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Fatigue Reliability Analysis of Early Steel Railway Bridges in India

Sécurité à la fatigue d'anciens ponts-rails métalliques en Inde

Ermüdungssicherheit früher Eisenbahn-Stahlbrücken in Indien

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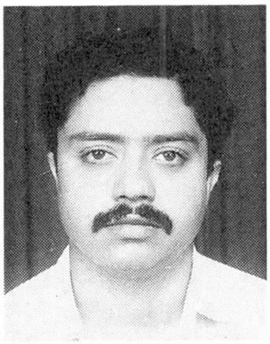

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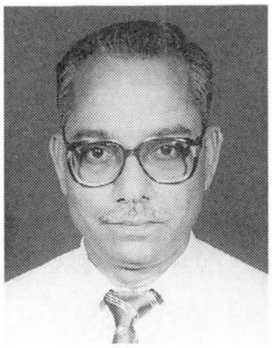

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SUMMARY
The paper deals with the fatigue reliability analysis of early steel railway girder bridges in India. Available published data on stress spectrum obtained under actual traffic load and on fatigue tests conducted on samples of the bridge members are used in the study. Limit state equation is formulated using S-N curve approach and Miner's rule. Using level II method, reliability index of girders, chords etc. are calculated. It is found that there is a linear relationship between this reliability index and the logarithm of number of cycles. The developed relationship gives insight in deciding about inspection creteria.

RÉSUMÉ
Cet article évalue la sécurité à la fatigue d'anciens ponts à poutres métalliques des chemins de fer indiens. Cette évaluation repose sur les données publiées à partir de spectres de contraintes, enregistrés sous les charges mobiles actuelles, et d'essais à la fatigue effectués sur des échantillons d'éléments porteurs des ponts. La capacité portante limite est déterminée à partir du diagramme de résistance à la fatigue et de la règle de Miner. A l'aide d'une méthode de vérification du 2e degré, l'auteur calcule l'indice de fiabilité des poutres, des membrures etc. Ce faisant , il démontre l'existence d'une relation linéaire entre cet indice et le logarithme des cycles de charge alternée. Cet indice de fiabilité fournit un aperçu des moyens de sélectionner les critères d'inspection.

ZUSAMMENFASSUNG
Der Beitrag behandelt die Abschätzung der Ermüdungssicherheit früher Stahlbalkenbrücken der indischen Eisenbahnen. Dabei stützt man sich auf publizierte Daten von Spannungsspektren, die unter Verkehr aufgenommen wurden, und auf Ermüdungstests an Proben aus Brückentraggliedern. Die Grentztragfähigkeit wird mittels des S-N-Kurvenansatzes und der Minerregel bestimmt. Mit einem Nachweis der Stufe II wird der Zuverlässigkeitsindex von Trägern, Verbänden usw. berechnet. Dabei findet man ein lineares Verhältnis zwischen diesem Index und dem Logarithmus der Lastwechselzahl, das eine Entscheidungsgrundlage für die Inspektionskriterien liefert.

1.0 INTRODUCTION

In Indian Railways, a large number of rivetted bridges which were built during the early part of this century are still in service and hence are in use for more than ninety years. With the increase in the train axle loading and their frequency of occurrence,these bridges are now subjected to relatively severe conditions and some of them have shown signs of distress. Even though most of these bridges have crossed their design life, their replacement with the new ones is not economically viable. With a rational method of evaluation, inspection and subsequent repair if needed, at regular intervals, their service life can be further extended at an acceptable risk level. A research study has been undertaken to develop a general method of reliability based design and evaluation of railway bridges. Attempts are being made to arrive at a rationally developed inspection strategy which would enable the designer to check about the possibility of service life extension of bridges.

The two key parameters required for any fatigue reliability analysis are :
a) the load spectrum or the stress spectrum and
b) fatigue test results to establish the S-N curve. Here S stands for stress range and N for number of cycles.

For getting the load spectrum, field measurements have to be done under actual traffic conditions for various members of different bridges. For conducting the fatigue tests, samples have to be taken from early steel girder bridges. An extensive study in this regard has been made by Research, Designs and Standards Organisation(RDSO)., Lucknow, India, the results being published as a report [1]. Necessary data for this study has been obtained from this report.

