Fatigue Life Prediction of Railway Bridge

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Abstract- *With mechanical failures growing day by day due to fatigue and brittle fracture, in various systems related to different spheres of engineering and technology, it is high time when low cost and effective methods should be adopted to determine life of existent structures and also design new ones more effectively. It is seen that repeated loads which are variable in nature cause damage five times more than the static loads. Generally members acting in tension and flexure, joints, etc are among the first ones tofail.*

In India there are about 250 important and 3000 major bridges older than 100 years and 180 important and 2900 major bridges aging 50-100 years. Steel bridges are reaching or have exceeded their original design life. These structures have experienced increasing traffic volume and weight, deteriorating components as well as a large number of stress cycles. Therefore, evaluation of remaining fatigue life for their continuing service has become necessary, especially for decisions on structure replacement, deck replacement, or other majorretrofits.

In the present study parametric study on four case studies is done. In the first parametric study only the material degradation is considered keeping the traffic volume same, the damage occurring in the most stressed member of the bridges is calculated. While in the second parametric study material degradation as well as increase in traffic volume is considered. Maximum increase in damage in comparison with first study occurs in 45.7 m Truss Bridge with the increase in traffic volume.

Prediction of remaining fatigue life is done for two cases namely, bridge history known and bridge history unknown. In the history known case, remaining fatigue life is calculated for 45.7 m Truss Bridge. While in history unknown case the past traffic volume and material properties are not known. To know the material properties experiments are done to derive S-N curve for the bridge material coupons.

I. INTRODUCTION

ASTM defines fatigue as ‘the process of progressive localized permanent structural change occurring in the material subjected to conditions which produce fluctuating stresses and strains at some point or points on which may culminate in fracture after a sufficient number offluctuations.’
It is a well known fact that any structural component loses its strength with repeated use. The branch of science, which deals with this process, is called fatigue analysis. In engineering science, fatigue is a process by which a material is weakened by repeated cyclic loading. The resulting stress may be below the ultimate tensile stress, or even the yield stress of the material, yet still cause catastrophic failure, in which after a certain number of cycles the residual strength of the component reduces down to the service stress and failure becomes probable.

Fatigue failure occurs in many different forms. The fluctuations in externally applied stresses or strains result in mechanical fatigue. Cyclic loads acting in association with high temperature cause creep-fatigue; when the temperature of the cyclically loaded component also fluctuates, thermomechanical fatigue is induced. Recurring loads imposed in presence of a chemically aggressive or embrittling environment give rise to corrosion fatigue. The repeated application of loads in conjunction with rolling contact between materials results in rolling contact fatigue, while fretting fatigue occurs as a result of pulsating stresses along with oscillatory relative motion and frictional sliding between surfaces. [Fatemi et al,1998]

Bridges play an important role in railway infrastructure throughout the world. In India there are about 250 important and 3000 major bridges older than 100 years and 180 important and 2900 major bridges aging 50-100 years. With the increase of traffic demands on railway networks, common problems have begun to arise. At present, rail authorities all over the world are paying special attention to evaluate the remaining fatigue life of railway bridges, since most of these bridges are approaching or exceeding their design fatigue lives. These structures are continuously experiencing increase traffic volume and loads, deteriorating components as well as a large number of stress cycles. The remaining fatigue life of bridges.

II. PREDICTION OF RESIDUAL FATIGUE LIFE

General

This chapter deals with the determination of remaining fatigue life of bridges. Fatigue life is calculated for two different conditions,

- Bridge History Known
- Bridge History Unknown

Bridge History Known

In this condition we know the history of loading over the bridge and the original properties of the bridge material at the time of construction. So, in this case residual fatigue life prediction becomes easy as no experimental work is required to be done. Only the degradation rate of the material properties and increase in traffic volume rate is required to be known. Remaining fatigue life is derived using the Miner's rule by two different ways.

Calculated Till Damage Index Becomes Unity

The new damage index (present D_i value) is calculated from the date of bridge construction to the present by considering the sequence of stress ranges of each critical member. Assuming that future sequence of passage is similar to that of the present day or some percent increase in traffic is considered, the time taken to reach the present day's D_i values to one (when D_i = 1 is considered as fatigue failure) is considered as the remaining fatigue life for each critical member. [Mesmacque et al, 2005]

For example:

Determine the residual life of the plate girder bridge which is analysed at the age of 60 years.

