CHAPTER-1

INTRODUCTION

1.1 General

Determining whether an existing bridge can operate safely for a given residual service life is the goal of the condition evaluation.

Depending on the structural state of the bridge under inquiry, guidelines for evaluating existing bridges are typically divided into phases, with a preliminary evaluation coming first, then a comprehensive investigation, an expert investigation, and an advanced assessment if needed.

Condition assessment of a bridge can be done by following ways:

(a) Visual inspection: The simplest and most common method involves visual examination by trained inspectors. This method provides an initial overview, detects visible defects, and helps assess the general condition; however, it is limited to surface-level inspections, may not identify internal issues.

(b) Finite element modelling: It involves modelling of bridge using FEM software like STAAD, SAP, ANSYS, ABAQUS etc. Advantages of numerical modeling for bridge condition assessment include its predictive analysis capabilities, providing a comprehensive understanding of structural behavior. It is cost-effective, non-intrusive, and enables parametric studies for optimal maintenance strategies. However, challenges arise from simplified assumptions, data requirements, and the need for accurate model validation.

(c) Non-destructive evaluation: Techniques that do not damage the structure are utilized here to assess internal conditions. Methods are ultra sonic inspection, color penetration test etc. This method reveals subsurface defects, measures material properties without causing damage; however, it requires specialized equipment and expertise, limited to certain defect types.

(d) Structural health monitoring: In this technique, continuous monitoring of the bridge due to dynamic loads is performed using sensors like LVDT, electrical strain gauge, accelerometer etc. Benefits of this techniques are real-time monitoring, early detection of anomalies, availability of long-term performance data etc. However, initial setup costs, ongoing maintenance, and data interpretation challenges are limitations with method.

(e) Load testing: In this method, controlled loads are applied over the bridge to assess its response and behavior. This method evaluates structural capacity, identifies deformations. Nevertheless, it is resource-intensive, may not replicate real-world conditions accurately.

As of 2016, the Indian Railways system has 1.41 lakh bridges, 27% of which were more than 100 years old and 34% were more than 80 years old (Awasthi et al. 2022). It is necessary to analyse the condition of these bridges before proceeding with upgrading or replacing them.

Three aspects of condition assessment are performed in this study: fatigue-based remaining life assessment, deep learning-based crack identification, and fuzzy-based bridge rating.

(a) Fatigue-based remaining life assessment:

Most prevailing fatigue assessment methods, such as those found in widely adopted standards like British code (BS 5400 part 10), Eurocodes (CEN, 2005), Indian code (IS:800), and American manual (AREMA 2011), rely on S-N curves and linear damage accumulation principles derived from the Palmgren-Miner rule (Miner, 1945). While these approaches are convenient during the design phase, they prove less effective for in-service structures. When faced with fatigue damage, such as fatigue cracks, these methodologies, specifically S-N curves, fail to calculate the remaining fatigue life of the damaged component and the overall structure. Additionally, they offer limited assistance in determining time intervals between inspections or the duration available before maintenance and retrofitting become necessary.

Conversely, railway department demands optimized inspection, maintenance, and retrofitting interventions to minimize economic impact. The aim is to reduce line closures to the shortest possible duration. Consequently, there is a need for novel experimental and numerical fatigue assessment methods to facilitate decision-making and intervention planning for railway managers, enhance safety in railway operations, and mitigate the costs associated with infrastructure maintenance.

As previously stated, the majority of standards and methods, such as BS 5400, CEN 2005, IS: 800, and AREMA 2011, use S-N curves and linear damage accumulation ideas to assess fatigue strength. Because of its easy application, this global stress level-based technique is extensively used to predict fatigue life till total breakdown. It does have some significant limitations, though.

Alternative methodologies developed for fatigue analysis focus on local behavior, as demonstrated by approaches utilizing structural stresses, structural strains, notch stresses, notch strains, and Fracture Mechanics. While these methods offer valuable insights, applying them to assess large structures in Civil Engineering presents considerable challenges, limiting their widespread use.

Typically, these methodologies involve subjecting the structural detail under consideration to a known loading history under load or displacement control. The subsequent computation of local stress or strain fields enables the calculation of fatigue damage indicators. However, complexities arise in the assessment of some structures where the loading history is often intricate, and the corresponding structural dynamical response remains unknown in many, if not all, points of interest. This complexity has constrained the broader application of these methodologies in the realm of Civil Engineering structures.

(b) Deep learning-based crack identification:

Examining masonry structures traditionally involves manual inspection, a process known for its labor-intensive, slow, and costly nature, demanding substantial time and resources for data processing. The subjective nature of this method, heavily reliant on inspector skills and physical condition, can result in inaccuracies, particularly due to lack of experience or fatigue. Safety concerns arise, especially in challenging-to-reach areas, and become even more pronounced in post-event scenarios like earthquake aftermaths, where numerous buildings need rapid inspection with limited resources. The variability in routine inspection documentation has also been a noted issue, affecting both condition ratings and related documents.