In this paper, the fatigue reliability analysis of Early Steel Girder Bridges has been presented. Using the results from RDSO report [1], S-N curve characteristics and equivalent stress range have been computed. A limit state equation based on Miner's rule has been formulated. Using the Advanced First Order Second Moment (AFOSM) method, the reliability index, β, has been found out for various cases.

2.0 ANALYSIS OF RESULTS OF FATIGUE TESTS AND STRESS SPECTRUM

The results of fatigue tests and stress spectrum have been taken from Reference [1].Fatigue tests have been performed on specimens obtained from early steel girder bridges namely a)Mahanadi bridge b)Netravathi bridge, and c)Koakhai bridge. The specimens contain five rivet holes and some specimens with rivets also have been tested. Using the test results, a linear regression analysis [2] has been carried out to get the S-N curve parameters. The results are presented in Table 1.

For most of the structural details, the value of slope of S-N curve, m is taken as 3 . However the results from Table 1 indicate that the range of m is 0.6954 to 4.6495 . This could be due the variation in chemical composition and other factors like age of the structure, method of rivet hole preparation, rivet clamping force ,variation in loads and their frequency etc.. In Table 2, the computed values of mean and coefficient of variation (COV) of m and K are given.

Under the actual traffic conditions, stress records have been obtained over a period of time and then using rain flow [3] method of cycle counting stress histograms are created [1].For the stress histograms available in Reference

Sl.No.	Details of the bridge	S - N curve parameters	
		Inverse slope m	Intercept K (in MPa units)
	A.Mahanadi bridge		
1	Bottom chords (BC)	4.649	2.473 E + 15
2	Stringers (ST)	1.298	1.518 E + 08
3	Cross girders (CG)	4.522	1.303 E + 15
4	Top chords (TC) + BC	1.567	7.518 E + 08
5	End rakers (ER) + Diagonals (DG)	2.651	6.233 E + 10
6	ER + DG + TC	2.628	5.389 E + 10
7	ST + CG	2.370	3.071 E + 10
8	All members	1.804	1.879 E + 09
	B.Netravathi bridge		
9	BC + DG + ER	1.033	6.780 E + 06
10	All members	0.695	1.815 E + 06
	C.Inter bridge combinations		
11	Cross girders	1.128	8.251 E + 06
12	Bottom chords	1.308	2.467 E + 08
13	End rakers	3.248	1.052 E + 12

Table 1 Linear regression results

Sl.No.	Description	Mean	Coefficient of variation (COV)
1	Intercept K	2.906 E + 14	2.575
2	Slope m	2.223	0.578

Table 2 Statistics of S - N curve parameters

[1], equivalent stress range S_{re} has been computed as follows [4]

$$S_{re} = \left[\sum f_i S_i^m \right]^{1/m} \qquad (1)$$

where f_i is the relative frequency of the stress range S_i, m is the average value of slope .The results obtained for various cases are listed in Table 3 .

Sl.No.	Description of bridge	S_{re} (MPa)	No. of cycles / day
	Mahanadi		
1	Stringer	17.881	1170
2	Cross girder	20.161	1160
3	Bottom chord	49.109	116
4	Diagonal	25.068	424
	Baitarani		
5	Stringer	28.144	1217
6	Cross girder	26.135	365
	Krishna		
7	Stringer	65.988	1966
8	Cross girder	74.273	1328
9	Bottom chord	104.799	188
10	Diagonal	52.831	36

Table 3 Equivalent stress range for all members

3.0 LIMIT STATE FORMULATION AND RELIABILITY ANALYSIS

To carry out the reliability analysis, the limit state equation has to be formulated. This equation is developed based on Miner's model for cumulative damage [5].

