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A State-of-the-Art Review on Fatigue Analysis of Steel Bridges

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Abstract: **-- Fatigue is a localized and progressive cumulative damage accumulation due to continuous cyclic movement on a structure. The effects due to this can be dangerous as compared to conventional static load. On bridges, fatigue occurs due to passage of vehicular load. In railway steel bridges, there are structural members with low dead load stresses but high live load stresses due to movement of wagons and locomotives. These high live load stresses cause a decrease in strength well below the design stresses. This, in turn, reflects the reduction in useful life of the bridge. Here, live load stresses are assessed for different members and details of bridges. Various analytical methods suggested such as nominal stress method, Hot spot stress method, Effective notch method, etc. The results of these methods are compared with the field measurement data obtained from strain gauges or structural health monitoring methods. The nominal stress method has been mentioned in various codes like BS 5400: 1980 (Part X), Steel Bridge Code, RDSO, etc. While the hot spot stress method depends on the finite element analysis of bridges. It finally concludes with the calculation of stress concentration factors for a particular detail. The failure due to fatigue does not depend upon the maximum stress, but on the stress range (absolute difference of maximum and minimum stresses) and the number of cycles corresponding to that stress range also called as stress history. Using the S-N curve and Palmgren-Miner's cumulative damage rule, the damage assessment for each moving load is calculated followed by useful life estimation of a structure. This is a brief methodology for nominal stress method. The revised fatigue Appendix 'G' in Steel Bridge Code, RDSO has incorporated this method in addition to geometrical stress method (or hotspot stress). The nominal stress method is widely used for fatigue evaluation and design of steel bridges, but the hot spot stress method is more accurate and effective. Though the field measurement data presents most accurate information for determining the fatigue life of the structure, the above said two methods can be applied successfully to fatigue analysis and design. The main objective of the study is to find the difference in methodologies for assessment of fatigue and its application on railway steel bridges. Recently, a number of studies have been started on the use of probability concept in fatigue life determination of bridges. Though, these require a combined basic of reliability and probability so they are more dependent on experimental and statistical data. Based on the above analysis, a predefined maintenance and inspection schedule can also be prepared. This schedule depends upon the service life of each structural member or details.**

Index terms: **- Palmgren-Miner's, S-N curve, Stress concentration, Stress History, Stress Range.**

I. INTRODUCTION

Fatigue is a localized and progressive cumulative damage accumulation due to continuous cyclic movement on structure. The effects can be dangerous as compared to conventional static load. On bridges, fatigue phenomenon occurs due to passage of vehicular load. In railway steel bridges, there are structural members with low dead load stresses but high live load stresses due to movement of wagons and locomotives. These high live load stresses cause the decrease in strength well below the design stresses. These in-turn reflects the reduction in useful life of bridge. Here, live load stresses are need to be assessed for different members and details of bridges. Fatigue is becoming one of the critical form of damage and prominent failure for steel structures and it is being less understood. So, development of new methodologies for assessment becomes necessary and conducting a reliable analysis will be important as it serve utmost component in transportation industry. Various analytical methods suggested such as nominal stress method, hot spot stress method and Effective notch method are being suggested in many literatures. Also, more refined forms of state methods are upcoming day by day. Since, fatigue is affected by various factors such as corrosion, temperature, load type, connection detail, etc. hence, the level of uncertainty increases. Therefore, an introduction of probability and reliability concept in fatigue assessment provides a new way of approaching the problem. Since past few years, reliability of structure based on fatigue is gaining more importance as it directly relates to the damage extent

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in structure. In finding it so, the versatile finite element method (FEM) is gaining popularity. The complex connection details are solved by this methodology only. FEM allows flexibility to different end conditions to simulate in models at different levels i.e. global, local and micro-scale. As the advancement in software development is reaching a new level, the solutions to complex geometry structures analysis are getting easier and visually clearer. This has led to identification of prediction of crack initiation for a predefined load sequence on bridge and can be useful for inspection and rehabilitation purpose.

