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Assessment of Fatigue Failure in Steel Arch Bridges

Estimation de la rupture de fatigue de ponts en arc métalliques

Beurteilung des Ermüdungs-Versagens einer Stahl-Bogenbrücke

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SUMMARY

On deck-type arch bridges, severe fatigue cracks have been found at joints of the strut and arch rib. These cracks have been assessed through fatigue analysis using simulated natural vehicle rows by computer. The main external cause of these cracks was due to the alternating stresses at the joint which is generated by traffic. Traffic management is finally discussed with reference to the parameter analysis for fatigue life.

RÉSUMÉ

Sur les ponts en arc à tablier supérieur, d'importances fissures ont été découvertes au niveau des raccords de nervure de cintre et d'entretoise. Ces fissures ont été évaluées grâce à des analyses de fatigue par ordinateur en observant le traffic routier. La cause extérieure principale de ces fissures est liée aux efforts alternés au droit des joints dûs aux passage des véhicules. Le contrôle du trafic a été déterminé en fonction des données paramétriques concernant le cycle de fatigue.

ZUSAMMENFASSUNG

An Bogenbrücken wurden Risse kritischer Länge im Anschlussbereich von Bogenträger und Stäben gefunden. Die Rissbildung wurde rechnergestützt simuliert; als Lastkollektive wurden repräsentative, wandernde Verkehrslasten angenenommen. Als Hauptursache der Rissbildung an den Anschlüssen, konnten die durch das Lastkollektiv erzeugten dynamischen Wechsellasten bestätigt werden. Zum Schluss der Untersuchung der Lebensdauer-Parameter wird der Einfluss verkehrsregelnder Massnahmen erörtert.

1. INTRODUCTION

In Japan, many deck type arch bridges have been built from the point of view of aesthetics and structural reliability. However, fatigue cracks have been frequently observed at the joints of struts with arch ribs in the bridges built until about ten years ago.
The struts have been designed as a column members loaded by reaction forces from floor systems, which were calculated using a simplified triangle influence lines. However, the actual struts are subjected to in-plane and out-of-plane bending moments due to deformation of the arch rib and fixation at joints. Furthermore, the joints of the struts with arch rib are subjected to alternating stresses by running vehicles on the bridge. Therefore, although poor consideration for details of the welding joints seems to be one reason for the cracks, missing of three-dimensional structural behavior at the original design and of the effect of vehicle loading seem to be main causes.
In this paper, fatigue assessments for a typical arch bridge were carried out by the latter two causes. That is, the effects of three dimensional behavior and of traffic loadings characteristics were evaluated through a simulation analysis of traffic flows and vehicle loads. Then, some traffic management methods in order to extend the remaining fatigue life of same type of arch bridges were discussed.

