Fatigue Crack Growth from the Rivet Hole in a Rivetted Built-up Section Subjected to Variable Amplitude Loading

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ABSTRACT

Fatigue crack growth under variable amplitude loading has been analysed for a crack emanating from a rivet hole in a web plate of a rivetted cross girder of a railway bridge, 80 years old. The analysis includes retardation effects within the spectrum loading. These effects have been experimentally studied on single edge notch specimen taken from a bridge member and the results are compared with theoretical models to select the appropriate retardation model.

KEYWORDS

Fatigue, crack growth, variable amplitude, retardation, railway bridge, rivetted assembly.

INTRODUCTION

A necessity for establishing a procedure for estimating realistic fatigue life of old railway bridges in India, numbering over 2000, has arisen to fix a replacement priority on a rational basis. Rivetted, built-up "I- sections" used in these bridges experience varying fluctuating bending loads and, therefore, are prone for crack initiation and growth at rivet hole, normal to the bending stress. From the conventional approach, one would use Miner's cumulative damage hypothesis (Miner, 1945). But it does not account for geometrical and load interaction effects of spectrum loading. Besides, a fracture mechanics analysis becomes necessary in view of the presence of cracks. This paper presents the analysis of the problem of cracks in built-up section, enabling a realistic residual fatigue life estimation.

STRESS INTENSITY FACTOR FOR WEB PLATE OF "I-SECTION"

The present analysis is for the crack growth at the rivet hole in the web plate of the built-up "I-section". To find suitable stress intensity factor (SIF) solution, it is necessary to examine whether the web plate is loaded through the rivets or by frictional resistance due to the clamping force of the hot forged rivets. Following analysis was therefore made:

(a) Assessment of the rivetting process used.
(b) Evaluation of load transfer.
(c) Influence of rivet hole on the SIF solution.

The heavy forging flow lines seen in the macro-section of the rivet (Fig. 1) indicate that hot up-setting has been used for rivetting. Such a process generates clamping force as the rivets cool from the forging temperature. Therefore, the relative motion between the stiffener angles and the web plate of the "I-section" can be inhibited due to the friction between the contact surfaces and the clamping force.

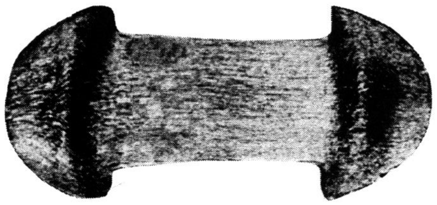

Fig. 1. Macro-section of the hot forged rivet

The results of the experiment conducted to assess the load required to overcome the frictional resistance are given in Fig. 2. From the load-displacement graph it can be seen that the point A represents the onset of slipping; A-B corresponds to the clearance between the rivet hole and rivet, and the point B represents the onset of load transfer through the rivets in shear. From a comparison of actual loads experienced by the bridge members and that required to cause slipping, it has been analysed that the load transfer is primarily through frictional resistance. In view of the above observations, the following assumptions can be made.

1) The web plate of the cross girder is in free bending.
2) There is no pressure acting on the rivet hole surface.

From this it follows that the web plate can be analysed in isolation without the stiffener by recalculating the bending moment which, when applied on the web plate alone, will cause

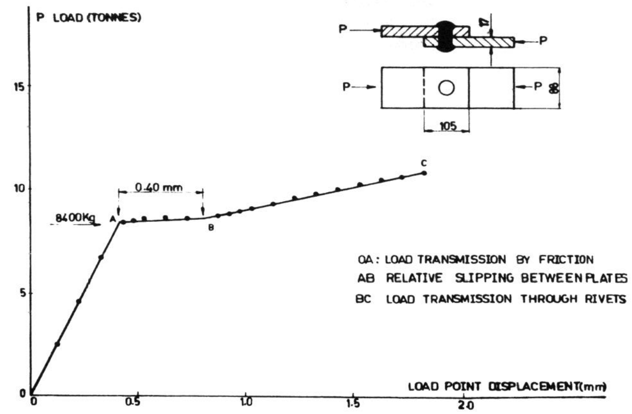

Fig. 2. Load-displacement graph from the compression test of the rivet assembly.