II. BASIC UNDERSTANDING TO FATIGUE

Fatigue phenomenon was reported in 19th century. The remarkable contribution was given by August Wohler, a technologist in the German railroad system in the early 1850s. He was mainly concerned with the failure due to repeated load on the railway steel truss bridges and conducted many laboratory tests for fatigue under cyclic stresses. This failure phenomenon was thought to be sudden without warning, but actually it is not so. There is start of micro-cracks nucleation followed by crack growth and finally the failure of structure. This understanding of failure led to development of fracture mechanics approach. This was related to micro-level activity going in the material. Though the fatigue activity is complex in nature so can't be easily understood. Apart from these, other traditional methods also developed i.e. nominal stress method, hot spot stress method and effective notch method. All these methods relate to traditional S-N curve. These are further discussed in detail.

A. S-N curve

Wohler while investigating the fatigue behavior of various element of railway bridges found out that for a particular application of million cycle, material exhibits a fatigue failure. This was repeated for different stress amplitude (S) and corresponding number of cycles at failure were recorded (N). Based on the observational data, a curve was plotted and called as S-N curve as shown in Fig. (a). Since, curve exhibits a curvilinear shape, it is plotted in log-log form for straight line shape.

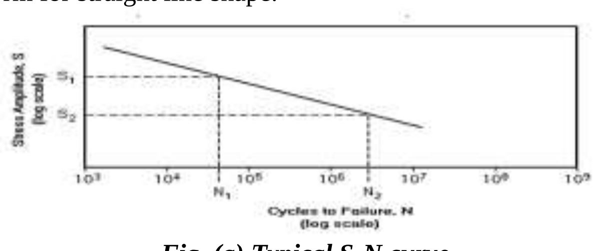

Fig. (a) Typical S-N curve

B. Palmgren-miner's rule

Real life loading experienced by bridges are unpredictable in nature. Due to this irregular and complex nature of loading, fatigue damage is quantified by Palmgren- Miner's rule [1]. It is based on linear damage hypothesis and extends this to variable amplitude loading. It is also called as cumulative damage rule. Suppose a component is subjected to n1 cycles at alternating stress σ1, n2 cycles at stress σ2, ..., nN cycles at σN. From the S-N curve for this material, then we can find the number of cycles to failure, N1 at σ1, N2 at σ2, NN at σN. It is reasonable in this case to let the fractional damage at stress level σi be simply ni / Ni, so that the Palmgren-Miner rule (refer to "(1).") would say that fatigue failure occurs.

$$D = \sum_{i=1}^{N} \frac{n_i}{N_i} \qquad (1)$$

Generally, failure is assumed to occur when D ≥ 0.3. A major limitation of the Palmgren-Miner rule is that it does not consider sequence effects, i.e. the order of the loading makes no difference in this rule. Sequence effects are definitely observed in many cases. A pictorial representation is shown in Fig. (b).

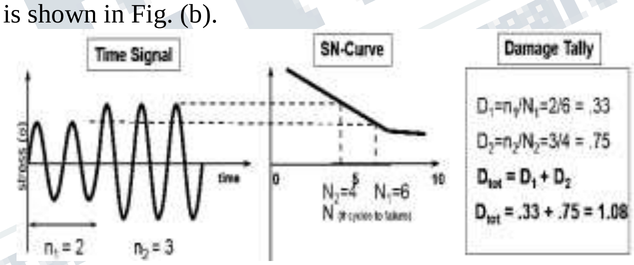

Fig.(b) Illustration of Palmgren-Miner's rule

III. FATIGUE ASSESSMENT METHODS

In order to know the extent of damage caused by moving load and remaining fatigue life of structure, it is necessary to determine the stress occurring at a particular detail or in a member. There are different procedures stated in literatures to calculate the stress in the cross-sectional members or detail.

A. Nominal stress approach

This is the simplest and most widely used method. BS 5400 [2] fatigue clause in Steel Bridge Code, RDSO [3] have incorporated this method. This method calculates the average normal stress on the given cross section properties using the classical structural mechanics approach. This stress can arise because of axial forces or bending action or both in structural member depending upon its nature of load resisting mechanism. It is important to be known that this does not consider the local stress raising effect of welded

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joint, but takes into account the macro geometric stress raisers such as large cutouts as shown in Fig.(c). Also, axial or angular misalignment has to be included in stress calculation. The major assumption in stress calculation is structure is assumed to behave within linearly elastic condition. After stress determination, each code or standard has variety of S-N curve relevant to specific structural details and loading conditions which are important and necessary for fatigue life assessment of steel bridges by use of the nominal stress method. Many codes have predefined structural details and corresponding stress range value. One of the major demerits of this method is that complex joint details or extraordinary geometry can't be assessed to get nominal stress and here finite element analysis is used. Indeed, this has been a commonly used method for fatigue life determination of steel bridges. Sometimes, the results are not reliable for steel bridges. Stress finding using the strain gauge can also be done to check the accuracy of results but strain gauge is placed outside the stress concentration fields.