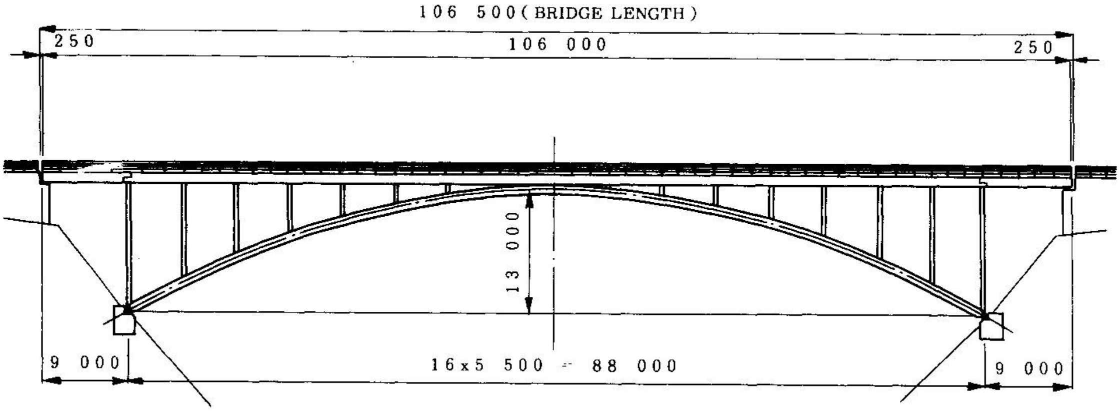

Fig. 1 General View of Deck Arch Bridge

2. BRIDGE MODEL AND S-N RELATION FOR THE ASSESSMENT

Fig.1 shows the arch bridge to be assessed. It was designed by the allowable stress design method and was built in 1963. The details of the jointing between a strut and the arch rib are shown in Fig.2. The gusset plates were welded to arch rib by fillet welding which forms a cruciform welding joint. The joints of No. - were really damaged by fatigue cracks after only 12 years service.
The laboratory fatigue data for the cruciform welding joint as shown in Fig.3 can be applied for the assessment. The equation for the median S-N curve shown in Fig.3 was obtained by a linear regression analysis. The curve seems to be suitable for the assessment because fatigue cracks have occurred at many points.

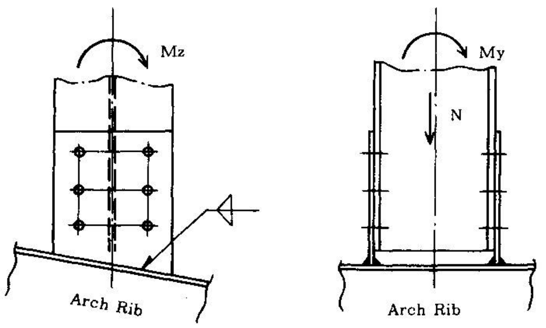

Fig. 2 Detail A

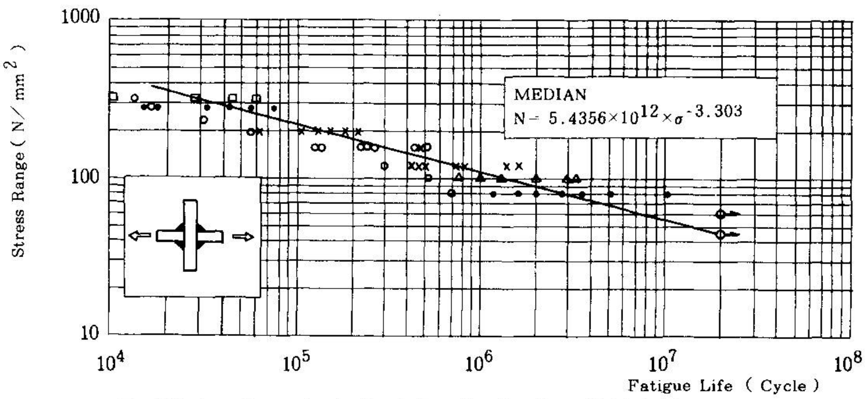

Fig. 3 Fatigue Properties for Load -Carrying Cruciform Welded Joints

3. METHOD OF ASSESSMENT

3.1 FATIGUE DAMAGE RULE

The effect of variable stress amplitude on fatigue is accounted with the cumulative damage rule called as Palmgren-Miner hypothesis. Failure occurs when the damage rate under variable stress amplitude(S_i) satisfies Eq.(1).

$$D = \sum D_i = \sum (n_i . Y_f / N_i) \geqq 1 \quad (1)$$

where, ni: repetition cycles in one year by an arbitrary stress range S_i,

$$Y_f . N_{eq} = Y_f \sum n_i (S_i / S_{rd})^m \geqq N_f \quad (2)$$

f(s): stress probability function,
N_0: traffic volume in one year,
Yf:fatigue life in year,
N_i: fatigue life at the stress range S_i.

On the other hand, when the equivalent repeating cycles by computing Eq.(2) becomes equal to the fatigue life by the fixed standard stress Srd, fatigue cracks will occur.

$$n_i = N_0 \int_{S_i}^{S_{i+1}} f(x)\, dx \quad (3)$$

where, Si:arbitrary stress range due to random loading,
Srd:an standard stress range,
m:inverse of absolute of the slope of S-N curve,

At the actual bridge, the traffic volume of large trucks has been reported as about 1000/day. Using this number, the total daily traffic volume can be calculated by the composition of vehicles. Then, probability density function of stress range were obtained by doing simulation analysis for the traffic volume of one year. After that, Neq for one year based on a standard stress level Srd can be obtained and the fatigue life Nf at the stress range Srd. Finally, the fatigue life represented by years can be obtained by Eq.(4).

$$Y_f = N_f / N_{eq} \quad (4)$$

3.2 SIMULATION ANALYSIS FOR STRESS RANGE DISTRIBUTION

As mentioned above, the fatigue cracks seem to be due to repetition of large bending stresses at the joint. Since those bending stresses will occur at random due to natural traffic flow, the probability density function has to be obtained through simulation analysis. Two-dimensional frame analysis is common in the recent design. However, actual structures behave in three-dimensions. So, the assessments were carried out with the stress results of the both two- and three- dimensional analyses.