To overcome these challenges, vision-based assessment and monitoring of civil infrastructure are becoming more prominent, with computer vision, especially for crack detection, capturing researchers' interest. Vision-based crack detection, crucial for historical structures bound by strict regulations, offers a non-destructive assessment. Deep Learning (DL), a subset of artificial intelligence, and its tool, Convolutional Neural Network (CNN), have demonstrated effectiveness in object detection. Unlike traditional machine learning, DL doesn't rely on hand-crafted features, providing end-to-end classifiers for automatic object detection. This, coupled with the advancement of graphics processing units (GPU), has expanded their application across various fields. DL for crack detection, applied in diverse case studies such as bridge inspections and asphalt surfaces, simplifies the process by allowing users to input additional photos and receive crack detection results without manual intervention.

In computer vision, image segmentation is fundamental, involving the division of an image into multiple segments or regions. Crack segmentation on masonry wall surfaces, a complex task due to surface texture variability, requires specialized techniques. Deep learning-based models, particularly in recent years, have exhibited remarkable performance in image segmentation tasks across various fields.

(c) Fuzzy-based bridge rating:

Railway bridges play a vital role in a country's transportation infrastructure, facilitating the safe and efficient movement of people and goods. However, these structures face environmental and operational challenges that can cause degradation over time. Effective maintenance and management are crucial for ensuring their longevity and safe operation. Condition rating, evaluating the physical state of bridge components, is a key aspect of this process. Traditionally, human experts perform condition rating based on visual inspection and field measurements, which is time-consuming, subjective, and error-prone.

This study aims to address these challenges by proposing a fuzzy logic-based condition rating system for railway bridge components. Fuzzy logic, a mathematical approach accommodating imprecise information, offers an objective, reliable, and consistent means to assess bridge component conditions. The system will consider various parameters, including visual inspection, field measurements, environmental factors, and operational considerations. The development process involves a comprehensive literature review, field measurements, and expert opinions. The proposed system will be validated through case studies and compared to existing rating systems to demonstrate its effectiveness.

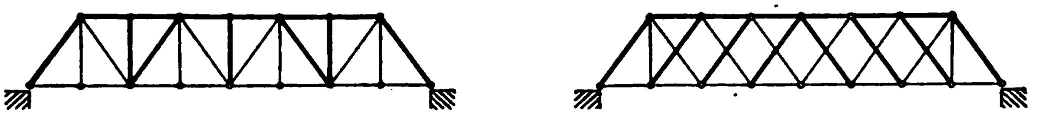
The envisioned fuzzy logic-based system is expected to contribute significantly to railway bridge maintenance and management. It promises an objective and comprehensive assessment, aiding efficient prioritization of maintenance and repairs, budgeting, and long-term planning. Additionally, it lays the groundwork for a predictive maintenance approach, reducing downtime and enhancing the safety and reliability of the transportation infrastructure. By leveraging fuzzy logic's ability to handle uncertainty, the proposed approach represents a novel contribution to the field of railway infrastructure, empowering decision-makers with more informed choices for maintaining and repairing railway bridge components. Ultimately, this study seeks to enhance the overall safety and reliability of rail transport systems.

1.2 Steel bridges

Before 1980, riveted bridges were used in Indian railway bridges. Since 1980, welded construction has been used to make plate girders (open deck) and composite girders (ballasted deck) for track bridges. Steel is a great choice for building railway bridge girders because it has similar strength in tension and compression. This makes steel widely used in railway bridge construction. Additionally, steel usually shows signs of potential failure, like a loss of camber, before completely breaking, giving maintenance engineers a warning and preventing sudden failures.

In the 19-20th century, used open web steel girders railway bridges were of following types: Howe truss, Pratt truss, Waren truss, Camel back truss, Baltimore truss and K-truss. Configuration of these bridges can be seen from Figure 1.1.

(a) Through Howe Truss (b) Through Pratt Truss



(c) Through Warren Truss (d) Quadrangular Through Warren Truss

(e) Through Whipple Truss (f) Camel Back Truss

(g) Through Baltimore Truss (h) K-Truss

(i) Through Petit Truss (j) K-Truss

Figure 1.1: Types of truss bridges (Ketchum 1920)

Different elements of an open web steel girder (truss) bridge are illustrated in Figure 1.2. Elements include top chord, bottom chord, end post, vertical, diagonal, stringer, cross beam or floor beam, top lateral, bottom lateral, portal, sway bracing etc.