the same bending stress as in the case of composite rivetted assembly. The problem, therefore, gets simplified further to a case of finding the SIF solution for a crack at a rivet hole in a plate in free bending. By comparing the Bowie solution (Bowie, 1956 and Paris <u>et al</u> , 1965) for the crack emanating from a hole in an infinite plate with the case of an infinite plate containing only the crack (Fig. 3), it can be seen that for A/R > 0.2, the influence of the hole can be neglected. Thus the SIF solutions for the eccentric crack in a finite plate in bending can be used (Rooke <u>et al</u> , 1979).

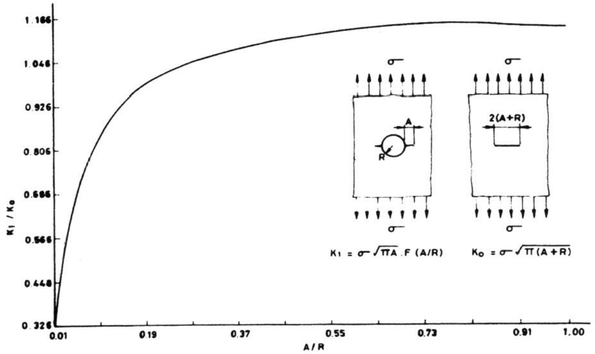

Fig. 3. Comparison of SIF solution for a crack in an infinite plate

The dimension details of the cross girder is given in Fig. 4, from which it can be seen that the crack tip A is in higher tensile stress region while the diametrically opposite crack tip B is in the lower stress region. The SIF at tip A & B will be different and therefore the fatigue crack growth rate will be correspondingly different. When the crack at tip A reaches the edge, a different SIF solution has to be used (Rooke et al 1979).

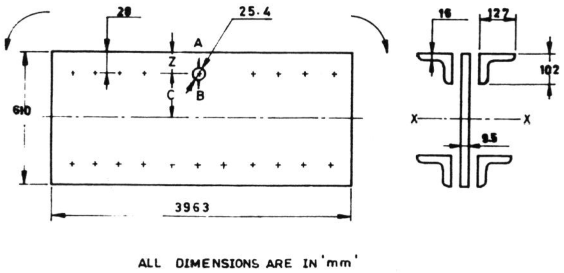

Fig. 4 Dimensional details of built-up "I-section"

EXPERIMENTAL AND THEORETICAL EVALUATION OF CRACK GROWTH IN SINGLE EDGE NOTCH (SEN) SPECIMEN

The nature of fatigue loading experienced by the bridge member is a variable amplitude type. Hence, retardation effects due to high to low load interaction in spectrum loading have to be considered for realistic crack growth estimates. For such analysis, retardation models (Wheeler, 1972 and Willenborg et al , 1971) along with the Forman's crack growth equation as given below can be used.

$$\frac{da}{dN} = \frac{C * (\Delta K)^m}{(1-R)Kc - \Delta K} \qquad (1)$$

where C & m are material constants
R is the stress ratio
ΔK is the stress intensity range
Kc is the plane stress fracture toughness
da/dN is the crack growth rate

Variable amplitude fatigue loading tests were conducted on SEN specimens made from material extracted from Phalgu bridge (built in 1899). Chemical composition and mechanical properties of the bridge steel is given in Table 1 and the details of the block loading is given in Table 2.

Table 1. Chemical composition in weight percent and mechanical properties of the bridge material

Identification	C	Mn	Si	P	S
P/BCP/C3	0.24	0.65	0.10	0.010	0.062
P/BCC/C3	0.22	0.57	0.10	0.069	0.048
P/BCC/C5	0.23	0.54	0.10	0.068	0.077

Yield strength .... = 26.3 Kg/sq.mm
Tensile strength .. = 46.7 Kg/sq.mm
% Elongation ..... = 40.7
% Reduction in area = 53.0
Imapact strength .. = 3.0 Kgf-m (at room temperature)
(CVN)

