CHAPTER-2

LITERATURE REVIEW

2.1 General

Initially Indian railway bridges were built to accommodate the then-current lesser loading standard. On Indian Railways, numerous bridges were built with former BGML and RBG loads in mind. High horsepower locomotives with greater tractive efforts and braking forces that impart higher longitudinal forces have also been added over time, along with a rise in axle loads and trailer loads. (Awasthi et al. 2022).

As per the report of the ASCE committee (ASCE 1982), fatigue and fracture cause approximately 80% to 90% of failure in the case of steel structures. For this reason, bridges are designed under High Cycle Fatigue (HCF) criteria. HCF includes a large number of cycles, (number of cycles greater than 1,00,000), and stresses as well as strains are kept within elastic limit. Most of the railway bridges in India have steel superstructures and they are subjected to stress fluctuation due to traffic movement. Fatigue assessment of old railway bridges (bridge life more than 50 years) is an important work to assess their suitability at current speed and current loading standard. Assessment of the remaining lifespan of steel bridges at enhanced speed, increased axle load, as well as increased traffic density considering actual field conditions is also challenging work.

2.2 Fatigue life assessment

2.2.1 Fatigue history

The phenomenon of fatigue damage or Historical perspective (Stephen et al. 2000) can be summarized as below:

In the 19^{th} century, several pioneering individuals laid the foundation for the understanding of metal fatigue. Wilhelm Albert, in 1829, conducted research on iron mine hoist chains, introducing the concept of metal fatigue. He designed a machine that repetitively loaded a chain, leading to the realization that fatigue resulted from repeated load cycles rather than accidental overloads.

Jean-Victor Poncelet, in 1839, furthered the understanding of fatigue by coining the term and applying it to metals worn down by cyclic loading. Meanwhile, William John Macquorn Rankine, in 1843, made significant contributions, distinguishing between fatigue cracks and other types of cracks, especially in railway axles.

August Wöhler, in the 1860s, conducted extensive fatigue tests on railway axles in Germany, pioneering the first comprehensive study of fatigue. He introduced stress versus life diagrams and demonstrated the importance of the S-N diagram and fatigue limit, highlighting the relevance of cyclic stress range over peak stress. Johann Bauschinger, in 1886, showcased the Bauschinger Effect, demonstrating that reversing inelastic strain could alter the stress-strain behavior of metals.

Moving into the 20th century, Ewing and Humfrey, in 1903, employed an optical microscope to delve into fatigue mechanisms, discovering the connection between fatigue fracture initiation and crystal structure evolution.

John Goodman, in 1904, explored the impact of mean stress on fatigue, laying the groundwork for the modified Goodman diagram. Basquin, in 1910, established a log-log linear relationship between alternating stress amplitude and cycles to failure, leading to Basquin's Equation.

The 1920s witnessed significant advancements, with Griffith's pioneering work on glass brittle fracture, Palmgren's linear cumulative damage model, and McAdam's corrosion fatigue investigations. Almen, in the 1930s, introduced shot peening, significantly reducing fatigue failures in the automobile industry.

Heinz Nueber, in 1937, introduced the concept of stress gradient effects at notches, contributing to the understanding of fatigue notch sensitivity. The mid-20th century saw Miner formulating the Palmgren-Miner rule in 1945, providing a linear cumulative fatigue damage criterion.

The 1950s brought about Irwin's extension of Griffith's work to ductile materials and the introduction of the energy release rate concept. Coffin and Manson, in the 1960s, linked low cycle fatigue to cyclic plastic strain range, while Paul C. Paris, in 1961, established the connection between fatigue crack growth rate and stress intensity factor range, resulting in Paris Law in 1964.

James M. Rice, in 1968, delved into potential energy changes in fracture formation and introduced the J-Integral for Elastic-Plastic Fracture Mechanics. Landes and Bagley, in the 1970s, proposed using a C-integral for creep fracture growth rates, and Saxena, in 1986, utilized the C-integral to characterize creep crack propagation in high-temperature alloys.

These collective efforts over the centuries have shaped our understanding of metal fatigue, paving the way for advancements in material science and engineering.

