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Analysis, Field Testing and Evaluation of Fatigue Life of Plate Girder Railway Bridge at Ravi River

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***Abstract*— Natural disasters like Earthquakes, Tsunamis, Sea and Wind Storms are common in the world. Their intensity and location are unpredictable. Major effects of these natural forces are the loss of human life and property. The damage to the property is different for different locations and for different types of structures. Extensive damage requires demolishing of structures. But moderate to medium level damage to the structures can be compensated by using the re-strengthening / retrofitting techniques. Re-strengthening / retrofitting is not a latest technique used for reinforcing the structure. It is as old as humanity. Usually everyone wants to restore their property with minimum cost. These days the framed structures are very common. Moderate level damages to these structures includes plastic hinge formation at the beam column joints, spalling and partial crushing of concrete, etc. The structures which have failed to such extent but are staying at their position can be restored by retrofitting. Generally, the member dimensions are increased and a bond is created between the new material and the old material so that they both contribute against loads. In this laboratory scale level study columns are prepared and loaded to the certain damage level. After that columns are re-strengthened/retrofitted by reinforced concrete jacketing and their behavior is studied after jacketing. Testing results show that load carrying capacity of the columns is increased and columns are still useable. In this way huge cost required for demolition and rebuilding can be saved.**

***Index Terms*— Re-strengthening, Retrofitting, Concrete jacketing, Reinforced concrete.**

I. INTRODUCTION

Most of Pakistan Railways bridges had been put in service more than 100 years ago. Nothing has been done on analysis of these bridges. However routine preventive maintenance and inspections are carried out by Railways. Similarly, Ravi Railway bridge has never been studied under modern loading and traffic requirements and neither has been rehabilitated or strengthened. Nevertheless, bridge piers have been reported to be repaired along with the routine maintenance involving painting of steel elements.

It has become a crucial requirement to work out remaining serviceable life of the railway bridge. Also with the transformation of Pakistan Railways on advanced model trains network with the use of latest and modern locomotives of high speed, it is a requirement of time to check the adequacy of existing old bridges. And as a result a rehabilitation and strengthening program is worked out.

The bridge under study links the towns of Badami Bagh and Shahdara and crosses over River Ravi. Up line has been supported on a deck bridge which is a riveted connected structure. The line was set up for traffic in April 12th, 1875. Down Line bridge has been supported on a truss deck structure that is with riveted connection too. This line was opened for traffic on January 10th, 1913. The railway bridge consists of 15 (fifteen) simply supported spans. Each span is of 94'-6". Up Line Track has been placed on top flange of the steel girder whereas Down line track has been fixed on top members of the steel truss.

In developing this paper, the basic and advanced concepts of fatigue have been taken from ESDEP (European Steel Design Education Program) lectures on Fatigue. These lectures at Ref-2 & 3 below introduce the main concepts and definitions regarding the fatigue process and the main factors that influence the fatigue performance of materials, components and structures.

Another research (Ref-6) describes the result of a study conducted on detailed examination of fatigue test data, other data from studies elsewhere in the world and the results of 14 fatigue and fracture tests on full scale members removed from bridges.

The paper by P. Kunz and M. A. Hirt(Ref-7) presented at Third International Workshop on Bridge Rehabilitation, Technical University, Damstadt, presents a method for evaluation of the failure probability of construction details. This probability has been recommended to be considered during decisions on maintenance and in particular for the selection of supervision and inspection intervals.

Another research paper at Ref-8 by R.K Goel presents a study of existing provisions of Indian Railway Standard Steel Bridge Code and the BS-5400 in respect of fatigue design of Railway Bridges.

II. METHODOLOGY

The prime objective of this study was to calculate the lapsed and balance fatigue life of Ravi Bridge. For this purpose, theoretical analysis as well as actual field testing have been carried out on the bridge. Theoretical values have been interpolated after comparing these with actual readings.