(a)No increase in traffic and (b) for increase in traffic of 2% per annum. The S-N curve used is of 80Mpa.

Sol:

Max Damage Index in Flexure (Top) + Axial = 0 .6775 for 410 Max Damage Index in Flexure (Bot) + Axial = 0.6775 for 310 Max Damage Index in Axial = 0.261E-04 for501
Max Damage Index in Shear = 0.233E-01 for630

Bridge is SAFE in fatigue for design life of 120 years for loads considered.

$D_{60} = 0.6775855$

n_R = residual cycles
N = no. of cycles at failure
No. of cycles per annum = P =12045

$$D_{60} = 0.6775855 = \frac{12045x60}{N}$$

N = 1066581.265

$$D_{60} + \frac{n_R}{N} = 1$$

$$\frac{n_R}{N} = 0.3224$$

$$n_R = 343865.8$$

(a) no increase intraffic

$$\text{Residual life} = \frac{343865}{12045} = 28.55 \text{ years}$$

(b) increase in traffic of 2 % perannum

$$\sum_{i=1}^{n} P(1+a)^i = n_R \qquad (4.1)$$

n = residual life a =
% increase
Residual life = 22.157years.

Calculated Till Remaining Cycles Reduce to Zero

Residual life of the 45.7m Truss Bridge is determined**.** The age of bridge under consideration is 60 years. By knowing the history the damage done till date is determined by detailed analysis. We determine residual fatigue cycles and then convert the cycles into no. of years by knowing the future traffic volume and degradation rate of the material properties.

$$D = \frac{n_1}{N_1} = 0.2658 \qquad (4.2)$$

Following table shows the maximum stress ranges for each train and future percentage usage for the respective trains.

Table 5.1 Maximum Stress Range and Percentage of Traffic Usage for each Train

Train	Max. stress range	% Traffic
1	86.04	15.79
2	109.67	15.79
3	84.18	5.263
4	113.06	15.79
5	118.54	31.579
6	118.56	5.263
7	78.98	5.263
8	109.62	5.263

The residual no. of cycles can be derived from the formula below.

$$\frac{n_1}{N_1}+\frac{0.1579n_2}{N_{21}}+\frac{0.1579n_2}{N_{22}}+\frac{0.0526n_2}{N_{23}}+\ldots+\frac{0.0526n_2}{N_{28}}=1 \qquad (4.3)$$

Where, n_2 = residual no. of cycles

N_{21} = Total no. of cycles at failure for maximum stress due to train 1 N_{22} = Total no. of cycles at failure for maximum stress due to train 2

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N_{28} = Total no. of cycles at failure for maximum stress due to train 8

Taking into account the degradation in the material properties and % increase in traffic volume we can derive residual fatigue life of the bridge. No degradation is considered and the constant traffic volume of 25 GMT till date is considered. However, degradation of 5%andpercentageoftrafficvolumeincreaseis10perdecadeisconsiderinfuture.

Following table shows the degradation and traffic volume increase rate and damage index till failure.

Table 5.2 Rate of Degradation, Increase in Traffic Volume and Damage Index for Case 3

Age	Degradation	% Increase in Traffic	Damage
60	0	0	0.265
70	5	10	0.324
80	10	20	0.402
90	15	30	0.502
100	20	40	0.637
110	25	50	0.804
120	30	60	1.025

Total no. of residual cycles = 1017452.624

Using the future degradation rate and increase in traffic volume remaining fatigue life is calculated using the equation 4.3

The Remaining Fatigue Life of the bridge = **59 years**

Bridge History Unknown

This study deals with the procedure for determining the remaining fatigue life of bridges when traffic history and the material properties are not known. The procedure for the prediction of residual fatigue life is as below.

1. Obtain coupons from the most stressed member of the bridge and then replace it with other piece of steel so, that the section of the member does not reduce and endanger the life of bridge.
2. Experiments are done on the coupons to derive S-N curve for the bridge material. Now we consider the bridge as new bridge and use the S-N curve derived from experiments.
3. Knowing the future degradation rate in material properties and increase rate of traffic volume the remaining fatigue life can be determined using the equation4.3.