2.2.2 Codes for fatigue

Indian codes offering guidelines related to fatigue assessment for highway bridges are IRC:24 (IRC 2010), IS:800 (BIS 2007), and for railway bridges are steel bridge code (RDSO 2017), BS:91(RDSO 2008). British code related to fatigue life assessment is BS:5400 part10 (BSI 1980). European code that discusses fatigue-based method is EN1993:part1-9 (CEN 2005). American code that provides fatigue assessment of highway and railway bridge are AASHTO (AASHTO 1990) and AREMA (AREMA 2002) respectively.

2.2.3 Literature related to fatigue life assessment

Various approaches for the assessment of fatigue strength and residual life based on different parameters are reviewed by Radaj (1996) for both welded as well as nonwelded structures. A detailed review of fatigue-based cumulative damage theories, classified into various categories like Miner rule, damage curve approach, double linear damage approach, life curve-based method, crack growth-based approach, Continuum damage mechanics model, and theories based on energy has been carried out by Fatemi and Yang (1998). Fatigue life of critical members of steel truss bridges due to various types of trains running at different speeds has been assessed by Garg et al. (1982). Impact percentage for different loading and speed combinations has been calculated by Garg et al. (1982) and the same has been compared with values given by American Railway Engineering Association (AREA) which concluded that calculated values are on the conservative side. Fisher et al. (1987) have found that the number of repetitions or the number of cycles corresponding to fatigue failure depends primarily on stress range (algebraic difference of maximum stress and minimum stress). The results of an experimental study conducted by Banjara (2011) on a railway steel plate girder bridge has been compared with the findings obtained through ANSYS-based numerical analysis of the same bridge. At fixed stress range interval, the remaining life of the steel plate girder railway bridge using the FEM model has been calculated using different cumulative damage theories by Banjara et al. (2014).

A new probabilistic fatigue life assessment (PFLA) procedure is proposed by Misra et al. (2023) to account for dynamic train loading, enhanced axle loads, and related uncertainties. Unlike conventional PFLA, which relies on Monte Carlo simulation (MCS) and rainflow counting methods, this new procedure uses a dual response surface method (DRSM). DRSM provides explicit equations for both mean and standard deviation of stress ranges, allowing fatigue life prediction via an Excel spreadsheet, eliminating the need for MCS. Validated on an Indian steel railway bridge and four other fatigue-failed bridges, the proposed method shows excellent agreement with MCS results and is computationally more efficient.

Numerical calculations and field strain data have been used to determine the remaining lifespan of a bridge. According to the field strain data, the bridge can continue to be used for traffic, but the numerical analysis indicates that it has no remaining lifespan. The predicted lifespan from the numerical analysis does not align with the lifespan obtained from the field data because the contribution of secondary members was not taken into account during the numerical analysis (Kashefi et al. 2010). Paderno bridge across the Adda river in Italy has been analysed using finite element analysis and after assessment of the fatigue life of the bridge at various traffic increase rate, suitable retrofitting works has been suggested by Pipinato and Modena (2010). The fatigue reliability of an old welded solid web steel girder bridge was examined using the crack propagation-based approach by Guo and Chen (2012). The LEFM is used to determine fatigue crack growth, and the limiting state is determined as a function that depends upon crack size.

Various methods for the life estimation of steel bridges based on fatigue criteria have been discussed. Both classical as well as reliability-based method has been reviewed which includes the stress life method (S-N method), strain life method (€-N method), LEFM approach, and field-measured data-based approach. (Ye et al. 2014). Method of fatigue assessment using global structural behavior and local plasticity approach has been described and applied for life estimation of Eyebar suspension steel girder bridge. Methodology proposed by Liu et al. (2019a) can be used to evaluate fatigue life for the riveted joint. By incorporating both local plasticity and global structural responses, the proposed methods for global-local fatigue analysis can be used to assess the fatigue damage of the area around the rivet hole effectively. The critical connection of same bridge has been analyzed by the same author for fatigue life assessment using AASHTO and EURO codes. It was found that stresses due to Euro code loading are more than those due to AASHTO loading due to higher gross weight and lower center-to-center spacing of axle of Eurocode vehicle (Liu et al. 2019b).