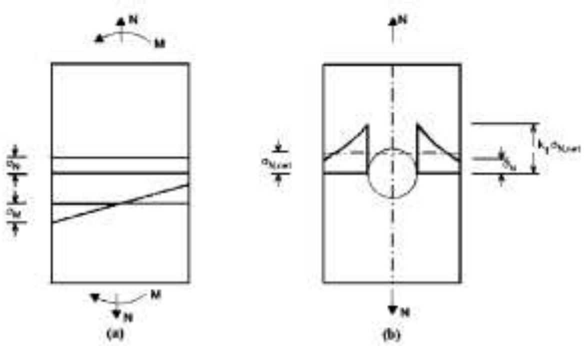

Fig. (c) Nominal stress

B. Hot Spot Stress Method

Steel bridges contains many longitudinal and transverse plates with welds at points of intersection in more or less complicated form. This may be of the form such as joints of main girder and floor beams, floor beams and stringer in plate girder, etc. So, at these welded joints there may be some form of structural or geometrical discontinuities which might further lead to local stress raising effect. These locations are prone to fatigue crack initiation and therefore accurate analysis is required. The accuracy can be achieved by this method. This method has an ability to simulate the complex welded connection details and is specially adopted by many researchers in case of welded structures. It is more reasonable and accurate than nominal stress method. The International Institute of Welding (IIW) [4] gives fatigue recommendation for hot spot stress method (HSM). This stress is calculated at the point of expected crack initiation, taking into account the true elastic deformation in the joint, i.e. not assuming plane sections to remain plane. It is also called as geometric stress. In fatigue phenomenon, it is not the maximum stress or minimum stress that affect the structure, but the stress range affects failure. Therefore, HSM refers to calculation of geometric stress range as basis of analysis. Geometric stress range is defined as the maximum extrapolated stress (range) to the weld toe, taking the global geometrical effects into account. IIW considers surface extrapolation as the favored condition. IIW has given different types of hot spot stress locations and their extrapolated formulas at weld toe. Generally, extrapolation point at distance from 0.4t (t = plate thickness) from weld is considered [4]. The method as defined here is limited to the assessment at the weld toe (Fig. (e)) and not applicable in cases where crack will grow from the weld root and propagate through the weld metal.

The hot spot stress is the stress value calculated by multiplying the nominal stress by stress concentration factors (SCF). The SCF can be determined using either the finite element analysis or experimental strain gauges. Some authors have defined the empirical formulas [4]for certain types of joints and discontinuities. But these parametric formulas are rarely used because practically load and connection details differ mostly than that stated. The mesh refinement for SCF calculation in finite element software plays a major role in determining the accurate values. Therefore, global finite element model along with detailed local model, where fine meshes at welded connection are marked, will yield better results.

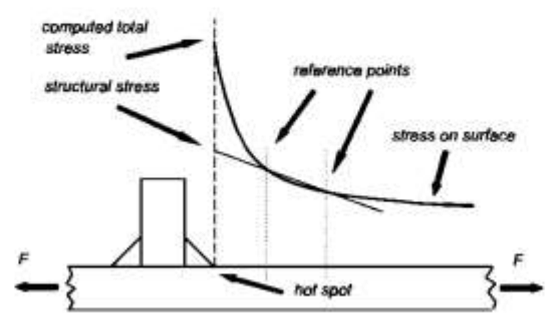

Fig. (d) Definition of Hot Spot Stress

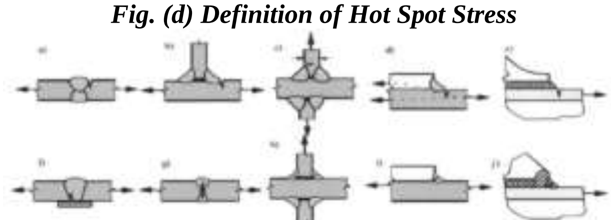

Fig. (e) Various location of crack propagation

Radaj et al. [5] has found that hot spot stress can be calculated either using surface extrapolation or linearization through plate thickness. Dong [6] suggested another alternative to combine surface extrapolation with the through thickness methods. Xiao and Yamada [7] proposed another method named as one-millimeter stress method. Authors computes the stress 1mm below the surface of plate thickness at the location of weld toe. The location is in the direction of corresponding weld crack initiation path. Poutiainen et al. [8] did comparison of all hot spot stress valuation methods i.e. linear surface extrapolation (LSE), through thickness at the weld toe (TTWT) and Dong method on 2D and 3D structural details TTWT and Dong methods revealed good results for all types of mesh variation. Chan et al. [9] has established the fact that HSM gives fairly more appropriate results than nominal stress method and proven by HSM on Tsing Ma Bridge which is steel suspension bridge.