Residual fatigue life of the case study 2 is derived using this method. Assuming that after doing the experiments the S-N curve for the material is of 80 MPa.

Table 5.3 Percentage of Traffic Usage and Maximum Stress for each Train

Train	% Traffic	Max stress range
1	15.79	70.98
2	15.79	75.33
3	5.263	71.70
4	15.79	72.05
5	31.579	74.53
6	5.263	75.59
7	5.263	73.91
8	5.263	76.12

Table 5.4 Rate of Degradation, Increase in Traffic Volume and Damage Index for Case2

Age	Degradation	% Increase in Traffic	Damage
10	0	0	0.027
20	5	10	0.072
30	10	20	0.137
40	15	30	0.225
50	20	40	0.344
60	25	50	0.510
70	30	60	0.746
80	35	70	1.072

The Remaining Fatigue Life = **78.28 years**

Summary

In this chapter procedure for predicting fatigue life is given for two conditions, namely bridge history known and bridge history unknown. Fatigue life prediction is done using the Miner's rule considering the degradation in the material properties with time and increase in traffic volume rate.

Fatigue Analysis by Simplified Procedure

Assessment for Simplified Load Models

This chapter deals with the fatigue analysis of 25 meter Plate Girder Bridge using simplified procedure given by IRS steel bridge code. The procedure is as follows:

1. Themaximumstress$\sigma_{P,max}$andtheminimumstress$\sigma_{P,min}$aredeterminedforadetail or structural connection by evaluating influenceareas.
2. The reference stress range $\Delta\sigma_P$ for determining the damage due to the stressspectrum is be obtainedfrom:

$$\Delta\sigma_P = |\sigma_{P,max} - \sigma_{P,min}|$$

3. The damage effects of the stress range spectrum may be representedbythe damage equivalent stress range related to 2 millioncyclesas

$$\Delta\sigma_{E,2} = \lambda * \Phi * \Delta\sigma_P$$

where

λ is the damage equivalence factor,and

Φ is the dynamic impactfactor.

$$\lambda = \lambda_1 \times \lambda_2 \times \lambda_3 \times \lambda_4$$

where

λ_1 is a factor that takes into account the damaging effect of traffic and depends on the base length of the longest loop of the influence linediagram

λ_2 is a factor that takes into account the annual traffic volume in milliontonnes

λ_3 is a factor that takes into account the design life of the bridge inyears

λ_4 is a factor to be taken into account when the bridge structure is loaded on more than onetrack

The value of λ_2, in terms of the annual volume of traffic may be obtained from the following expression:

$$\lambda_2 = 0.5193 * T_a^{0.2036}$$

Where T_a is the annual volume of traffic expressed in million tonnes.

λ_3 = 1.04 for design life of 120 years.

λ_4 = 1

Partial Safety Factor

Partial safety factor for fatigue loading γ_{Ff}

To take account of uncertainties in the fatigue response analysis, the design stress ranges for the fatigue assessment procedure shall incorporate a partial safety factor γ_{Ff}.

The partial safety factor γ_{Ff} covers the uncertainties in estimating:

- the applied load levels,
- the conversion of these loads into stresses and stress ranges,
- the equivalent constant amplitude stress range from the design stress range spectrum,
- the design life of the structure, and the evolution of the fatigue loading within the required design life of the structure.

Here γ_{Ff} = **1** is used.

Partial safety factor for fatigue strengthγ_{Mf}

In the fatigue assessment procedure, in order to take account of uncertainties in the fatigue resistance, the design value of the fatigue strength shall be obtained by dividing by a partial safety factor γ_{Mf}. The factor γ_{Mf} covers the uncertainties due to the effects of:

- the size of the detail,
- the dimensions, shape and proximity of the discontinuities,
- local stress concentrations due to welding uncertainties.
- variable welding processes and metallurgical effect

Here γ_{Mf}= **1** is used.