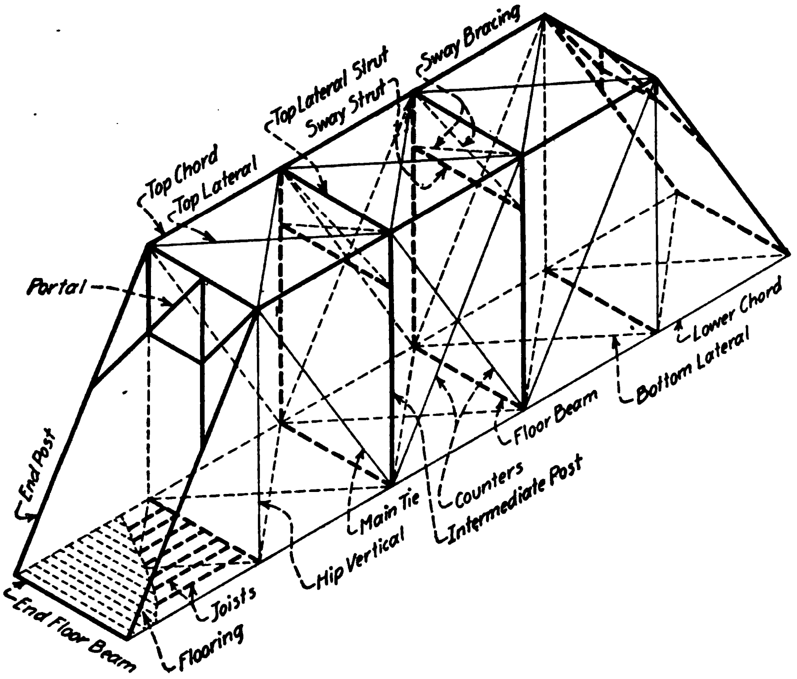


Figure 1.2: Different elements of Truss (Ketchum 1920)

1.3 Summary of railway and roadway bridges in India

(a) Railway bridges:

As of April 2022, there were 1,56,417 bridges in Indian railways (IR), of which 739 are important, 12,590 major, and 1,43,088 minor. In 2021–2022, 1,541 bridges are strengthened, renovated, or rebuilt to improve train operating safety. Based on type of bridges (important, major, and minor bridge) their percentage distribution is shown in Figure 1.3.

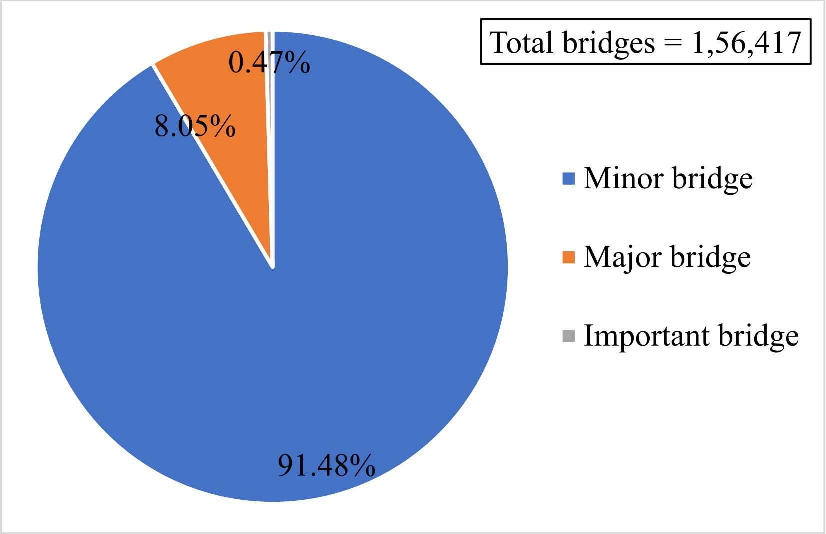


Figure 1.3: Classification of Indian railway bridges (Indian railways year book 2021-22)

(b) Roadway bridges:

IBMS has been implemented since 2015. This scheme was launched by ministry of road transport and highways (MoRTH), India. Aim of the scheme is to provide the data of existing bridges over National highways (NH) including history of bridge, dimensional details, repair & maintenance record, latest images, current condition rating etc. MoRTH, India has inventoried (MoRTH 2019) 1,72,517 bridges lying on NHs in India under a scheme called Indian Bridge Management System (IBMS). For total 1,72,517 bridges, span wise percentage distribution of bridges is shown in Figure 1.4.