The cumulative damage, D, is given by

$$D = \sum n_i / N_i \qquad (2)$$

where n_i is the number of cycles of stress range S_i and N_i is the number of cycles to failure at constant stress range S_i.The value of N_i is to be chosen from S-N curve. Failure state is reached when D is equal to one. If summation is written for each cycle,

$$D = \sum 1/N(S_i) \qquad (3)$$

summation being carried out for each cycle. From the S-N curve, the following relation is written for constant stress range.

$$K = N\, S^m \qquad (4)$$

However, for variable amplitude stress range, knowing the stress histogram, equivalent stress range can be calculated from Eq.1 . Hence Eq.3 is written as

$$D = (N/K) \sum S_i^m \tag{5}$$

Introducing the equivalent stress range, S_{re}, the above equation reduces to

$$D = (N/K)\ (S_{re})^m \tag{6}$$

Hence the limit state equation is

$$g = D-(N/K)\ (S_{re})^m \tag{7}$$

and the failure surface equation is

$$D-(N/K)\ (S_{re})^m = 0 \tag{8}$$

The modified form of limit state equation is obtained by taking logarithm on either side of Eq.6. Thus

$$\log(D\ K)-m \log S_{re}-\log N = 0 \tag{9}$$

is the equation for the failure surface and the modified limit state equation is

$$g = \log(D\ K)-m \log S_{re}-\log N \tag{10}$$

The random variables are D, K and m. The statistics of K and m have already been fixed and given in Table 3 . Mean value and COV of D, obtained from Reference[6], are 1.044 and 0.3 respectively. Having Eq.10 as the limit state equation, reliability index,β, is computed for various cases using a program based on AFOSM method. N represents the desired life in cycles. All the variables are assumed to be lognormally distributed. The computed values of β are presented in Tables 4 and 5 for different bridges.

4.0 DISCUSSION AND CONCLUSION

In this study, fatigue reliability analysis of early steel girder bridges with S-N curve approach has been presented. Using the fatigue test results and stress measurements obtained from Reference [1], β values for various cases have been presented in Tables 4 and 5 .Table 1 presents the S-N curve characteristics.

From Tables 4 and 5, it can be seen that the average value of β is around 2 which corresponds to a probability of failure of 2.3 per cent. This average value of β is the same as proposed by Moses et al [7] for fatigue evaluation of highway bridges. Bottom chords being the main members of a truss bridge have a higher stress range than other members and hence there is a reduction in beta value for these members. However from Table 3, it is observed that the number of cycles per day for bottom chords is very low when compared to other members. It is also seen that there exists a linear relationship between β and logarithm of number of cycles, N.For various cases, this relationship has been established and the results of this analysis are presented in Table 6 . A typical plot of β versus log N values for stringer of Mahanadi bridge is shown in Fig.1 .Considering all the members and bridges together , an average β versus log N curve is obtained as shown in Fig.2. .

Sl. No.	No. of cycles $N \times 10^6$	Reliability index β			
		Stringer	Cross girder	Bottom chord	Diagonal
	Mahanadi bridge				
1	12.81	2.076	2.001	1.517	1.870
2	2.00	2.270	2.194	1.711	2.064
3	1.75	2.283	2.208	1.724	2.072
4	1.50	2.299	2.223	1.740	2.092
5	1.25	2.316	2.240	1.757	2.110
6	1.00	2.338	2.262	1.779	2.132
7	0.75	2.365	2.289	1.806	2.160
8	0.50	2.403	2.327	1.845	2.197
9	0.25	2.466	2.390	1.907	2.260
10	0.10	2.546	2.470	1.987	2.340
	Krishna bridge				
1	12.81	1.381	1.329	1.186	1.483
2	2.00	1.575	1.523	1.380	1.677
3	1.75	1.588	1.536	1.393	1.690
4	1.50	1.603	1.552	1.408	1.705
5	1.25	1.621	1.569	1.426	1.723
6	1.00	1.643	1.591	1.448	1.744
7	0.75	1.670	1.618	1.475	1.771
8	0.50	1.708	1.656	1.513	1.809
9	0.25	1.771	1.719	1.576	1.872
10	0.10	1.851	1.799	1.656	1.952

Table 4 Value of reliability index for members of Mahanadi and Krishna bridges

S.No	1	2	3	4	5	6	7	8	9	10
$N \times 10^6$	12.81	2.00	1.75	1.50	1.25	1.00	0.75	0.50	0.25	0.10
β for* ST	1.805	1.998	2.012	2.027	2.044	2.066	2.093	2.131	2.194	2.274
β for* CG	1.846	2.040	2.053	2.068	2.086	2.108	2.135	2.173	2.236	2.316