The size effect for the fatigue assessment of structural elements with defects and material nonlinearity has been reviewed by Zhu et al. (2022) from a statistical, geometrical, and technological perspective. Li et al. (2023) have proposed two unified rules, one for the macro-scale and one for the micro-scale. Each unified rule can be used for fatigue life estimation of metallic bridges that have been subjected to either the HCF or LCF regime. A parametric study using the LEFM approach has been performed to assess the life of the bridge. An approach to get governing shape function for fatigue life estimation using the Monte Carlo Simulation technique has been provided (Marques et al. 2018).

Johnson (2021) provides the fundamentals of highway and railway bridges. A detailed analysis of a railway bridge is available with Arya and Kumar (2022). Life assessment of a 100-year- old single lane-roadway bridge is done by Ghule (2012) using STAAD. Different cumulative fatigue damage theories including linear damage rule and prediction of life based on these theories are detailed in this study (Fatemi and Yang 1996). Using six theories of various theories (Fatemi and Yang 1996), damage index is calculated by experimentally validated FEM model of a solid web steel girder bridge considering CC+8+2T railway loading (Sriniwas et al. 2013). Using bridge FEM model, railway loading, and damage theories of Sriniwas et al. (2013), remaining life of bridge is assessed at 10MPA stress band for six different speeds (Banjara and Sasmal 2014).

Based on the connection types or details, fatigue damage-based results of more than 100 cases of steel and composite bridges were reviewed by Haghani et al. (2012). 3-D analysis of a three-span, two-lane highway truss bridge was carried out by Birajdar et al. (2014) using STAAD software and identified the reason for bridge failure. To prevent bridge failure, a higher load factor is recommended. A strengthening scheme for a newly constructed highway bridge, whose design was similar to the design of bridge (Birajdar et al. 2014), was provided based on space frame analysis in STAAD (Birajdar et al. 2015). Various methodologies using different codes for fatigue life assessment of railway bridges are discussed in Albuquerque (2015). Garg et al. (2020) summarize the failure of more than 2000 bridges during four decades since 1977. The onset of damage, its propagation and collapse consequences of steel truss bridges has been described by Lopez et al. (2023).

A damage accumulation model was validated using existing literature data and real case study. This model introduces the time domain to the existing S-N curve, which can simulate variable amplitude loading (Aghoury and Galal 2013). A comparison of probabilistic and deterministic approaches was presented and same was supported with a case study of an existing railway bridge (Adasooriya 2016). S-N curve attributes were obtained using the least-squares and orthogonal regression methods for two riveted joints. Regression analyses in connection with non-deterministic models applied for the fatigue assessment of railway bridge (Correia et al. 2023).

Instead of already available fatigue load data on standard documents like codes and reports, they obtained fatigue loads through experimental vibration tests which were performed under actual live loads. And, experimentally obtained fatigue loads are used for fatigue analysis and life assessment of an existing bridge (Kuzawa et al. 2018). Ye et al. (2012) present SHM-based method for fatigue life evaluation of steel bridges. The proposed methodology was applied for evaluation of fatigue life over a bridge carrying both highway and railway traffic. Software was developed by Souto et al. (2019) for fatigue damage assessment and named fatigue damage tool (FDT), and damage of an existing railway bridge using the software was assessed. This software was based on assumptions of standard codes and utilizes Miner rule for damage assessment.

A calibrated computer model was used for calculating residual life of the railway bridge. Strengthening scheme of a fatigue prone bridge component is suggested for life extension (Caglayan et al. 2009). Field based measurement data has been used to assess failure in metallic railway bridges (Torres et al. 2023). Wang and Leander (2023) utilized reliability-based method for fatigue assessment of bridges. Fatigue strength of riveted joints of the railway bridges were assessed on the basis of experimental study in the laboratory (Silva et al. 2021).

2.3 Deep learning based crack detection

Previous studies related to the detection of surface cracks using deep learning techniques are reviewed here.