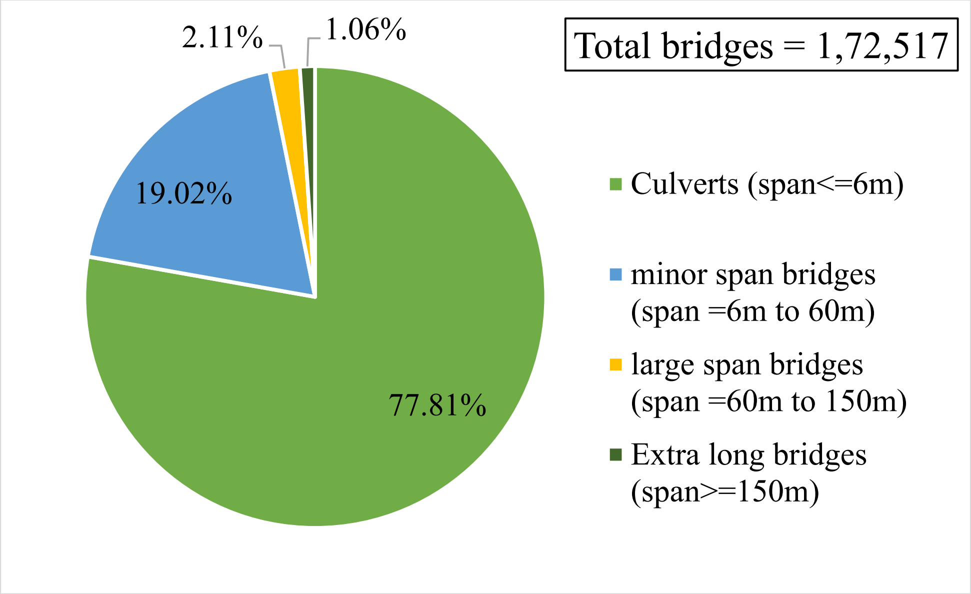
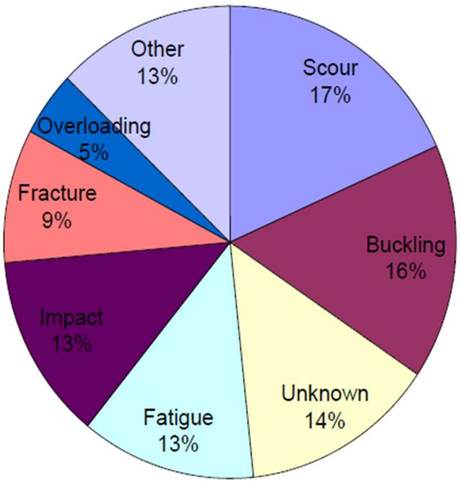


Figure 1.4: Classification of Indian roadway bridges (MoRTH 2019)

1.4 Failure of metallic bridges

As per the ASCE committee (ASCE 1982) report, 80 to 90 percent failures of metallic structures are due to fatigue and fracture. A review of 164 metallic bridge failure cases is presented by Imam and Chryssanthopoulos (2010). Bridges include mainly railway and highway bridges. 87 of 164 bridges were classified as collapse bridges. 13% of collapse bridges were failed due to fatigue. 73 of 164 bridges were classified as bridges that ceased functioning and caused bridge closure or retrofitting works. 67% of such bridges were not functioning due to fatigue. Proportion of various failure modes leading to collapse of metallic bridges is shown in Figure 1.5. Proportion of various failure modes that ceased functioning and caused bridge closure is shown in Figure 1.6.



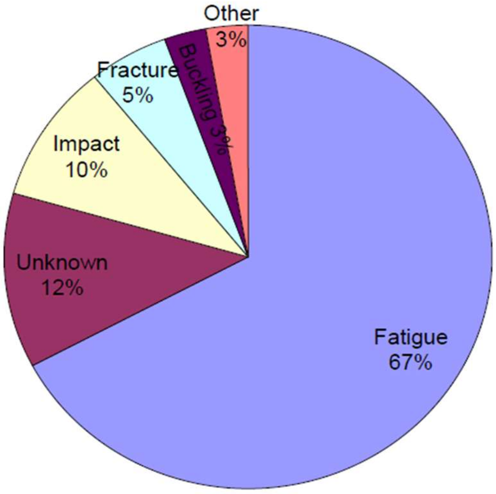


Figure 1.5: Failure modes leading to collapse of metallic bridges (Imam 2010)

Figure 1.6: Failure modes for non-collapsed metallic bridges (Imam 2010)

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).

Steel girder bridges, particularly truss bridges, are more prone to failure than other types of bridges. Wardhana and Hadipriono (2003) conducted a statistical assessment of 500 bridge failures in the United States from 1989 to 2000. Steel beam/girder and steel truss bridges were found to be the most common types of failed bridges in their analysis, with 145 (29%) and 107 (21%) instances, respectively. These failed bridges account for more than half of the total bridge. The onset of damage, its propagation and collapse consequences of steel truss bridges has been described by Lopez et al. (2023).

