THEORETICAL FRAMEWORK ON THE USE OF FRACTURE MECHANICS APPROACH IN FATIGUE LIFE PREDICTION OF RAILWAY BRIDGES

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INTRODUCTION

Most of the steel structures fail due to fatigue. Fatigue failure is critical since it initiates microscopically at low-stress levels than to the allowable stress when the structure is subjected to cyclic loading. The initiated crack grows to macroscopic size and propagates during the service and when the crack reaches the critical point, the structure fails catastrophically without warning.
The effects of various mechanical, microstructural and environmental factors on cyclic deformation as well as crack initiation and growth in a vast spectrum of engineering materials have been the topics of considerable research in the past four decades (Suresh,1998). Steel structures such as railway bridges need continuous monitoring to prevent failures. It is understood that the failures in the steel railway bridges are also due to repeated loading. A significant amount of research is going on these fatigue failures and the material used for the structure of the bridges to reduce the failures and increase the service life of the bridges. Failure of railway bridges is destructive and a mechanism is needed to predict the life of the bridge or specifically the critical members of bridges. A railway bridge in the coastal railway line of Sri Lanka was visually inspected and defects were identified. Crack was identified in; one of the rail bearers and the connecting plate made out of steel grade S275 (Figure.1). These failures occur periodically due to repeated loading so it needs attention and needed to be replaced.

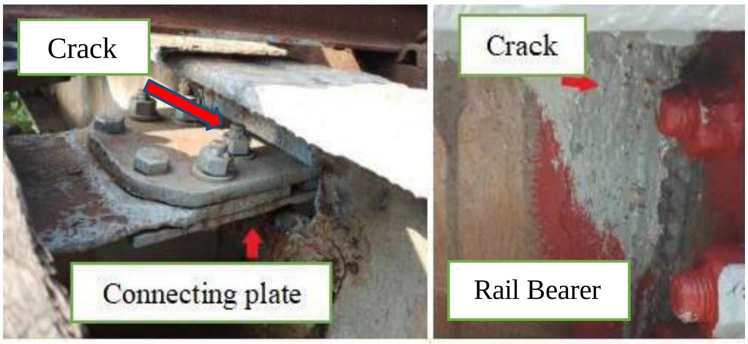

Figure 1. Cracks in connecting plate and Rail bearer

Stress-life and fracture mechanics approaches are currently adopted to study and analyze the life of steel bridges. The fracture mechanics approach provides provisions for in-depth analysis of the crack initiation and propagation aspects, it is appropriate to use for bridge failure predictions and lifetime assessments. The results would lead to; identify fatigue performance of bridges, formulate a well-planned inspection routine, strengthening and repair schedules, could ensure continuous and satisfactory performance of bridges during their service life.

METHODOLOGY

The methodology followed in this study is summarized as follows,

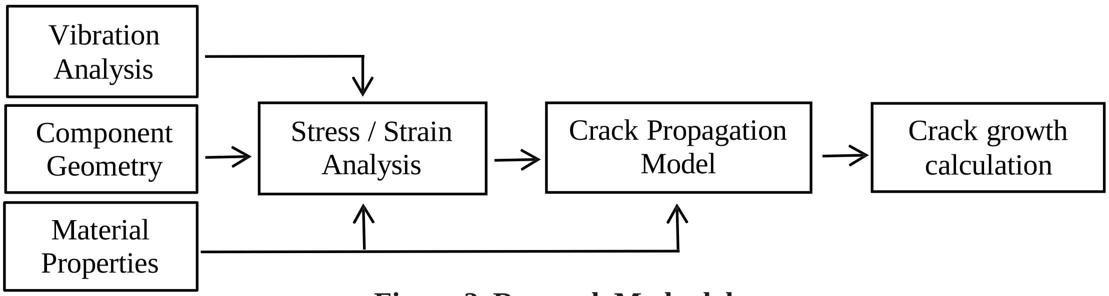

Figure 2. Research Methodology

Load history of the structure is obtained by performing the vibration analysis on selected connecting plates and rail bearers. Maximum stress experienced during the service is determined and it can be considered during the laboratory testing. The microstructure of the material was examined following ASTM E3-01 and the average grain size was 25 µm was determined using the mean linear intercept (MLI) method following ASTM E112-2010. S275 has 0.09% Carbon by weight also it has 0.20% of Silicon, 0.51% Manganese, 0.018% Phosphorus, 0.014% of Sulphur and 0.13% of Chromium.

The mechanical and fatigue properties of S275 can be determined through the standard testing methods, ASTM E8/E8M-09 and ASTM E466-15. The fatigue crack propagation data was obtained experimentally with single notched specimens, 62.50×60×7mm thick (Figure 3) of S275 following ASTM E647-15.