Pakistan Railways have been contacted to share the historical record of rail traffic passed over the bridge and the same have been considered to evaluate fatigue strength. With this analysis, stress ranges and corresponding stress cycles have been worked out that are supposed to be induced in the bridge with the passage of trains to date.

These values have then been plotted on Wohler Curve and fatigue life has been worked out.

III. FATIGUE

Fatigue is the wear and tear caused by repeated (cyclic) application of stresses. Normally these stresses are quite lower than the ones the structure can resist in static condition. Areas and regions experiencing tensile stresses starts becoming weaker and ultimately the failure of the material takes place when the material and its cross section becomes too weak to withstand the stresses. Initiation of cracks and their subsequent propagation is the basic mechanism of failures subject to fatigue. Finally, a Ductile or a brittle failure takes place once the propagating crack reaches its critical length. In the figures below, fatigue crack propagation is shown along with the beach marks (curvy parallel lines). The crack initiates at the edge and propagates perpendicular to the beach lines.

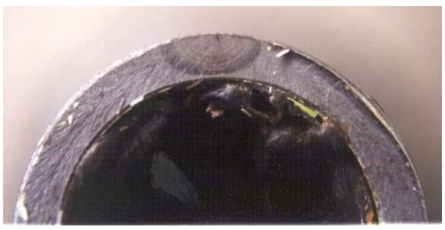

Figure 1 Propagation of fatigue crack initiating from origin along with failure surface. Crack and the beach lines are visible.

Fatigue in structures or in connections can result in failure caused by cyclic application of stresses that are even lesser in magnitude than the ones structure can resist if applied once and not in repetitions. When locomotives and trains pass over a railway bridge, they develop repeated application of stresses due to their movement. With the development of heavy locomotives and carriage cars in railways, the fatigue conditions of older bridges still in service have been put to serious concerns. A bridge might have been carrying a huge number of trains over passed many years and experiencing cyclic stress applications. Such a scenario is highly prone to undergo a fatigue stress and eventually could become a victim of the same.

Fatigue cracks propagates easily in the regions of stress concentration like an abrupt change in geometry such as notches, holes, re-entrant cuts, or any other sudden changes in stiffness.

In a bridge structure all the members are not likely to become a victim of fatigue. All such members which experience compressive stresses under the application of live and dead loading never fail by fatigue. Top chords and end posts of truss structures top flanges of girders and beams are the examples of members never exhibit compression. However, the members experience tensile stresses under dead and live loading like bottom chords and diagonal chords are more prone to fatigue failure.

Stress pattern and cycles under service conditions of rail road loading are not simple enough. It is because of the fact that more than one repetition of stresses may be obtained under certain conditions against a single pass of train. Also there may be some members that undergo only one stress cycle for each pass of train. For the first case the number of stress cycles is the same as the number of axles in a train, but in the second case only one stress cycle is developed for a complete train pass. Hence, the number of stress cycles is a function of spacing and number of the axles of the vehicle, span dimension of the member and the whole structure, and the location of the member in the bridge.

IV. FIELD TESTING OF BRIDGE

Pakistan Railways had arranged the physical testing of Ravi Bridge On Up-line in 2006. During the testing of bridge, 40 (channels) strain gages were fixed at predefined positions on girders and rails. Out of total number of channels, 38 channels were used for installing strain gages and 2 were used to record the LVDTs (Linear Variable Differential Transducers). A control software named STRAIN SMART had been used to process data from strain gages.

The strain gages were fixed to record the readings at predefined location that undergo maximum bending moment, maximum shear forces, and maximum deflections. To monitor the maximum flexural stresses, the gages were installed at mid span of girders situated at top and bottom flanges. Similarly, gages were installed at webs of both girders for monitoring the maximum shear stresses. These were placed at a distance of 3 feet from either supports. Maximum deflection was likely to occur at mid span so (LVDT, Linear Variable Differential Transducers) had been installed at mid span on the flanges of each girder.

Some of the gages had also been installed at rails- Their purpose was to calculate the actual value of wheel loads for each pass of the train at different velocities.