Fig.4 shows the flow of simulation analysis. The outline of the analysis can be explained as follows:

(1) Firstly, the influence lines have to be created for the aimed points. The root of welding of the damaged joints were focused. Here, the influence lines of in-plane and out-of-plane bending moment and axial force regarding to the roots were prepared by the two- and three-dimensional analyses.

(2) Using the probability characteristics of vehicle weight and composition ratio of vehicles, the rows of vehicle weight are generated with Monte Carlo simulation method.

(3) The row of weight is rearranged by the natural traffic flow characteristics such as gaps of vehicles, passing position and dimensions of vehicles. The probability density functions of the gaps and the passing position are Log-Normal distribution of LN(200m,58.1m) and Normal distribution of N(1.303m, 0.24m), respectively. The impact ratio is supposed by N(0.044,0.055).

(4) All vehicle weights are divided into axle loads because the stresses at the aimed point seem to be due to local loading of axles.

(5) The arranged axle weights are moved on the influence line on the bridge. Every one meter movement, the total stresses at the aimed point is calculated. Then, the stress series in real time are obtained.

(6) Stress range distribution is obtained from the series by the rain flow method. Finally, equivalent number of cycles Neq can be estimated by Eqs.(2) and (3).

3.3 INPUT DATA

The Ministry of Construction and Hanshin Expressway Public Corporation etc. have published their traffic data obtained from field measurements. The authors have also carried out several field measurements to establish the characteristic of traffic loads on national highways. Those data shown in Table 1 were used for the assessments. Data (A) seems to represent the traffic characteristics on national highway, Data (B) represents the one on urban elevated highway and the Data (C) represents typical traffic characteristics in a commercial city.

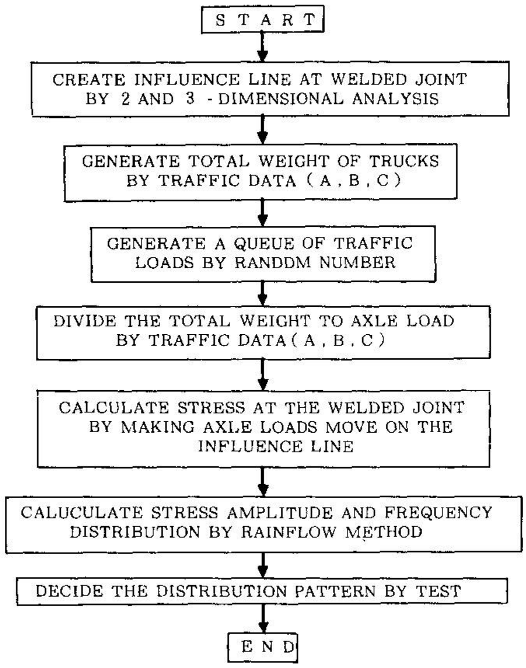

Fig. 4 Flow Chart of Fatigue Analysis

	No	Vehicles	Distri. Pattern	Weight (N) Max	μ	σ
A	①	Car	LN	30.4	12.7	3.5
	②	S . T	LN	123.5	35.3	13.2
	③	M . T	LN	179.3	63.7	24.5
	④	L . T 1 - 2	LN	443.0	166.6	61.7
	⑤	L . D 1 - 2	LN	606.6	196.0	96.0
	⑥	L . T 2 - 1	LN	330.3	156.8	68.6
	⑦	TRL	LN	849.7	294.0	117.6
	⑧	BUS	LN	183.3	135.2	23.5
B	①	Car	LN	28.4	13.4	3.6
	②	M .T	LN	126.4	48.7	29.3
	③	L.T 2 (NL)	N	359.7	74.9	20.9
	④	〃 (L)	LN	359.7	139.0	25.6
	⑤	〃 (OL)	EXP	359.7	217.6	21.6
	⑥	L.T 1 - 2 (NL)	N	370.4	112.8	20.7
	⑦	〃 (L)	LN	370.4	203.8	33.0
	⑧	〃 (OL)	EXP	370.4	316.4	22.4
	⑨	TRL (NL)	N	670.3	134.0	20.3
	⑩	〃 (L)	LN	670.3	250.9	104.6
C	①	Car	LN	19.6	13.13	2.84
	②	S.T	LN	124.5	31.07	15.88
	③	L . T 2	LN	176.4	60.47	37.73
	④	L . T 2 - 1	LN	205.8	162.68	62.33
	⑤	L . T 1 - 2	LN	284.2	136.81	37.83
	⑥	TRL	LN	460.6	235.59	115.35