The most popular technique for assessing infrastructure, visual examination, and its challenges are discussed in this study. The study also provided guidelines for crack measurement and presented preliminary findings from a crack identification algorithm. The research suggests an image-based crack detection approach using Unmanned Aerial Vehicle (UAV). The paper emphasizes the issues with automated crack detection and its use with UAVs (Ellenberg et al. 2014). More than 25 methods and datasets related to DL techniques for SS have been reviewed by Garcia et al. (Garcia et al. 2017). Deep network architecture AlexNet, VGG, GoogleNet, ResNet, and ReNet have been briefly discussed. Datasets have been provided with their purpose and properties. Existing Methods are summarised based on contribution and significance. Methods and databases are classified based on various criteria.

A Deep Convolutional Neural Network (DCNN)-based approach has been proposed for detecting concrete cracks without manually extracting defect features (Cha et al. 2017). Traditional edge detection methods have been used in comparison studies to evaluate the performance of the proposed CNN. The proposed CNN is stronger at detecting small-size cracks under low light conditions that make crack detection difficult while using traditional Canny and Sobel methods. In order to facilitate the inspection process of historical sites, Chaiyasarn et al. (2018) suggested an automatic crack detection system for masonry surfaces. The system combines DCNN and SVM to extract features from RGB images and improve classification performance. Results demonstrated that the DCNN and SVM model works better than the DCNN-only model. For automatic image crack detection, Liu et al. (2019) developed a deep CNN called DeepCrack, consisting of FCN and Deeply supervised nets. In contrast to typical approaches that simply use the last convolutional layer, the model is designed to learn and incorporate multi-scale and multi-level data from low to high convolutional layers. The final predictions are refined using guided filtering and Conditional Random Fields (CRF) approaches. For crack detection on actual concrete surfaces, the deep CNN, created by modifying AlexNet, has been claimed to have more than 98 percent accuracy. The method detects cracks in images from real concrete surfaces. The trained CNN model is also integrated into an android application (Li et al. 2019).

A crack segmentation Network (CSN) was proposed for SS, and results were obtained using CSN method compared with patch based-CNN method for images with contrast, hue and noise. CSN-based method has been found to be more robust and efficient than the patch-based CNN method. The paper proposes a crack detection network based on deep learning-based semantic segmentation for robust and accurate crack detection (Lee et al. 2019). Rezaie et al. (2020) compared the performance of the threshold method and the DCNN method for detecting cracks from stone masonry wall images taken for digital image correlation (DIC). The two methods are evaluated in terms of performance metrics namely precision, dice coefficient, and sensitivity. It concludes that the DL method is more accurate than the threshold method.

More than 65 ML-based SS methods have been reviewed to provide an idea of current development in the field of segmentation. Then 8 ML-based SS models were compared concerning various performance metrics, including recall, F1 score, precision etc., using 3D payment images (Hsieh et al. 2020). DCN based crack detection methods highlighting SS methods have been reviewed in this article. A benchmark study examined the effects of various pre-processing methods and image data on SS performance. In this article, the study was conducted using the Fused Image data set for CNN based crack Detection (FIND) image data set, which is openly accessible. Four different images types raw range, filtered range, raw intensity, and fused image (raw intensity and range)-are included in the FIND data set. (Zhou et al. 2023)

Recently, Deep Transfer Learning (DTL) and SS-based automated methods are applied to locate and isolate masonry surface cracks. The proposed method classified cracks in masonry images and assessed the generalization performance using DTL and data augmentation. In order to isolate the identified cracks, the paper compared the effectiveness of the two SS techniques, canny edge and heatmap (Aliu et al. 2023).

A Computer Vision (CV)-based method for automating crack detection in masonry structures, especially railway bridges, which humans currently inspect under complex working conditions, has been proposed. Faster R-CNN has been used as crack object detectors, and tested networks like ZF512, mobilenetv2, and resnet50 have been utilized as feature extractors for crack segmentation. Mobilenetv2 has been shown to be faster than Resnet50 for complex networks (Marin et al. 2021). A system for automatic crack segmentation and real-world crack length measuring of masonry walls utilising CV and DL methods has been presented. A sizable dataset of manually labeled images of various styles has been created and tested DeepLabV3+, U-Net, and FPN, among other DL-based SS models to get the results. This paper suggests an algorithm for measuring actual crack length by identifying brick units (Dang et al. 2022).