Following figures show the installation of strain gauges at various parts of the bridge.

Visual inspection showed some minor irregularities on few structural parts. A similar buckled lower flange of the girder is shown in fig-2.

Figure 2 Deformed/buckled parts of the girder near the support.

Strain gauges for recording maximum flexural tensile stresses had been installed at the bottom of lower flange of girders. Fig-3 shows installation of same strain gauge.

Figure 3 Strain gauge at bottom of main girder.

A computerized arrangement of interconnection of all gauges had been set up at site for recording their readings against all scan sessions during testing. Figure-4 shows the arrangement set up at site.

Figure 4 Data acquisition and recording systems.

For recording maximum shear stresses, the strain gages had been installed at middle height of the girder at the support. Such a strain gage has been shown in fig-5.

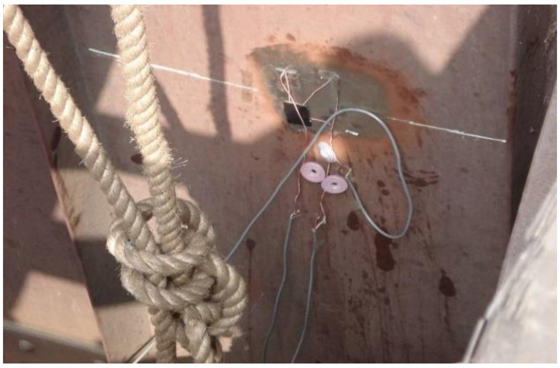

Figure 5 Strain gauge installed at middle height of girder at the support for recording maximum shear stresses.

Some of the strain gauges had also been installed directly at the rails. These were intended to work out the impact value with varying speed of test train. Such gauges have been shown in fig-6 below.

Figure 6 Strain gauge installed at rail for wheel load impact calculations.

Maximum deflections always occur at mid span on a simply supported girder. A system of LVDTs had been installed at the soffit of girders at mid span. The LVDTs are shown in fig-7 below.

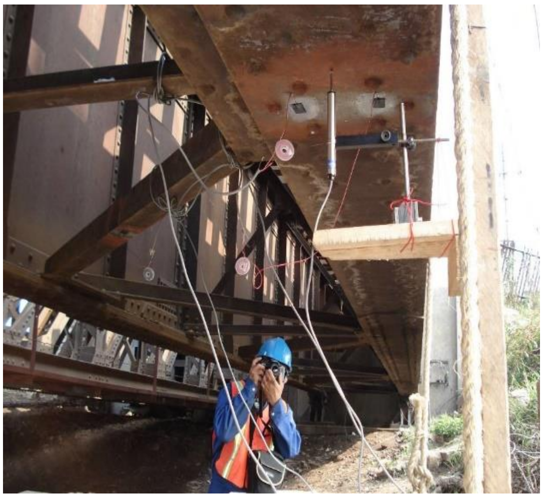

Figure 7 LVDTs installed at girder for max deflection.

Pakistan Railways had arranged a specially assembled TEST TRAIN for physical testing of Ravi Bridge. The TEST TRAIN passed over the bridge on both UP and DOWN directions at different predefined speeds, called SCAN SESSIONS. The schematic diagram of wheels, their spacing and loads acting on each wheel of test train is shown in fig-8.

The installed strain gages recorded and stored the readings against each of 24 train passes. The speed of the Test Train ran over bridge varied between 3.5 km/h and 90 km/h. All the data recorded during testing of bridge under test train, had been processed through STRAIN SMART software. As a result, the strains and deflections and subsequent stresses have been worked out.