S . T : Small Truck
M . T : Medium Truck (2 - axles)
L . T 1 - 2 : Large Truck (Rear Tandem)
L . D 1 - 2 : Large Dump (Rear Tandem)
L . T 2 - 1 : Tank Rolly (Front Tandem)
L . T 2 : Large Truck (2 - axles)
TRL : Trailer

Table 1 Constitution of Traffic (Data (A)(B)(C))

4. ASSESSMENT RESULTS FOR FATIGUE LIFE

Fig. 5 is the obtained frequency distributions of stress amplitude at the aimed point due to three traffic data. These distributions can be fit by a Weibull distribution function. Fig.6 shows the comparison of fatigue damage Di of every stress level at fatigue failure by the three traffic data. The difference of the traffic characteristics became clear by this figure.

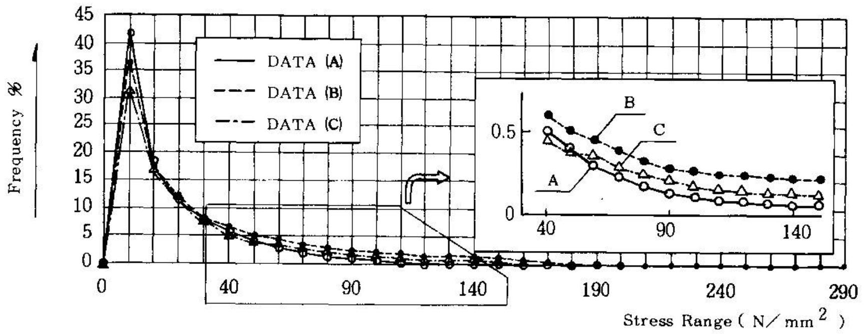

Fig. 5 Freqiency Distribution of Stress Range

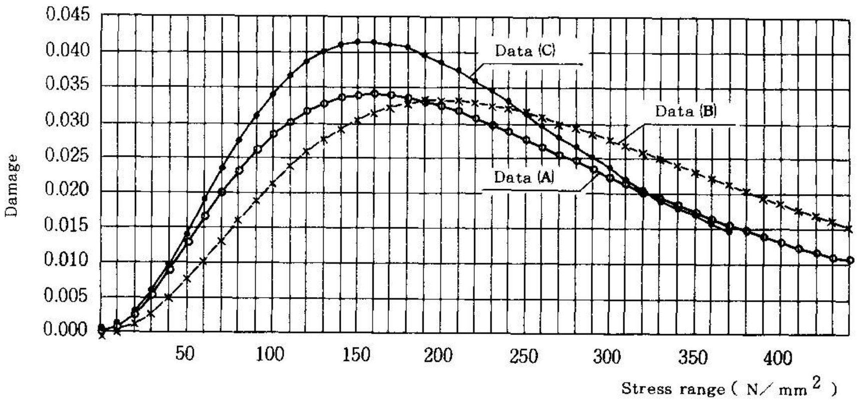

Fig. 6 Failure Probability (Data(A) , Data (B) , and Data (C))

The results of Y_f for three traffic data are shown in Figs. 7. The actual fatigue life was about 12 years. For the life, the results of Data(A) and Data(C) firstly seem to be right because the actual bridge is located in a national highway and can be supposed to be subjected to similar traffic load characteristics of those Data.
Secondly, the difference of assessed fatigue lives by two- and three-dimensional analysis has to be paid attention. Three-dimensional analysis gives significantly shorter life than two-dimensional one. The difference is attributed to out-of-plane bending moment acting on struts. Actually, as the joints are subjected to three-dimensional stresses, the result of three-dimensional analysis should be considered more rigorous. Therefore, the result of three-dimensional analysis of Data(A) can be concluded as the rigorously assessed life.