According to R. K. Garg (2020), from 1977 to 2017, around 2130 bridges in India fell (culverts and pedestrian bridges excluded). These failed bridges had an average lifespan of 34.5 years, which is much less than the bridges' anticipated design life. 35% bridges failed within 10 years of service. The nation's economy is burdened by a premature bridge collapse in addition to upsetting the lives of the local population. 123 bridges failed at various points during the building process. Sixty-three percent of the 2130 failed bridges they examined were made of RCC and PSC, 19% were made of steel, 6% were Bailey bridges, 5% were made of masonry, and 3% were steel suspension bridges.

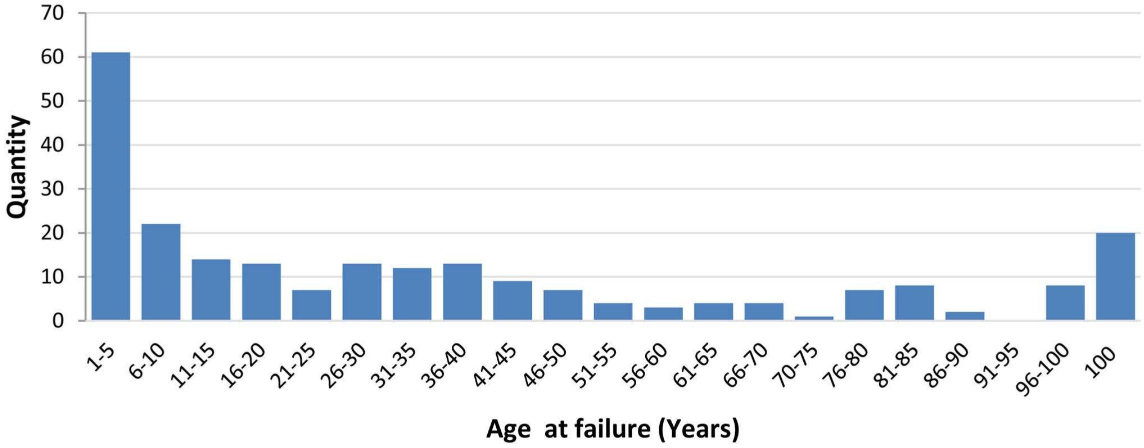


Figure 1.7: Number of bridges failed at different age groups (sample size =232) (Garg et al. 2020)

Three cases of bridge failure are summarized in the following paragraph.

(a) Failure of I-35W Bridge (A Steel truss bridge): One famous example of a sudden collapse is the August 1, 2007 collapse of the I-35W bridge over the Mississippi River in Minneapolis, Minnesota, which killed 13 people and injured more than 100 others (Liao et al., 2011). Figure 1.8 depicts the collapse of the I-35W bridge (A. Astaneh-Asl, 2008).

Figure 1.8: View of the collapsed I-35W bridge (A. Astaneh-Asl 2008)

The bridge's superstructure featured two primary longitudinal trusses that extended continuously over three spans measuring 81m, 139m, and 81m. These longitudinal trusses were linked by transverse trusses at each panel point. The bridge accommodated eight lanes of traffic (A. Astaneh-Asl, 2008). Over its service life, the bridge underwent several repairs and modifications, with significant reconstructions in 1977 and 1998. These involved augmenting the concrete deck thickness from 6.5 to 8.5 inches and adding new concrete parapets and guard rails. Initially, the concrete deck constituted 70% of the total bridge weight, and subsequent additions increased the bridge weight by over 30%, imposing a substantial load on structural components. The mental image suggested that adding 2.0 inches of concrete to the deck was akin to doubling the weight of the steel (A. Astaneh-Asl, 2008).

Structural analysis of the I-35W Bridge revealed that the main truss members had acceptable safety factors during their design, with capacity exceeding demands throughout the bridge's lifespan, including the day of the collapse. While numerous truss members fractured upon falling, there was no evidence suggesting that the failure of a truss member triggered the collapse.