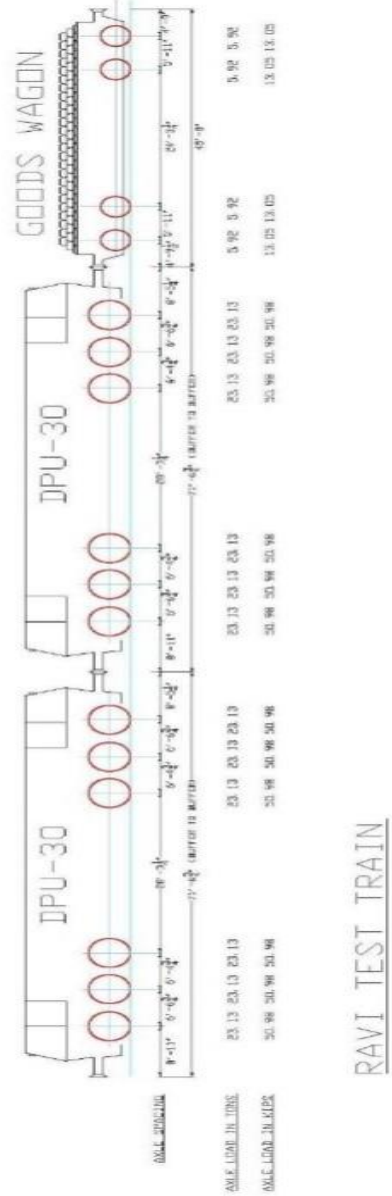

Figure 8 Details of the test train.

Shear Stresses had been worked out for both the girders at their either end. These are tabulated below:-

Shear stress in South Girder East End = 11.51 ~ 14.69 MPa.
Shear stress in South Girder West End = 12.27 ~ 14.13MPa.
Shear stress in North Girder East End = 10.82 ~ 13.72MPa.
Shear stress North Girder West End = 13.38 ~ 15.17MPa.

Flexural tensile and compressive stresses had been worked for both the girders and their values are shown below: -

Flexural Compressive Stress South Girder = 41.51~49.99MPa.
Flexural Tensile Stress South Girder = 35.99~41.16MPa.
Flexural Compressive StressNorth Girder = 42.26~44.81MPa.
Flexural Tensile Stress North Girder = 35.71~ 42.26MPa.

Mid span deflections had been computed from the gauges installed at bottom of both the girders at mid length. Their values are shown below: -

Maximum mid span deflection South Girder = 15.62 mm.
Maximum mid span deflection North Girder = 15.82 mm.

V. THEORATICAL ANALYSIS OF BRIDGE AGAINST TEST TRAIN

The Up-line Bridge has been modeled and analyzed in STAAD PRO 2005. The test train of figure 8 had been modeled in STAAD PRO. Moving load command had been used in STAAD PRO to apply the test train loading in moving pattern. The result of analysis in terms of resulting stresses and strains have been worked out in software and the critical ones are listed in Table 1.

Table 1 Comparison of maximum theoretical and experimental results for the test train

COMPARISON OF MAXIMUM THEORATICAL & EXPERIMENTAL RESULTS												
Sr #	LOCATION OF GAGE	COMPUTER ANALYSIS (TEST TRAIN WADING) Stresses (MPa)		EXPERIMENTAL RESULTS OBTAINED FROM STRAIN GAGES								
		PLANE FRAME MODEL	SPACE FRAME MODEL	3.5 KM/ H	10 KM/ H	20 KM/ H	30 KM/ H	40 KM/ H	50 KM/ H	60 KM/ H	75 KM/ H	90 KM/ H
1	Shear Stresses-East end of south Girder	26.20 *	26.20 *	11 58 *	11.86 *	13.51.	14.41 *	13.51 *	12.34 *	11.79 *	11.79 *	12.20 *
2	Shear Stresses-East end of north Girder	26.20 *	26.20 *	26.89 *	12.27 *	12.07 "	12.55 *	12.20 *	12.27 *	11.86 *	11.58 *	11.93 *
3	Flexural Compressive Stresses-South Girder	-76.04 *	-63.71 *	-45.78 *	-41.92 *	-42.75 *	-43.78 *	-44.06 *	-42.51 *	-43.30 *	-44.47 *	-43.71 *
4	Flexural Tensile Stresses-South Girder	76.04 *	63.55 *	36.54 *	36.89 *	38.27 "	41.02 *	40.39 *	36.61 *	37.78 *	36.61 *	37.09 *
5	Flexural Compressive Stresses-North Girder	-76.04 *	-62.86 *	-42.82 *	-42.95 *	-43.02 *	-44.13 *	-44.20 *	-43.44 *	-45.09 *	-44.40 *	-43.71 *
6	Flexural Tensile Stresses-North Girder	76.04 *	63.5 *	36.06 *	36.54 *	38.20 *	41.44 *	39.99 *	38.40 *	39.09 *	39.09 *	38.27 *
7	Shear Stresses-West End of South Girder	26.20 *	26.20 *	13 10 *	13.24 *	13.03 *	13.51 *	13.72 *	13.51 *	13.51 *	12..27 *	14.13 *
8	Shear Stresses-West End of North Girder	26.20 *	26.20 *	14.27 *	14.41 *	14.48 *	14.48 *	14.62 *	14.48 *	14.48 *	14.07 *	13.72 *
´-SHEAR STRESSES, NOTE:COMPUTER ANALYSISINCWOES THEIMPACT VALUEAS PER PAKJSTAN Railways "BRIDGE RULES" ´´. - COMMRESSJVE FLEXURAL STRESSES												