C. Effective Notch Method

The effective notch stress method was proposed by Radaj et al. [5]. This method is based on stress averaging in Neuber's micro-support theory for steel with a reference radius of 1 mm in a plate thickness of 5 mm and above [5]. For smaller plate thicknesses, Zhang and Richter [10] have proposed the use of a reference radius of 0.05 mm, which is based on the relationship between the stress intensity factor and the notch stress. Apart from taking the geometrical changes into account, as the hot spot method does, the effective notch stress method also takes the effects of the weld itself into account. The effective notch stress method can be used in both 2D plane elements and 3D solid elements. The effective notch stress at fatigue-critical points can be computed using the sub-modelling technique, as a very fine-meshed region around the critical points is required to capture the maximum elastic stress. The finite element sub-modelling technique is generally used to transfer the displacements when defining node-base sub-regions or to transfer the stresses at the integration points when defining surface-based sub-regions from the coarsely meshed global model to the refined meshed local models.

Aygül et al. [11] did a comparative study on five selected welded joints commonly used in steel bridges to investigate the accuracy of three different stress-life methods, i.e. nominal stress method, hot spot stress method, and effective notch stress method. The results revealed that the effective notch stress method, despite its more cumbersome procedure for both modeling and computation, provides an insignificant improvement in estimation of the fatigue strength.

IV. SHM BASED FATIGUE ASSESSMENT

Structural Health Monitoring (SHM) refers to the damage detection and strategy of characterization for engineering structures. This ensures life safety throughout the service life of structures and can give warning before the collapse, deterioration or high cost repair of structures. This technique is gaining more popularity now a days. The advancement in technology of sensors, equipment and data extraction through signals accelerates the use of this method. It is one of a kind of field measurement data which ensures structural and operational safety especially for long span bridge as they have large investment and contribute more towards the economy.

One of the main aim of SHM is to deliver accurate and precise structural health and performance along with correct estimation of remaining fatigue life of structure [9]. The structural response obtained from monitoring can be used in combination with various different numerical methods, which can be grouped into two main categories: model-based and parameter-based. The first relies on a reference structural model, e.g. FE model, whereas the main characteristic of the second is a general mathematical description of specified parameters or system features, e.g. analysis of time-series details by means various other theories [12]. This is one of the method to get the field measurement data. The location of sensors for recording the strain due to moving load is first determined and generally chosen at points of critical values. After fixing the strain gauges, it is connected to data acquisition system, which records the data and plots the strain-time history. The detail methodology was presented in [12] and was proved using three different case studies.

This is new methodology in field of civil engineering which have been established by various authors through successful case studies, and there is a little work done with no standardization. Li and Chan [13] carried out online SHM on Tsing Ma Bridge to assess the fatigue condition of deck slab. They also tried to combine continuum damage mechanics along with fatigue damage assessment procedures. Ye et al. [14] did statistical analysis of stress spectra for fatigue life assessment on Tsing Ma Bridge with help of structural health monitoring data. SHM is carried out to obtain the actual stress-time history on bridges due to passage of moving loads. SHM is basically employed for railway steel bridges due to fact that steel bridges are mostly used for railway mode of transport. Häggström et al. [15] has investigated the critical member of existing steel truss bridge i.e. stringer for fatigue assessment using SHM. Nominal stress and hot spot stress method was adopted to check the accuracy of real state of stress from SHM. For accurate fatigue life prediction, the degradation of material properties in time, such as changes in the mass, stiffness and damping ratio, should be quantitatively considered, and the finite element (FE) model has to be updated accordingly. So, Lee and Cho [16] presented a new approach for probabilistic fatigue life prediction for bridges using finite element (FE) model updating based on structural health monitoring (SHM) data. The proposed method is demonstrated by application to a numerical model of a bridge, and the impact of FE model updating on the bridge fatigue life is discussed.

