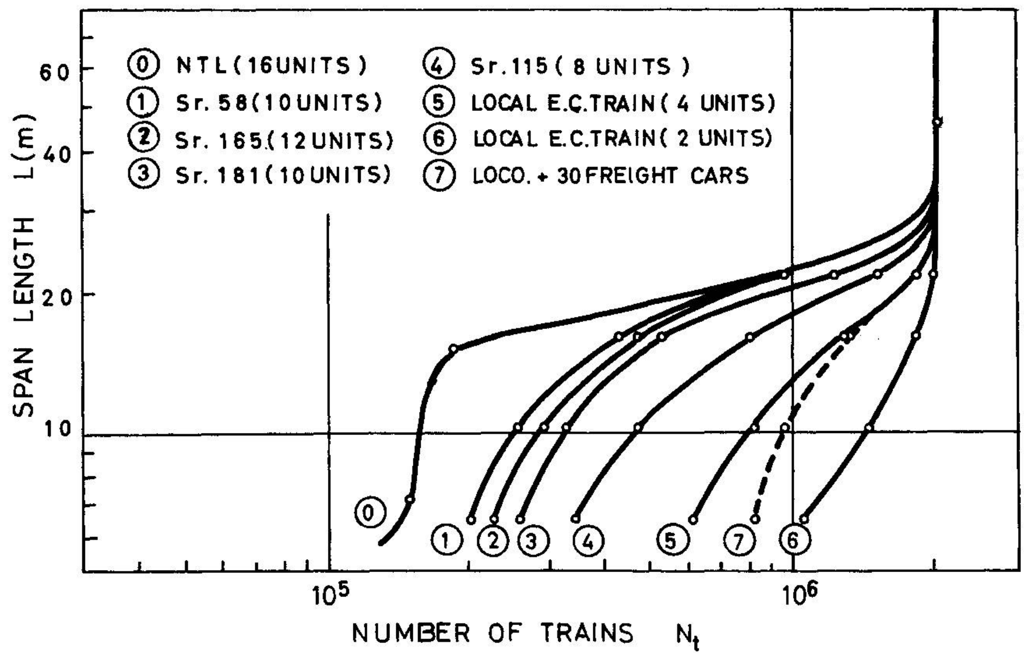

Fig. 8. Relation between span length and number of train passage to failure.

Figure 8, summerizing the results of such measurements, illustrates the relation between span length and number of train passages to failure just like in figure 2. Thus it can be said that the results of analysis based on measured waveforms are in the same tendency as the results of static calculations. So far as the range measured here is concerned, a slight difference in the stress-time relation and the small amount of vibration seem to have no large bearing on fatigue.

This, however, does not mean that N_{e1} is not sensitive to the speed. The author has some data which show extremely great influence beyond certain critical speed. In spite of these results, nothing conclusive can be said about the general tendency in the effect of speed on N_{e1}, because even among girders looking similar, some are influenced heavily by the speed, and others are little influenced by it, while still others are almost free from the influence of speed.

After all, above-mentioned equivalent numbers of loading, instead of crude statistical distributions of counted data on stress-time relations in railway bridges, seems to have a merit or possibility to be used as one of statistical quantity to measure the remaining life to fatigue failure under actual train loadings.

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SUMMARY

A kind of fatigue life estimating method combining that of Corten and Dolan with modified range-pair count method is suggested, which is practical to calculate the fatigue damage of existing railway bridge members.

The result of the illustrative applications of this method on simply supported girders shows that equivalent numbers of loading cycle depend on the span length of the girder and the arrangement of the wheel axles.

RESUME

L'auteur présente une méthode pour prédire la résistance à la fatigue des éléments de ponts ferroviaires. Il s'agit de la combinaison de deux méthodes; l'une permettant d'évaluer la limite de fatigue, proposée par Corten et Dolan, et l'autre étant une modification de la "range-pair count method".

Les résultats d'application de cette méthode à la poutre simplement appuyée nous montre que la fréquence équivalente des charges dynamiques dépend considérablement de la portée de poutre et de la répartition des essieux du train.

ZUSAMMENFASSUNG

Für die Ermüdungsdauer wird eine Schätzmethode, jene von Corten und Dolan mit dem abgeänderten Verfahren des "Schwingungsweite-Zählens" kombinierend, vorgeschlagen, die erlaubt, das Ermüdungsversagen für Eisenbahnbrückenteile einfach zu berechnen.

Das Ergebnis der Anwendungen auf einen einfach aufgelegten Träger zeigt, dass die Anzahl Lastwechsel von der Trägerspannweite und der Radachsenanordnung abhangen.

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