The prime objective here is to calculate the lapsed and balance fatigue life of Ravi Bridge. For this purpose, theoretical analysis as well as actual field testing has been done on the bridge. Theoretical values have been interpolated after comparing these with actual readings.

VI. THEORATICAL ANALYSIS OF BRIDGE UNDER VARIOUS GROUPS OF LOCOMOTIVES

Analysis of the same Railway Bridge has also been done for various groups of locomotives. These locomotives have been reported to pass over the bridge throughout their life. Computer analysis models using STAAD software were prepared for each group loading and the resulting stresses were calculated. The maximum stresses obtained from these results are shown in Table 2.

Table 2 Analysis results for various trains.

Stress Type	Shear Stress. LHR End (MPa)	Shear Stress. SHAHDRA End (MPa)	Flex. Tensile Stress (MPa)	Flex. Comp. Stress (MPa)
ML Load. 1926	31.71	31.71	100.59	100.59
Gr-1 Loco.	24.82	24.82	74.12	74.12
Gr-2 Loco.	24.13	24.13	75.29	75.29
Gr-3 Loco.	22.06	22.06	70.81	70.81
Gr-4 Loco.	20.00	20.00	64.47	64.47
Gr-5 Loco.	17.24	17.24	58.47	58.47

VII. LOAD SPECTRUM FOR FATIGUE ANALYSIS

For the fatigue evaluation, loading is converted into load spectrums. The load spectrums consist of bars representing constant load levels, and the frequency of occurrence of each level. The stress ranges can be taken from the single application of the load from the structural analysis and the corresponding number of stress cycles can obtain from the number of cycles produced by one passage of train multiplied with train traffic record of the controlling authority.

For preparation of load spectrum of the bridge under consideration, stress ranges for each locomotive group train have been worked out in this study. The railway traffic history defining the groups of locomotives has been acquired through Railway Authorities. Table 3 shows the stress ranges and their corresponding with the number of cycles corresponding to each stress range.

Table 3 Groups of locomotives trains Stress ranges and corresponding number of cycles.

Sr #	GROUP ID	STRESS RANGE (MPa)	Δσ (MPa)	NO. OF CYCLES (n)
1	Group-1 Trains	0 ~ 74.12	74.12	225892
2	Group-2 Trains	0 ~ 75.29	75.29	14157
3	Group-3 Trains	0 ~ 70.81	70.81	801214
4	Group-4 Trains	0 ~ 64.47	64.47	112946
5	Group-5 Trains	0 ~ 58.47	58.47	734147

The above mentioned data can also be transformed in form of a traffic histogram and load spectrum as below. The same shall be utilized for the calculation of fatigue life of the bridge.