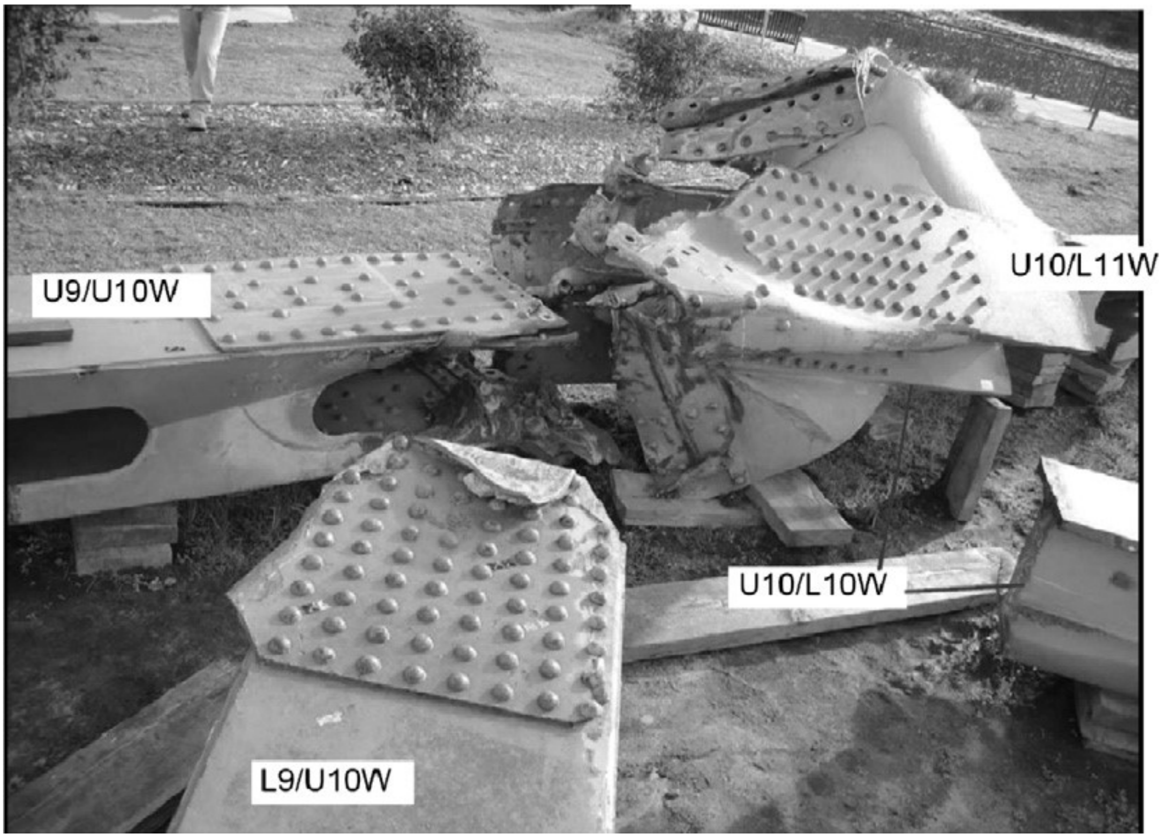


Figure 1.9: Gusset plate failure at joint U10 (Liao et al. 2011)

All bridge joints were connected by 1-inch-thick gusset plates, except for top chord joint U10, where 1/2-inch-thick gusset plates were used (Figure 1.9). Investigations and finite element analyses by various researchers concluded that the undersized gusset plate at joint U10 was the primary cause of the catastrophic and sudden failure (Liao et al., 2011). Fatigue was one of the reasons to failure of the bridge (Hao 2010).

(b) Failure of Chauras Bridge, India:

A 190m-long bridge spanning the Alaknanda River near Srinagar, Uttarakhand, India, was under construction. The intended location was between Srinagar and Chauras on the left bank of the river. A three-span continuous open web steel girder with measurements of 40, 110, and 40 metres made up the bridge's structure. Tragically, on March 24, 2012, during the process of laying the concrete deck slab, the bridge collapsed (Birajdar et al. 2014) (Figure 1.10), resulting in the loss of six lives. The bridge, designed with a carriageway width of 7.5m and 1.5m-wide footpaths on both sides, was intended to support two lanes of traffic.

An analysis of the bridge structure aimed to pinpoint the members responsible for the collapse. The bridge was modeled using STAAD software. The buckled view of member U13U14 at the Chauras bridge collapse is presented in Figure 1.11. The analysis also noted the overstressing of member U13U14. The root cause of the failure was identified as a flawed sequence in the casting of the deck slab. Commencing the laying of wet concrete from the middle of the 110m span led to lifting at the end spans. The bridge collapse might have been prevented if the deck slab had been cast correctly.