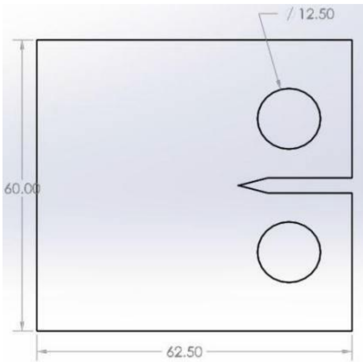

Figure 3. C(T) Specimen

Instron material testing machine is to be used for carrying out all the fatigue tests. Mirror polished specimen are to be tested with the pre-crack of 0.1mm. The crack propagation is to be monitored and measured using a metallurgical microscope.

Loading histories to be used in this investigation for the application of load. Six specimens will be tested with different numbers of cycles (N_1, N_2, N_3, .. N_6) at different stress levels. The final crack length of each specimen will be measured at the end of each test and crack length a versus Number of cycles N will be plotted. The crack growth rate da/dN is obtained from the crack propagation curve. A typical constant amplitude crack propagation curve is shown in Figure 4.
Stress intensity factor range ΔK for the C(T) specimen can be determined as follows (ASTM E647, 2015).

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)$$

Where $\alpha = a/W$, B is thickness, a is crack size, ΔP is force range ($P_{max} - P_{min}$) and W is the width of the specimen.

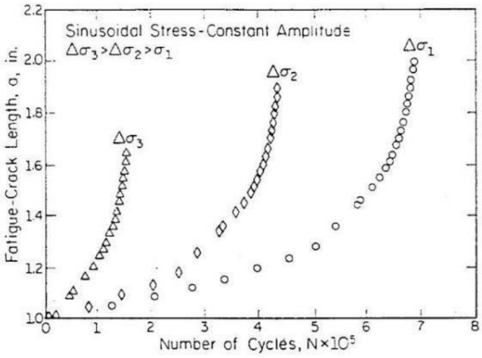

Figure 4. Constant amplitude crack propagation curve (Bannantine et al., 1990)

Paris law (Paris & Erdogan, 1963) can be modified to satisfy the results obtained from the curves and an empirical relationship between da/dN and ΔK can be formed for constant amplitude loading conditions.

$$\frac{da}{dN} = X.C(\Delta K)^m$$

Where C and m are material constant and X to be determined.

THEORITICAL FRAMEWORK

Crack tip plasticity models

These models assume that crack growth rates under variable amplitude loading can be related to crack tip plastic zones developed during the overload. These models predict the crack growth through the cycle-by-cycle analysis. Interaction effects occur within the plastic zone until the crack grows beyond the plastic zone created by the overload.

Wheeler Model

Wheeler model predicts that retardation in crack growth rate after an overload may be predicted by modifying the constant amplitude growth rate. This model modifies the constant amplitude growth rate by an empirical retardation parameter C_p. Paris relation for constant amplitude crack growth rate,

$$\frac{da}{dN} = C(\Delta K)^m$$

Stress intensity factor,

$$\Delta K = f(g)\, \Delta\sigma\sqrt{\pi a}$$

Where $f(g)$ is geometric correction parameter, $\Delta\sigma$ is the global stress range and a is instantaneous crack length. Wheeler's modification with retardation parameter,

$$\frac{da}{dN_i} = (C_P)_i\left(\frac{da}{dN}\right)_{CA\,i}$$

And,

$$\frac{da}{dN_i} = (C_P)_i[C(\Delta K_i)^m]$$

Where $(da/dN)_{CAi}$ is a constant amplitude growth rate approximated by stress intensity factor ΔK_i, and the retardation parameter $(C_p)_i$ is a function of current plastic zone size to the plastic zone size created by the overload.

$$(C_p)_i = \left(\frac{r_{yi}}{a_p - a_i}\right)^p$$

Where r_{yi} is the cyclic plastic zone size due to the i^{th} loading cycle, p is an empirically determined shaping parameter, a_i is the crack length at the i^{th} loading cycle and a_p is the sum of the crack length which the overload occurred. Figure 5, shows the plastic zone parameters used in this model.

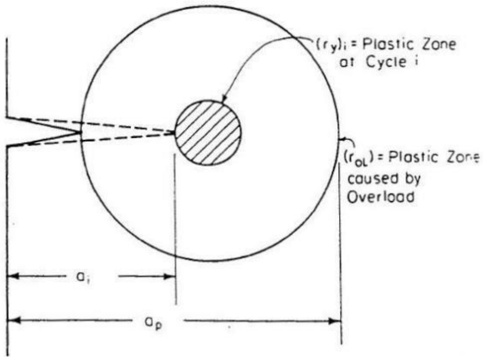

Figure 5: Plastic zone parameters (Bannantine et al., 1990)

Crack retardation occurs as long as the current plastic zone is within the plastic zone created by the overload and the retardation ceases when the boundary of the current plastic zone touches the boundary of the plastic zone created by the overload. Crack growth is summed after each cycle until the crack passes the plastic zone created by the overload as shown in the equation.

$$a_r = a_0 + \sum_{i=1}^{r} \left(\frac{da}{dN}\right)_i$$

Where a_0 is initial crack length, a_r is crack length after r cycles and $(da/dN)_i$ is crack growth during i^{th} cycle.