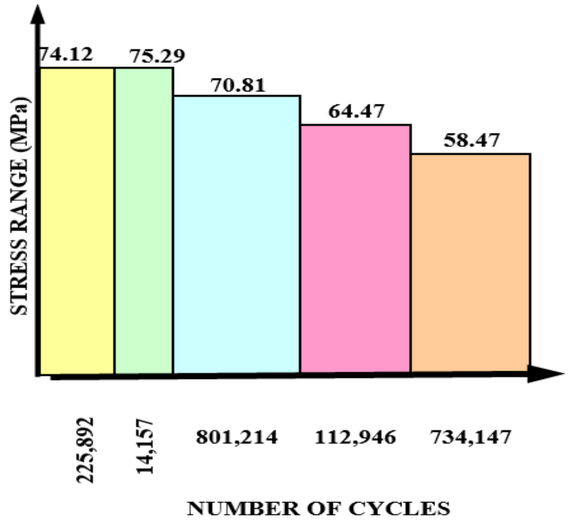

Figure 9 Loading spectrum for service life of Ravi Bridge.

VIII. A - VALUE

The theoretically computed stress ranges vary from the stresses actually induced in the structural members during testing. This difference is related in form of a ratio of measured stresses to those values computed theoretically and is termed as α –Value.

α-Value for Ravi bridge has been worked out as follows using the results of test train and computer analysis for same loading: -

α – Value (Actual Stress/Theoretical Stress)

=38.26/76.04 = **0.503**

The theoretically calculated stresses have been corrected with α –Value, and are given in Table 4.

Table 4 Corrected stress range for groups of locomotive Trains.

Sr #	GROUP ID	STRESS RANGE (MPa)	NO OF CYCLES	CORRECTED STRESS RANGE (MPa)
1	Group-1 Trains	0 ~ 74.12	225892	**0 ~ 37.30**
2	Group-2 Trains	0 ~ 75.29	14157	**0 ~ 37.85**
3	Group-3 Trains	0 ~ 70.81	801214	**0 ~ 35.58**
4	Group-4 Trains	0 ~ 64.47	112946	**0 ~ 32.41**
5	Group-5 Trains	0 ~ 58.47	734147	**0 ~ 29.44**

IX. WOHLER CURVE

WÖHLER was the first one to conduct systematic studies on fatigue of materials. He graphically presented his results in the form of an S-N Curve or Wöhler Curve. These curves are drawn going through a large number of tests. The number of stress cycles is shown on x-axis using logarithmic scale, while the algebraic difference between the two extremes of a stress cycle, called the stress range ($\sigma_{max} - \sigma_{min}$), is taken on the y-axis. A series of Wöhler Curves are plotted for a number of typical welded or bolted connection details showing the relationship between the stress range and the logarithm of the number of cycles.

AREMA (2000) specifications classify various structural members based on the possibility of stress concentration for various types of connection details. The seven stress concentrations categories are named A, B, C, D, E, E/, and F (Fig-9.7.3.4.2A of AREMA 2000). These S-N curves for each category are developed for 95% confidence limit using the available test data. These S-N Curves are reproduced in figure 10.

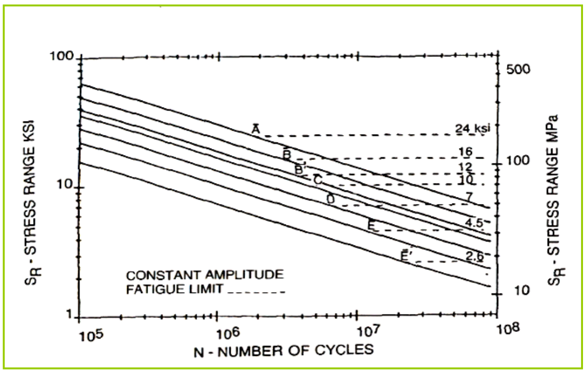

Figure 10 S-N Curve for different categories of structural members.