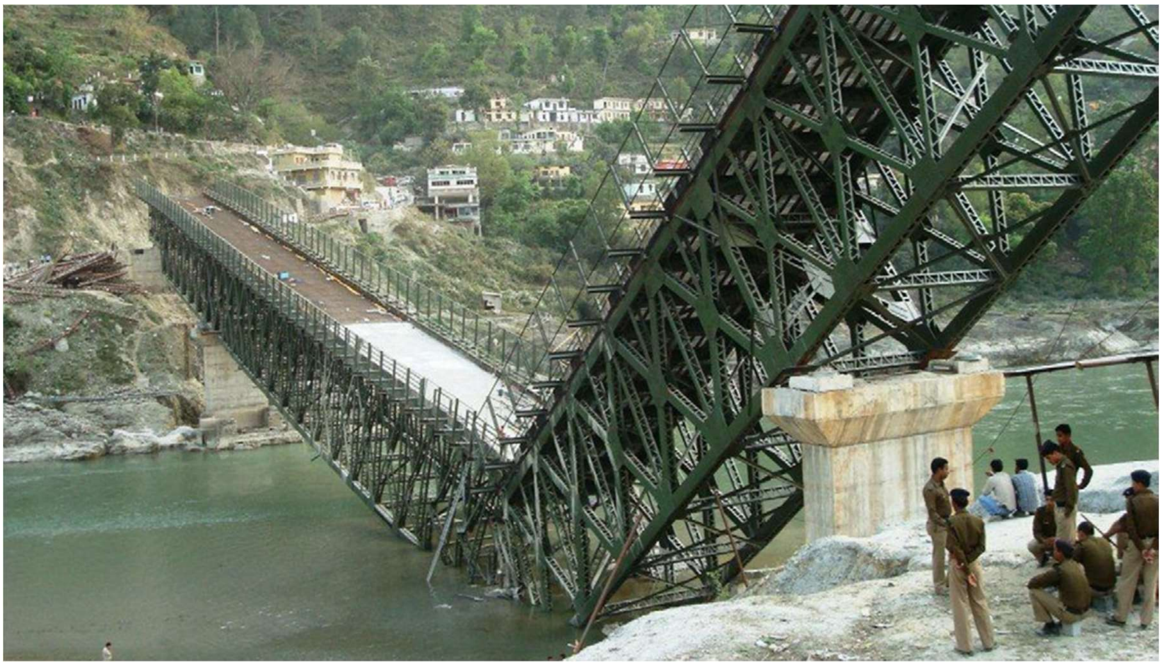


Figure 1.10: Failed Chauras bridge during deck casting (Birajdar et al. 2014)

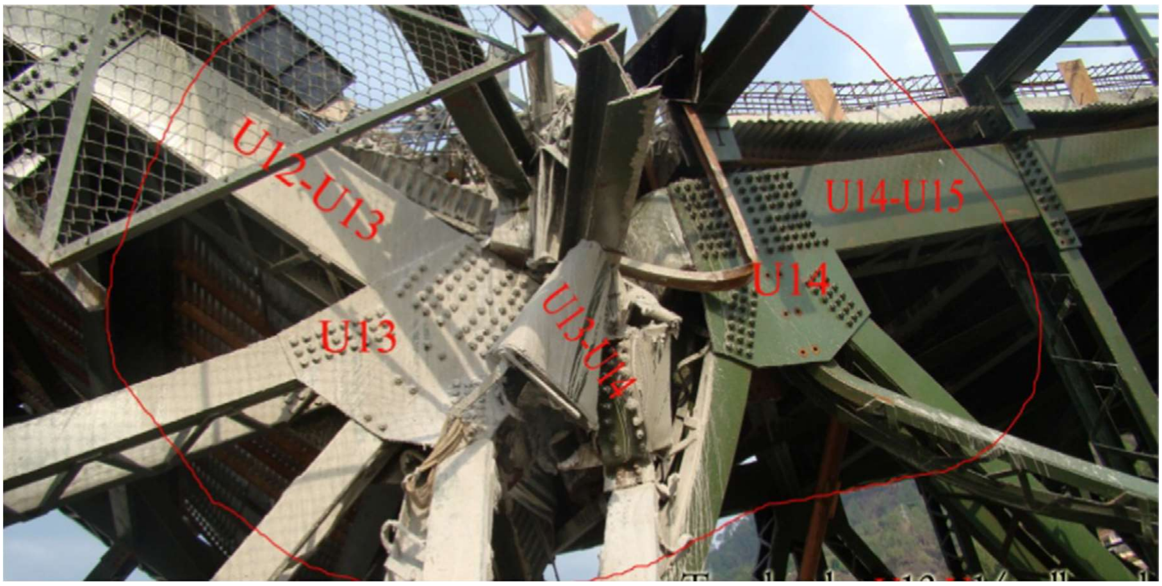


Figure 1.11: Joints U13, U14 and buckled member U13U14 (Birajdar et al. 2014)

(c) Failure of suspension bridge Morbi, India:

The pedestrian bridge crosses the Machchhu River and is 233 meters long, with a width of 1.25 meters. It links Darbargadh Palace in Gujrat, India, to Lakhdhirji Engineering College. The suspension bridge has been in operation since 1879. Unfortunately, on October 30, 2022, a tragic incident occurred: the suspension bridge over the Machchhu River in Morbi Town collapsed, resulting in the loss of 135 lives. There is no literature on the collapse of this bridge to date. So much information on bridge failure causes could not be provided. Collapsed pedestrian bridge is shown in the Figure 1.12. However, the probable reason of bridge failure is a lack of frequent bridge condition assessments and maintenance.