The paper examines the viability of Deep Learning (DL) methods for crack detection on photographs of masonry walls. The study investigates the performance of deep learning networks based on U-net and FPN architecture to describe the automatic visual inspection process using digital images. The masonry structures images dataset has been generated for the study. Various deep learning networks are considered for crack detection on masonry surfaces, and transfer learning is used. This study has achieved a crack detection F1 score of 80% at the pixel level. Networks that have proved their suitability on concrete and asphalt surfaces has been used for masonry surface (Dais et al. 2021).

SegNet, an FCN architecture for semantic pixel-wise segmentation, is introduced by Badrinarayan et al. (2017). Concerning many parameters, DeepLab-LargeFOV and DeconvNet designs have been compared to SegNet. In comparison to other architectures, SegNet has been demonstrated to be more effective and use less memory during inference time. Dung (2019) proposed a method for autonomous concrete crack detection using a deep FCN. The authors evaluated the performance of VGG16, InceptionV3, and Resnet for image classification and subsequently trained the FCN network with the VGG16-based encoder on a subset of 500 crack-labeled images for SS. VGG16 has been proposed as best method for SS.

Semantic segmentation has made substantial use of end-to-end networks known as fully convolutional networks (FCNs) (Long et al. 2015). The final prediction by FCN, an enhanced version of CNN, was an image with semantic segmentation rather than a class identification. Yang et al. (2018) directly extracted geometric features like length and width from photos without the need for manual measurement by fusing morphological techniques and FCNs. Different backbones used as pre-trained CNNs with FCN have been examined by Elharrouss et al. (2022). Dao et al. (2023) has done segmentation of medical images using deep NNs.

2.4 Fuzzy based bridge rating

The literature related to visual inspection (VI) approach, fuzzy logic approach, and hybrid fuzzy logic technique for bridge condition evaluation is critically reviewed by Khan et al. (2020). This paper presents the significance of bridge condition evaluation and the difficulties involved with traditional VI approaches. The emphasis is on analysing the state of the art in condition evaluation for bridges in developing countries utilising VI-based fuzzy logic, determining applicability, and identifying potential future research areas in this subject.

There are two methods for condition evaluation of bridges: periodic or continuous. Periodic assessment, which involves visual inspection (VI) followed by NDT, and continuous assessment using instrumentation like strain gauge, linear variable differential transducer (LVDT), accelerometer etc. (Agdas et al. 2016, Sengupta et al. 2015). Bridge condition assessment techniques have been categorizes into five groups, namely VI, load testing, NDT, SHM, and Finite element modelling (FEM) by Omar and Nandi (2018). While non-destructive testing (NDT) and continuous monitoring systems are costly, require bridge experts, and are not used frequently, VI is the traditional and economical method but suffers from subjectivity and uncertainty due to inspectors' judgment. This leads to incomplete and inconsistent information.

While VI is cost-effective, it is subject to human subjectivity and judgment, resulting in imprecision and inconsistency. Fuzzy-based models, which are known for coping with unclear data, are gaining favour in bridge condition assessment to address these difficulties. There is need for a mathematical treatment to address these issues. Fuzzy-based models are used to handle uncertain data in infrastructure management.

The use of fuzzy logic to roughly characterize a complicated or ambiguous situation that is challenging to express in conventional quantitative terms was initially demonstrated by Zadeh (1965). Fuzzy logic reasoning is necessary because it may formalise the imprecise knowledge of specialists into quantifiable consequences for decision making that are both understandable and actionable. Fuzzy mathematics started to be widely used in construction technology and management engineering fields after Zadeh's (1965) study. To analyze the condition of existing bridges, this technique has been frequently employed in the literature (Jain et al. 2012, Omar et al. 2017, Tarighat and Miyamoto 2009, Liang et al. 2001).