The above mentioned data is transformed into a constant-amplitude stress range from variable-amplitude stress spectrum for different groups of trains and is used for fatigue life evaluation. AREMA RMC relationship (Art. 15-9-34) has been used to transformation a variable-amplitude stress ranges into an equivalent constant-amplitude stress range: -

$$S_{re} = \alpha\ (\Sigma\ \gamma_i \times SR_i^3)^{1/3}$$

Where:

S_{re} = Effective stress range for total number of variable stress cycles, N_v.

γ_i = Ratio of the number of occurrences of SRi to the total number of variable stress cycles N_v.

SR_i = Stress range of cyclic stress corresponding to the number of occurrences n_i.

α = Actual stress / theoretical stress.

N_v = Total number of loading cycles.

For a given resulting applied stress parameter "S_{re}", a horizontal line is drawn on the fatigue strength (S-N) curve to reach the curve corresponding to the selected connection detail. A vertical line is then drawn to read the fatigue life. If the number of loading cycles that has actually taken place is less than the loading cycles given by the curve, the structure has not passes its fatigue life. Further, the remaining service life of the structure may also be estimated.

It is to be noted that if the "S_{re}" is less than the constant amplitude fatigue limit or if loading cycles are in compression, the fatigue life is infinite.

If the calculated "Sre" value lies over the S-N curve or the horizontal line through the stress range cannot intersect any curve, it means that the member is already over-loaded and proper attention is required to prevent any damage and to continue the service life.

X. RESULTS

Total number of loading cycles "N_v = 1888356 cycles" and effective stress range "S_{re}=33.58MPa as calculated using AREMA RMC relationship (Art. 15-9-34)" when plotted on Wöhler Curve (S-N Curve) and observing the fatigue life against fatigue category "D, riveted structure", the elapsed and balance fatigue life for the bridge are shown in figure 11.

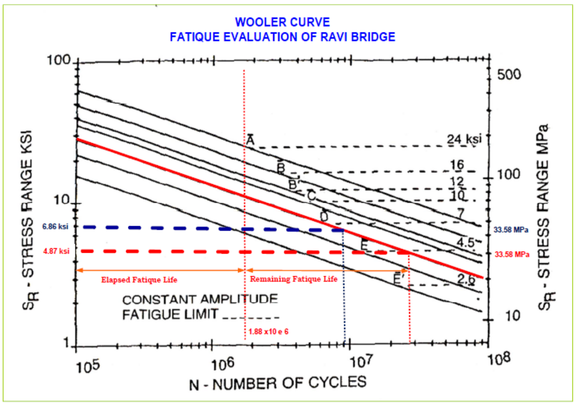

Figure 11 S-N Curve for Ravi Bridge showing elapsed and balance fatigue lives.

The S-N Curve for Ravi Bridge shows that so far the bridge has consumed only approximately 6.7 % of its fatigue life [1.88 x 106 / 2.8 x 107 x 100 = 6.7 %]. The values correspond to red dashed line in figure-11 above.

XI. BRIEF DISCUSSION ON RESULTS

The elapsed fatigue life of the bridge comes out to be just 6.7 % which is a very small figure. This might be due to the combined or individual effect of following reasons: -

- Loading cycles obtained from Pakistan Railways history might be at a lower side. The under consideration bridge was constructed in 1910. And the traffic history record may have a chance of showing lesser number of train passes.
- The bridge girder is supported on a pin support at one end and a roller support on other. Practically there is neither perfect pin nor a roller. Moreover, with this much time elapsed, the behavior of pin and roller might get farther away from true sense of roller and pin.
- □–Value for Ravi Bridge has been worked out as 0.503. Usually this value should range from 0.70 to 0.85. Nevertheless, assuming a value of 0.85 gives a stress range of 47.32 MPa (6.86 ksi). This value is also plotted with blue color dashed line in figure-11 above. Which also results into a 20% elapsed fatigue life.
- The bridge was tested in year 2006 and as such 11 more years of service have already passed.

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