Figure 1.12: Collapsed pedestrian bridge, Morbi, Gujrat (The Hindu)

1.5 Motivation

The study conducted by Garg et al. in 2020, examining 232 bridges (including both highway and railway bridges), revealed that the average age of these structures is only 34.5 years. Notably, within the first five years of operation, 26.3% of these bridges failed, and an additional 9.5% failed within the subsequent five to ten years. These findings underscore the urgent need for a comprehensive and integrated approach to assess the condition of these vital infrastructures.

Moreover, as of April, 2016, the Indian Railways system boasted an extensive network of 1,40,919 bridges. Amazingly, 27.1% of these bridges are more than 100 years old, and an additional 34.1% are more than 80 years old, as reported by Awasthi et al. in 2022. This scale of aging bridges within the railway system necessitates a thorough investigation into their structural health before contemplating any upgrading or replacement strategies.

1.6 Objective and scope

Whole study is divided into 4 sections and section wise objectives are given below.

(a) Assessment methods for steel bridges and their application:

- To describe different methods for assessing the remaining life of existing steel bridges.
- To utilize both the stress life method and fracture mechanics-based method on a numerically simulated riveted open web steel girder railway bridge, exploring the impact of different stress bands (5 MPa and 10 MPa) on forecasted lifespan.
- To provide guidelines for stress band selection in the stress-life-based method.

(b) Comprehensive Analysis of Large Multi-functional Bridge:

- To analyze a bridge exceeding one kilometer in length, accommodating both roadway and railway, considering various loadings, speed criteria, and stress bands.
- To assess the residual life for major and minor spans, considering various futuristic loadings, speed criteria, and stress bands (SB5, SB10, SB15), and compare outcomes with a reference stress band ('SB').
- To investigate pattern of variations in remaining life and per vehicle passage damage (PVPD) for different stress bands.

(c) Deep learning-based crack detection on masonry surfaces:

- To investigate and compare deep learning models for semantic segmentation of cracks on masonry surfaces, assessing their performance on existing masonry culvert bridges.
- To evaluate the performance of various deep learning architectures with different backbone networks using metrics like dice coefficient, IoU, and F1 score.
- To apply the developed models to real-life structures, specifically small masonry culvert bridges, overcoming challenges of uneven texture using an image-based crack detection method with deep learning networks.

(d) Fuzzy-based condition assessment for railway bridges:

- To develop a fuzzy-based system for accurate and efficient condition assessment of railway bridges, overcoming limitations of the current conservative and manual grading practices.
- To introduce a 10-point crisp rating scale, utilizing triangular MF for rating and structural importance, combine condition rating and weight using the FWGM technique, and apply the centroid approach for defuzzification, focusing on assessing railway bridge components and the entire structure.
- To address the inefficiencies of the current 5-point numerical rating system and contribute to increased safety and reliability in railway infrastructure.

The study collectively aims to advance the methodologies for assessing the remaining life of steel bridges, analyze large multi-functional bridges comprehensively, improve crack detection techniques on masonry surfaces, and introduce a more accurate and efficient fuzzy-based condition assessment for railway bridges. The findings from each objective contribute to enhancing the safety, reliability, and maintenance efficiency of various types of bridges in different structural contexts.

1.7 Organization of thesis

The present thesis is divided in seven chapters. General introduction, different aspects of condition monitoring, failure of bridges, summary of bridges in India, objectives and scopes of the study are discussed in Chapter 1. The Chapter 2 provides the literature review on fatigue analysis, DL based crack detection, and fuzzy based rating of the existing bridges. In Chapter 3, different methods of fatigue life assessment are discussed with special emphasis on stress-life method. Application of stress life method and LEFM approach is presented using a case study of an existing railway bridge in this chapter. In Chapter 4, the stress life approach is used to evaluate the fatigue-induced per vehicle passage damage (PVPD) and remaining life of a rail-cum-roadway bridge. Patterns of PVPD variation and remaining life variation are found for various stress bands using a best fit distribution analysis. In Chapter 5, Comparative study of 23 combinations with various types of segmentation models and backbone networks has been performed over masonry data set and Performance of top performing networks has been investigated over a case study. A fuzzy-based system for rating bridges has been suggested and implemented across three case studies in Chapter 6. In Chapter 6, the rating derived using Indian Railways' current technique is compared with the suggested methodology. Chapter 7 provides a summary of the conclusions derived from the current study and the scope of future work.