The development of a fuzzy weight for different bridge components, the creation of a membership function (MF) for condition rating, the fuzzification of linguistic condition rating and weight, the fuzzy technique for combining the condition rating and weight, and the defuzzification of MFs to scalar rating are the general steps of a fuzzy logic-based condition assessment technique (Tee et al. 1988). The creation of MF for condition rating, weight, and fuzzy set aggregation are essential processes that require particular focus to apply fuzzy logic-based condition evaluation in developing nations. Visual inspection based method for condition assessment of existing bridges is done either by classical fuzzy logic or FWA technique. In the literature, average of fuzzy numbers is often calculated as fuzzy weighted average (Dong and Wang 1987; Kao and Liu 2001; Guh et al. 2001).

Application of fuzzy based approach for rating of bridge was firstly described by Tee et al. (1988). Fuzzy weighted average (FWA) was used for personal judgement and non-uniformly combination process. Tee and Bowman (1991) developed fuzzy based resolution identity technique to assess bridge condition. Liang et al. (2001) proposed Fuzzy based multilayer model for condition assessment of RCC bridges. On the basis of subjective and objective data, fuzzy inference system for rating RCC bridge deck was developed by Tarighat and Miyamoto (2009). Here, subjective data was obtained by VI and objective data collected by NDT. Omar proposed fuzzy weight synthetic evaluation approach to convert identified defects into fuzzy condition sets, they are combined using FWA technique to develop rating of bridge deck.

Ejegwa (2020) investigates the application of fuzzy mathematics and the processing of fuzzy data, demonstrating that the two mathematically identical representations of a fuzzy number, via membership functions and α-cuts, are not algorithmically equivalent. The α-cut format is found to be more effective in handling fuzzy data. Rogulj et al. (2021) presents a unique approach to systematically evaluate the condition of existing road bridges using an expert system based on fuzzy logic and sets of α-cuts. Proposed method is validated using existing historic road bridges. Each bridge is categorized into bridge components and each component is further divided into different elements. For comparison among bridge components, Analytical hierarchy process (AHP) is applied. Abdelrahman et al. (2022) presents an overview on current bridge inspection practices in United States and research gap and future needs are also investigated while reviewing literature on bridge inspection. Rogulji and Pamukovic (2023) developed a decision-making approach for restoring historic highway bridges using modified form of BMS. Multi criteria driven priority ranking analysis of bridges using artificial intelligence (AI) techniques is done to provide bridge rating.

With technology's development, bridge inspection and maintenance are being done by bridge management system (BMS) (Dabous 2008). Almost all developed countries use computerized BMS to deal with the complexity of bridge management decision-making. Nevertheless, the BMS of each country is different due to their approach to inspection, maintenance, and allocated budget for inspection and maintenance.

Developing countries are taking the lead in managing bridges with BMS. For example, India has established the Indian bridge management system (IBMS) to manage highway bridges. Joshi (2022) describes the start of IBMS and the transition from IBMS to a UBMS. He also described Unified bridge management system (UBMS), Bridge information model (BIM), and BIM integration with UBMS, as well as BIM integration with BMS. For the management of Indian railway bridges, till date, no computerised rating system has been launched.

2.5 Research gap

After a careful examination of the existing literature, some gaps in condition assessment of bridges were found; these need to be filled in order to strengthen and improve the process. A few of the research gaps found throughout our literature evaluation are the focus of the current thesis. Among these gaps are:

1. Previous research did not give a fatigue analysis of a rail-cum-road bridge that took into account actual past, present, and future loading and used a validated FEM model to estimate PVPD and bridge remaining life.
2. No single study demonstrates variation pattern or best-fit distribution in remaining life and PVPD using different stress bands in regard to the reference stress band in the fatigue analysis of railway bridges.
3. While most previous research have detected cracks on smooth and uniform surfaces such as concrete and bituminous surfaces, relatively few studies have shown crack detection on uneven surfaces such as masonry surfaces.
4. Fuzzy-based bridge ratings have previously been investigated, but primarily for roadway bridges; no previous work provides bridge ratings solely for railway bridges.
5. Although work has been done in the fields of fatigue analysis, bridge rating, and crack detection, there is lack of wholistic approach for conditional health assessment of steel railway bridges.