(Allen,1988) modified the Paris equation for constant amplitude loading and reported that fatigue life for various steels under variable amplitude loading is influenced by stress ratio R.

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

Where stress ratio $R = (\sigma_{max}/\sigma_{min})$, C and m are Paris constants.

Willenborg model

Willenborg assumed that crack growth retardation is caused by compressive residual stresses acting on the crack tip. These compressive residual stresses are developed due to the elastic body surrounding the overload plastic zone, which causes this zone to be put into compression after the overload is removed. In this model, crack growth rate is determined by substituting the effective stress intensity factor ΔK_{eff} and effective load ratio R_{eff} in Forman equation.

$$\frac{da}{dN_i} = \frac{C(\Delta K_{eff})_i^m}{[1-(R_{eff})_i]K_c - (\Delta K_{eff})_i}$$

This model predicts that crack arrest occurs if the ratio of the overload stress intensity, K_{OL}, to the stress intensity of the subsequent lower loads levels, K_{max}, is larger than or equal to 2.

RESULTS AND DISCUSSIONS

Crack propagation model under constant amplitude loading can be used to determine the crack growth rate as explained in this paper. In actual service, railway bridges are experiencing variable amplitude loading and it has to be taken into consideration for accurate life prediction. Formulated empirical relationship,

$$\frac{da}{dN} = X.C(\Delta K)^m$$

According to the Wheeler's model, crack growth rate under variable amplitude loading can be written as,

$$\frac{da}{dN_i} = (C_P)_i\left(\frac{da}{dN}\right)_{CA\,i}$$

With the empirical relationship; crack growth rate becomes,

$$\frac{da}{dN_i} = (C_P)_i[X.C(\Delta K)^m]$$

Fatigue propagation life N_p can be given as,

$$N_P = \int_{a_i}^{a_f} \frac{da}{(C_P)_i[X.C(\Delta K)^m]}$$

Where a_i and a_f are initial and final crack length respectively. This equation can be numerically integrated and N_p can be determined.

CONCLUSIONS

A theoretical framework based on fracture mechanics for estimating the propagation life of S275 structural steel has been presented. This methodology can be adapted to determine the fatigue propagation life for steel railway bridges. The crack propagation model was tested under constant amplitude loading and crack growth rate *da/dN* was obtained. Relationship between *da/dN* and ΔK formed by modifying the Paris equation. Crack propagation under variable amplitude loading was modeled using Wheeler's retardation model. An empirical relationship for fatigue life prediction of steel railway bridges has been formulated.

REFERENCES

Suresh.S. Fatigue of Materials.2nd Edition, University of Cambridge, Cambridge,1998; ISBN 0-521-57847-7.

Bannantine.Julie A, Jess J.Comer, James L.Handrock. *Fundamentals of Metal Fatigue Analysis.* Prentice Hall, Englewood Cliffs, New Jersey 07632, ISBN 0-13-340191-X.

Chathuranga D.D.K, Karunanratna T.E.H, Karannagoda H.C, Premaratne R.D.D.N.K and Karunannanda P.A.K. *Fatigue Life Estimation of Critical Railway Bridges in Kelani Vally Line Sri Lanka.* 8th International conference on Structural Engineering and Construction Management,2017, ICSEM2017-152.

Allen R.J, A Review of Fatigue Crack Growth Characteristics by Linear Elastic Fracture Mechanics, Part III, Fatigue Fract. Eng. Mater. Struct., Vol 11 (No. 2), 1988, p 45-108.

Khan Z, Rauf A and Younas M, Prediction of Fatigue Crack Propagation Life in Notched Members under Variable Amplitude Loading, JMEPEG (1997) 6:365-373, ©ASM International.

Paris P.C and Erdogan F., (1963). A Critical Analysis of Crack Growth Propagation Laws. Journal of Basic Engineering,85, pp.528-534.

ASTM.(2015). *Standard practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Test of Metallic Materials* (E466-15). www.astm.org.

ASTM.(2015). *Standard Test Method for Measurement of Fatigue Crack Growth Rates* (E647-15).

ASTM.(2009). *Standard Test methods for Tension Testing of Metallic Materials* (E8/E8M-09).

ASTM.(2001). *Standard Guide for Preparation of Metallographic Specimens* (E3-01).

ASTM.(2010). *Standard Test Methods* for *Determining Average Grain Size* (E112-2010.