V. STRESS TIME HISTORY GENERATION

Stress time history refers to the variation of stress w.r.t. time due to moving load on steel bridges as shown in fig. (f). The stress history is a record and/or a representation of the fluctuations of the fatigue actions in the anticipated service time of the component. It is described in terms of successive maxima and minima of the stress caused by the fatigue actions as shown in fig. (f). It should aim to cover all loading events and the corresponding induced dynamic response in a conservative way. The stress range may vary in both magnitude and period from cycle to cycle. This is generated from the above stated fatigue resistance methods i.e. fracture mechanics approach, nominal stress method, hot spot stress methods and effective notch methods. Depending upon the structural connections complexity, stress raising effects, corrosion extent, nature of moving load, etc. suitability of any method(s) is decided. All these factors are tested under constant amplitude loading. But in actual practice fatigue actions are irregular in manner and therefore gives rise to variable amplitude loading spectra. These variable amplitude spectra are difficult to analyze and therefore need to be simplified i.e. conversion to constant amplitude loading spectra. More accurate the mathematical model is, more refined will be the stress time history. Therefore, Imam and Righiniotis [17] as well as Imam et al. [18] did Fatigue evaluation of riveted railway bridges through global and local analysis. Global FE model refers to modelling of a bridge superstructure with actual boundary conditions using shell elements and doing the analysis. While on the other hand, global-local analysis refers to detail modelling of critical fatigue connection which is to be decided based on the S–N basis and remaining fatigue life estimates from global FE model analysis. Similarly, Kiss and Dunai [19] adopted the same approach for generating the stress history specifically for truss bridges and named it as multi-level model. A 3D truss model was prepared using plate / shell elements and a 3D critical connection detail was formulated. The results were compared with beam element model and using gauge results. It was observed that results that of gauge and multi-level model were showing more or less same results and beam element model was entirely different.

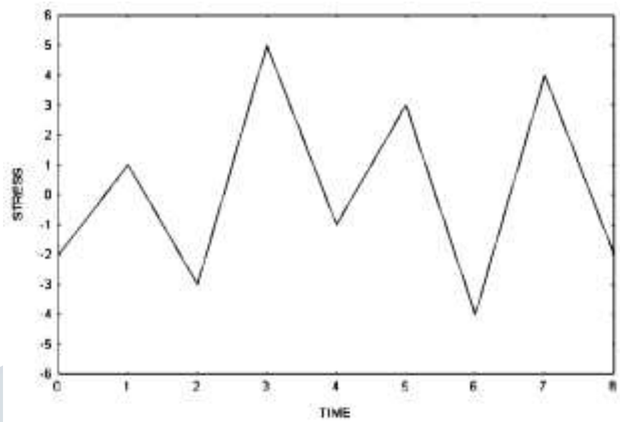

Fig. (f) Sample Stress time history

VI. CYCLE COUNTING METHODS

Constant amplitude stress history is in simplified form whereas variable amplitude stress history can't be directly used for fatigue assessment. With limited input data, constant amplitude fatigue analysis is used to make a simple and quick estimate of the likely fatigue performance or durability. Actual loading on bridge produces variable amplitude loading and are more complex in nature. In practice the pattern of the stress history with time at any particular detail is likely to be irregular and may indeed be random. So, it is a need to convert variable amplitude stress spectra to constant amplitude stress spectra. This process of conversion is called as cycle counting. A number of alternative methods of stress cycle counting have been proposed to overcome this difficulty. The converted constant amplitude stress range cycles will produce the same amount of damage to that of original sequence. Various methods that are available in different literatures are as follows –

Zero crossing counting
Peak counting
Range pair counting
Rain flow counting
Reservoir Counting Method

From these stated methods, reservoir counting methods and rain flow counting methods are found to be suitable for welded connection or structures. These two methods are

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most commonly used and adopted by various codes and standards namely BS 5400 and Steel Bridge Code, RDSO. The rain flow method is somewhat more difficult to apply correctly than the reservoir method and it is recommended that both for teaching and for design purposes the reservoir method should be used. These two methods are discussed with illustration in [20], [21]. The end results of this cycle counting yields to stress histogram generation. It consists of a number of constant stress range blocks as shown in fig. (g) which corresponds to number of cycles n and stress range Δσ.