Table 6.1 λ_1 for 25m span and MBG loading and $\Delta\sigma_{E,2}$ for all train

Train	$\Delta\sigma_p$	λ_1	λ	$\Delta\sigma_{E,2}$
1	46.21	0.6782	0.3663	24.04
2	47.80	0.7558	0.4451	30.22
3	47.52	0.7332	0.4088	27.59
4	49.25	0.6623	0.4726	33.06
5	50.66	0.7382	0.6515	46.87
6	50.89	0.8967	0.6342	45.83
7	46.14	0.8527	0.3821	25.04
8	47.59	0.6511	0.3015	20.38

Solution gives as many no. of $\Delta\sigma_{E,2}$ as that of no. of trains. So, superposition of $\Delta\sigma_{E,2}$ is required.

III. SUMMARY

In this chapter attempt is made for the fatigue assessment of 25 m Plate Girder Bridge using the damage equivalence factor given in the fatigue provisions in IRS steel bridge code. In this, to know whether bridge is safe for design life or not $\Delta\sigma_{E,2}$ is compared with $\Delta\sigma_c$. But, we get as many number of equivalent stress ranges as number of trains. So, superposition of the equivalent stress ranges is required for comparison with $\Delta\sigma_c$can play a major role in making cost-effective decisions regarding rehabilitation versus replacement of existing bridges.

IV. CONCLUSION

Fatigue damage primarily depends on stress range level, number of cycles, and type of structural detail category. In the course of this project parametric study is done on three casestudies.Case1is25mPlateGirderBridge,Case2isa30mTruss bridge,Case3isa 45.7 m Truss Bridge. In the parametric study considering only degradation in material properties and same traffic volume, damage occurring from time of construction of bridge upto 120 years is calculated per decade interval. Minimum damage occurs in the 25 m Plate Girder Bridge as the section used for the girder is large enough to take the damage exerted, while the maximum damage in the 45.7 m Truss bridge as the section is comparatively small with respect to 45 m span and the stress range is higher.

In the second parametric study degradation in material properties as well as 10 % of increase in traffic volume per decade is considered. So, for the Case 1 at the end of 120 years with the increase in traffic volume of 70 % with initial traffic volume, the damage is increasedby40.42%.WhileforCase2attheendof120yearsthedamageisincreasedby 38.12 % and for Case 3 by 47.74 %.

In the third parametric study effect of higher axle loads is considered on the three case studies. In case when boogie axle loads are less than locomotive axle load, stress increases gradually as the locomotive is over the bridge, as the locomotive passes away stress decreases to certain level and remains constant and we get a single large stress range value which does the maximum damage. While in the case when boogie axle loads are more than the locomotive axle loads, stress increases to maximum and remains in the same range till end and in this case also we get a single large stress range which does the maximum damage of about 95-98 % of total damage. For the same traffic volume but higher axle loads, more damage occurs in the bridge members, so rather than increasing the axle loads for carrying more loads, traffic volume should be increased or long trains of less axle loads should be used to increase the life of bridges.

Procedure for prediction of residual fatigue life is given for two cases namely,

(i) Bridge history known and (ii) bridge history unknown.
For (i), residual fatigue life is calculated for case study 3. This method can give good residual fatigue life prediction as both the material degradation and increase in traffic volume can be taken into account. While in the case (ii), the past traffic volume and material properties are not known. So, experiments are required to be done for deriving S-N curve and fatigue calculations are done considering the bridge as a new bridge.

Simplified procedure derived in this study is based on EN-1993. A damage equivalence factor is calculated for various spans and for different trains. So using the damage equivalence factor and maximum stress range we get equivalent stress range at 2 million cycles. Then $\Delta\sigma_{E,2}$ is compared with $\Delta\sigma_c$. This gives whether the bridge is safe for the designed life or not. But here we get no. $\Delta\sigma_{E,2}$ as the no. of trains, so superposition is required and we cannot get the solution. The damaged equivalence factor is independent of the S-N curve used and is also partially independent on the section modulus properties of the member. This is because at certain stage the slope of the S-N curve changes from 5 to3.

V. SCOPE OF FUTUREWORK

The future work for this project can be

- Studying degradation in properties of steel with respect to time and the environmental exposure.
- To propose a simplified procedure for fatigue life assessment.
- To propose a Fracture Mechanics based approach.

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