Table 2. Stress spectrum used in fatigue test

S.No.	Max. Stress Kg/sq. mm	Min. Stress Kg/sq. mm	No. of cycles
1	5.30	3.7	8400
2	6.90	3.7	8000
3	8.50	3.7	6500
4	10.10	3.7	9500
5	11.71	3.7	1800

The composition of the block has been selected such that even at the minimum stress level of the block, the stress intensity range (ΔK) would be above the threshold stress intensity range (ΔKth). For this class of steel, the ΔKth has been estimated from the empirical relation (Garwood, 1978) given below.

$$\Delta Kth = 6.004 - 4.55 * R \qquad (\text{in MPa } \sqrt{m}) \qquad (2)$$

This was done to facilitate the study of retardation effects in the SEN specimen only due to the high to low load interaction. The experimentally measured crack growth data has been compared in Fig. 5 with the theoretically predicted crack growth using the various models. Fig. 6 shows the beach marks on the fracture surface of the specimen subjected to variable amplitude fatigue test.

It can be noted from Fig.5, that the Wheeler's model for predicting the crack growth does not give results which are close to the experimental data even with a shaping exponent, 'n'=3.5 and does not improve significantly when 'n' is increased to 6.0.

In the case of Willenborg's model, the compressive self stresses are calculated from the stress required to overcome the over load plastic zone at any instant. For the crack growth calculations, the effective stress intensity range is calculated by applying correction on the operating maximum and minimum stresses to the extent of the calculated self stresses. The effective stress intensity range is used for calculating the retarded crack growth. From Fig.5, it can be seen that the crack growth estimates using Willenborg's model are in fair agreement with the experimental data.

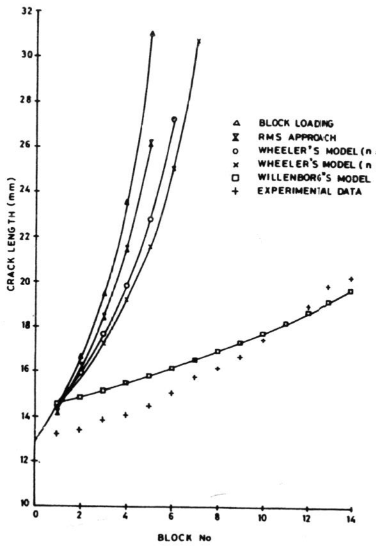

Fig. 5 Crack growth analysis

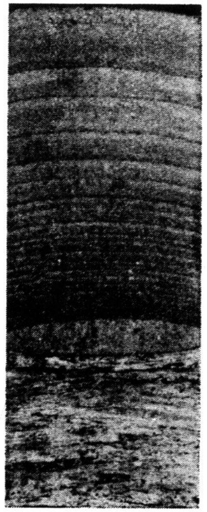

Fig. 6 Fracture surface

Apart from the fatigue crack growth analysis using the retardation models, theoretical analysis have been made for the crack growth in SEN specimen by using a root mean square (RMS) SIF values. In this method, the RMS values of the maximum and minimum stresses have been separately calculated from the composition of the block loading. The SIF corresponding to the RMS values were then computed for use in Forman's equation for fatigue crack growth analysis. The crack growth analysis using RMS approach does not correlate with the experimental data.

For these theoretical analyses the Forman's constants 'C' and 'm' are required. These have been determined from constant amplitude fatigue tests conducted on SEN specimens using Instron fatigue testing machine. The constant amplitude experimental crack growth data has been analysed using a computer program for determining the constants 'C' and 'm'.

This program uses 5 point incremental polynomial for regression analysis of the fatigue crack growth data. From the above data, log-log plot of ΔK and (da/dn)*[((1-R)Kc $-\Delta K$) has been made as shown in Fig.7 for determining the material constant 'C' and 'm'. Plane stress fractrure toughness, Kc was approximately determined from the constant load amplitude fatigue test data considering the crack length at fracture and the maximum load during fatigue testing. The value of Kc was found to be around 160 MPa $\sqrt{m}$ for the specimen thickness of 14.0 mm