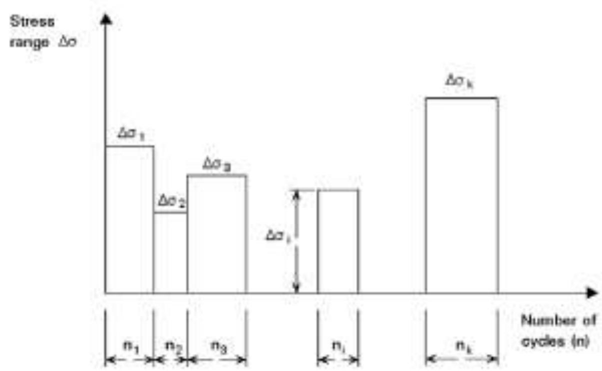

Fig. (g) Typical Stress Histogram

After getting the stress histogram, fatigue damage calculation using Palmgren-Miner's rule is done so as to calculate the fatigue life. Since, for a particular loading condition the number of cycles experienced (n) by detail for corresponding stress range (Δσ) is known. Now, there is need to calculate the number of cycles to failure (N) for corresponding stress range or amplitude (Δσ) using S-N curve. This will finally give the fatigue damage value using Palmgren-Miner's rule. In order to determine the fatigue life, the inverse of fatigue damage value (D) will give the fatigue life in days. Fig. (b) gives the pictorial representation of the stated text.

VII. RELIABILITY BASED ASSESSMENT

Over the past several decades, the concepts and methods of structural reliability have developed rapidly and become more widely understood and accepted. Applied loads on the bridge vary randomly, and this results from the uncertain nature of the input loading conditions, such as traffic schedules, passenger volumes, and so on. To guarantee the target bridge life, bridge maintenance activities such as local inspection and repair should be undertaken properly. Tobais and Foutch [22] proposed reliability-based fatigue evaluation of railway bridges and generated probability density function of fatigue resistance and loading. Also, Miner's damage law was transformed into performance function. Murty et al. [23] dealt with derivation of fatigue strength distribution as a function of number of cycles to failure. The viability was established by three different examples by authors and co-authors. Kim et al. [24] proposed that passenger volumes are assumed to be random, which are determined based upon the provided data and on-site visual observations. Chryssanthopoulos and Righiniotis [25] defined limit state function for S-N curve methods and fracture mechanics approach and includes the development of a probabilistic fracture mechanics methodology for the prediction of fatigue reliability, using up-to-date crack growth and fracture assessment criteria and incorporating information on inspection and subsequent management actions. Imam et al. [26] applied methodology to short span riveted railway bridges to develop response spectra for a fatigue-critical connection and Weibull distributions were fitted to the response histograms. Kwon and Frangopol [27] presented an approach using probabilistic distributions associated with stress ranges is proposed to effectively predict equivalent stress ranges. Wang et al. [28] combined the probabilistic characteristics of the Non-Destructive Inspection (NDI) techniques, the probabilistic fatigue failure method, and the Bayes theorem, thereby presenting a procedure for assessing and updating the fatigue reliability of existing steel bridge components. Rao et al. [29] developed an expression for probability density functions of number of cycles to failure and accumulated fatigue damage in the closed form and Monte Carlo simulation, for the cases of without and with modeling error considered in fatigue life estimation, respectively. Adasooriya [30] found out a new probabilistic fatigue assessment approach consisting of a new damage indicator, which captures the loading sequence effect of variable amplitude loads more precisely than the Miner's rule. Lee et al. [31] recently updated to a new level of system reliability approach so that it can handle a varying-amplitude load and update the system-level risk of fatigue failure for railway bridges after inspection and repair.

VIII. CONCLUSION

In general, two different approaches to the formulation of the fatigue limit state are considered, the first based on S–N lines in combination with Miner's damage accumulation rule, and the second based on fracture mechanics crack growth models and failure criteria. Often, the two approaches are used sequentially, with S–N being used at the design or preliminary assessment stage and fracture

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mechanics for more refined, remaining life or inspection and repair estimates. This paper will provide as framework solution to fatigue analysis of steel bridge. Although, most of the work is more towards the railway truss bridges, yet they can be extended to other types steel bridges also with a little deviation. This paper also highlighted the recent advances in fatigue analysis through SHM and reliability concept introduction in conjunction with S-N curve.

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