* Note: ST- Stringer; CG- Cross girder

Table 5 β values for members of Baitarani bridge

Sl.No	Description	Equation to the line
	Mahanadi bridge	
1	Stringer	$\beta = -0.2219 \log N + 3.6655$
2	Cross girder	$\beta = -0.2219 \log N + 3.5895$
3	Bottom chord	$\beta = -0.2219 \log N + 3.1065$
4	Diagonal	$\beta = -0.2219 \log N + 3.4594$
	Baitarani bridge	
5	Stringer	$\beta = -0.2220 \log N + 3.3939$
6	Cross girder	$\beta = -0.2219 \log N + 3.4354$
	Krishna bridge	
7	Stringer	$\beta = -0.2220 \log N + 2.9706$
8	Cross girder	$\beta = -0.2220 \log N + 2.9188$
9	Bottom chord	$\beta = -0.2220 \log N + 2.7757$
10	Diagonal	$\beta = -0.2219 \log N + 3.0719$
11	All the cases	$\beta = -0.2219 \log N + 3.2387$

Table 6 Relationship between β and log N for various cases

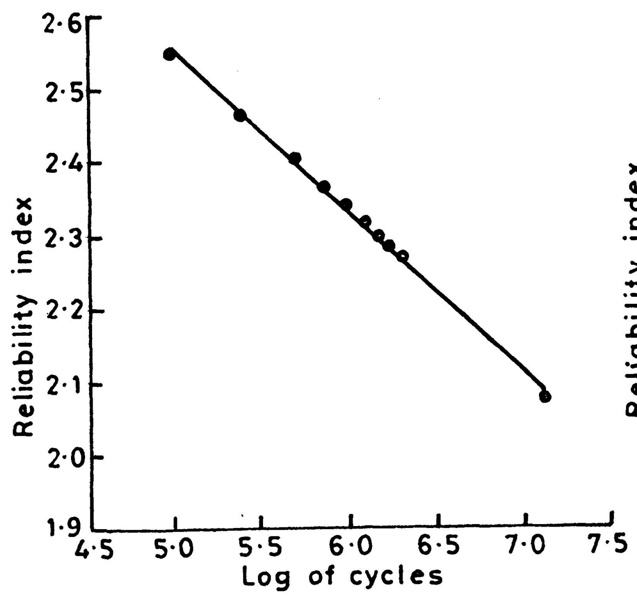

Fig. 1 Relationship between β and log N for stringer of Mahanadi bridge

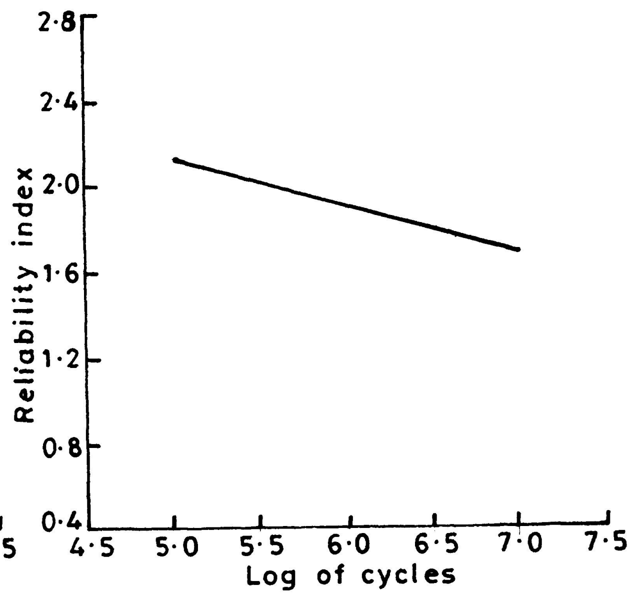

Fig. 2 Relationship between β and log N considering all cases

From Fig 2 , it can be seen that for a β value of 2 , log N is equal to 5.5. This gives the number of cycles as $\simeq 0 \cdot 3 \times 10^6$. For the stringer of Mahanadi bridge undergoing 1170 cycles per day, this would mean that a detailed inspection has to be done once in every 250 days. Similarly for the bottom chord of Krishna bridge, the optimum inspection interval would be four years. Hence if the inspection is accompanied with subsequent repair if needed, the service life of the member of the bridge could be further extended at a acceptable risk level . Thus these results provide an insight to the fatigue behaviour of early steel girder bridges and also help in deciding about the optimum interval for inspection and evaluation . These results also aid in fixing a target reliability index for the design of steel bridges.

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