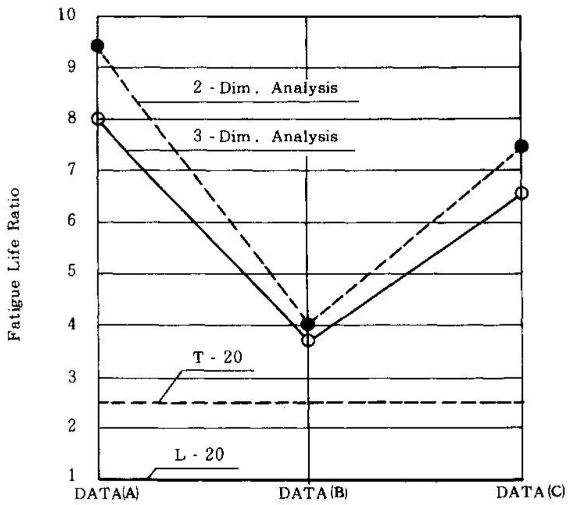

Fig . 7 Comparison of Fatigue Life in Each Data

5. DISCUSSION FOR EXTENSION OF FATIGUE LIFE

Now, as there are many same type of arch bridges, the safety for fatigue of those bridges have to be checked. If any fatigue damage does not occur yet, we have to do some effort to extend the remaining fatigue life. Three kinds of method can be considered. The first is reinforcement for the connection parts which actually carried out for the bridge. The second is to do regulation to prohibit simultaneous loadings of heavy trucks, and the third is a regulation of the maximum weight of trucks.

5.1 Regulation for simultaneous loading of truck

To make clear the influence of simultaneous loading of vehicles on the bridge, the simulation by single vehicle loading was done using the same traffic condition of Data(A). The fatigue life increased to about 47.8 times of common traffic flow under which simultaneous loading were allowed. From the results, traffic regulation seem to be an effective method to extend of the fatigue life. The regulation can be done by setting prohibition traffic signs on the both entrance of the bridge.

5.2 Regulation of truck weight

Fig.8 is the results of the simulation analyses using Data(A) by limiting the maximum vehicle weight up to the values shown in the Figure. As the result, the limitation of the maximum weight of large truck also can be recognized to be very effective. In Japan, the design service life of 50 years is very common. If the fatigue life Yf is shorter than 50 years, the remaining life Yr=(Yf - Yi), here Yi is the service period from the construction to the inspecting time in year, should be extend to Yr=(50-Yi) according to the maximum vehicle loads by using the ratio of the fatigue life which can be calculate from the curve of Fig.8. The limitation seem to be possible with a traffic signs and some enforcement by policemen.

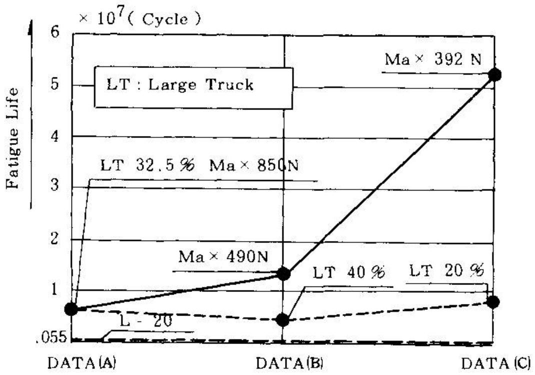

Fig. 8 Influence to Fatigue Life due to Max Truck Weight and Occurrence Ratio of Large Truck

6. CONCLUSIONS

The fatigue life of an existing arch bridge was discussed. The simulation analysis using actual traffic data can make possible for such an assessment. The main conclusions are :

(1) The fatigue life of actual arch bridge can be correctly assessed under actual traffic loadings generated by simulation analysis.

(2) The main cause of the fatigue cracking seems to be due to the simultaneous loading of heavy trucks which was not considered in the original design.

(3) For the extension of fatigue life of existing same type of arch bridges, regulation of the maximum truck weight is the most effective method.

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