CRACK GROWTH ANALYSIS IN THE WEB PLATE

Having studied the crack growth in SEN specimen under variable amplitude loading and ascertained the applicability of the Willenborg's retardation model, the next endeavour was to develop a computer software to theoretically predict the crack growth in the web plate. It is highly interactive with a provision for data entry, editing, storage and retrieval from a floppy diskette. The program performs crack growth calculations with various options such as (1) Without considering the retardation effects, (2) Wheeler's model, (3) Willenborg's model. The crack growth calculations are terminated at K_T, the onset of stage III crack propagation. K_T has been estimated from the following relation (Rolfe et al)

$$\frac{K_T^2}{E\ \sigma_{ys}} = 0.04 \text{ (mm)} \qquad (3)$$

For the given stress ratio R, ΔKth has been estimated using the relation proposed by Garwood (Garwood, 1978 and Doc V.F-162-86, 1987). The stress history for the cross-girder has been analysed by on-site in-situ experimental stress analysis and the data has been classified into convenient stress history block of one year (Table 3).

Table 3. Stress history of cross girder

S.No.	Max. Stress Kg/sq. mm	Min. Stress Kg/sq. mm	No. of cycles
1	1.3	0.3	125560
2	2.3	0.3	198560
3	3.3	0.3	79935
4	4.3	0.3	13140
5	5.3	0.3	4015
6	6.3	0.3	1095
7	7.3	0.3	360
8	8.3	0.3	360
9	9.3	0.3	360

Crack growth analysis in the web plate has been evaluated:

a) with and without retardation effects
b) with and without threshold considerations

The results are presented in Fig. 8. For the fatigue crack growth analysis with retardation effects, Willenborg's model has been considered. The effective stress intensity range is calculated from the bending moment required to overcome the plasticity effects of the previous overload.

Fig. 8 presents the crack growth data in terms of number of blocks of fatigue loading. It can be seen that the crack growth estimates using retardation effects are significantly lower compared to the estimates without considering retardation effects. Referring to the experimental studies on SEN specimens, it can be inferred that crack growth estimates using retardation can be quite realistic.

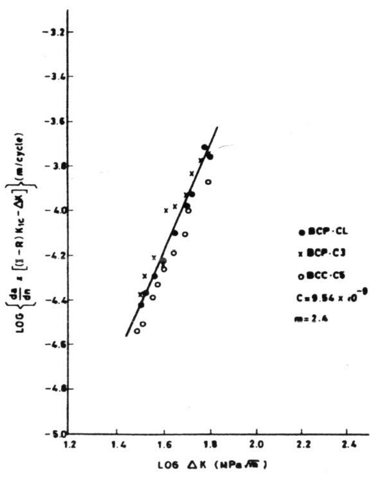

Fig. 7 Fatigue test data (constant amplitude)

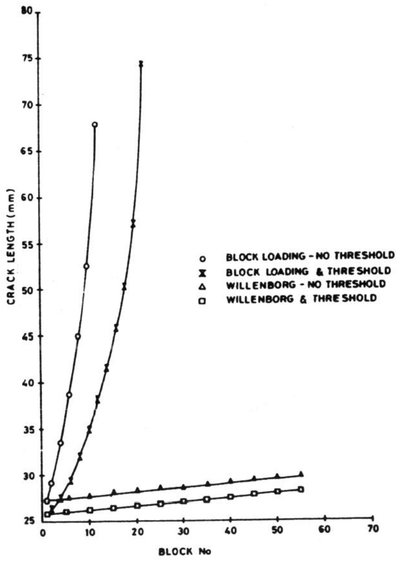

Fig. 8 Crack growth analysis in the web plate

CONCLUSIONS

The complex fatigue problem of a crack growing from a rivet hole of a web plate of rivetted built-up "I-section", has been investigated by evaluating the appropriate SIF solutions. This has been arrived at based upon the load transfer test on the rivet assembly.

Retardation models have been considered for realistic estimates of the crack growth. Experimental studies on variable amplitude loading on SEN specimen revealed that the experimentally measured crack growth data correlate well with the predictions using Willenborg's model.

Computer based methodolgy has been developed for realistic fatigue life estimates of rivetted bridge members.

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