Enhancing Sustainable Infrastructure: The Role of Fatigue Analysis in the Rehabilitation of Steel Railway Bridges

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Abstract

This Article elucidates the critical role of fatigue analysis in the maintenance and sustainability of steel railway bridges within the context of India's developing urban infrastructure. According to India's Ministry of Railways reporting 37,689 bridges over 100 years old and at potential risk due to evolved service conditions (Railway board , 2019), the paper advocates for a proactive strategic rehabilitation approach. By drawing comparisons to the problems in Europe, where over 50% of railway bridges exceed 50 years, the urgency of addressing structural deficiencies through two main strategies—replacement or upgrade and repair—is underscored. The methodology leverages rigorous fatigue assessments through inspection, condition assessment, and service life forecasting to pinpoint structural damage and estimate bridges' remaining life. The paper describes detailed European standards that guide the fatigue analysis, emphasizing a combined use of finite element modelling and real-time stress monitoring data to manage the dynamic loads experienced by bridges. In India, the implementation is contextualized through the Indian Bridge Management System (IBMS) and the guidelines from the Indian Roads Congress (IRC), highlighting the Steel Bridge Code by RDSO for comprehensive fatigue analysis. However, challenges persist due to underemployment of maintenance personnel and the need for upgrading inspection technologies.The conclusion ties the significance of fatigue analysis to the achievement of the United Nations Sustainable Development Goals (UNSDGs). It underscores that targeted maintenance through fatigue analysis not only enhances bridge durability and safety but is also congruent with responsible resource consumption and environmental protection. Such an approach aims for a resilient infrastructure that supports sustainable urban expansion and conservation of natural habitats, aligning with global sustainability initiatives.

Key Words: Railway, Infrastructure, Bridges, Sustainable & United Nation Sustainable Goals

1. Introduction

The indispensable role of steel railway bridges in fostering sustainable urban development is unparalleled, directly supporting UNSDG goals by facilitating the movement of people and commodities. Ensuring the longevity of these structures is crucial for the safety and sustainability of our transportation networks. This paper underscores the significance of fatigue analysis in the strategic rehabilitation of these bridges, revealing how a careful and predictive approach to maintenance serves not only safety imperatives but also the broader sustainability goals, including responsible resource management. It also contributed to decarbonizing to net zero and in the existing river bridges, aids the preservation of aquatic habitats. In conclusion, fatigue analysis positions itself as an indispensable tool in the quest for sustainable infrastructure that underpins our societies.

According to the Ministry of Railways Report (Railway board , 2019), India boasts 1,47,523 bridges throughout its railway network, with 8% classified as major or significant, spanning linear waterways greater than 18 meters. It has been observed that 37,689 of these bridges are over 100 years old (Railway board , 2019). The railway administration has noted that these older bridges were designed for lighter loads and service conditions, which have drastically evolved due to the introduction of faster and heavier trains. Consequently, the integrity and safety of these aging structures could be at risk, potentially leading to critical safety lapses. The Standing Committee on Railways Seventeenth Lok Sabha has stressed the necessity for the Ministry to strategize proactively for the timely rehabilitation of these bridges and to implement measures that prevent injuries, loss of life, property damage, or destruction, especially during natural disasters. The data underscores a significant need for rehabilitation efforts across the railway network.

In the aftermath of World War II, a significant number of bridges were constructed across Europe to accommodate the burgeoning demand for road and railway connectivity. Presently, these infrastructures are showing their age, with a substantial number deemed structurally unsound or outdated, necessitating immediate restoration or modernization. Research involving 17 European railway authorities indicates that over two-thirds of the continent's railway bridges have surpassed the half-century mark, with a full half exceeding a century in service (Kliger & Rempling, 2013). The situation in France is particularly dire, with upwards of 50% of its 20,000 bridges requiring repairs and over 20% classified as structurally deficient. Similarly, Hungary faces a critical situation where over half of its primary and secondary highway bridges urgently require refurbishment (Kennedy et al., 2001) . An analysis of 161 failed metallic bridges pinpoints fatigue and fracture as the most prevalent causes of collapse, accounting for over 45% of these incidents (Imam & Chryssanthopoulos, 2010).

Retrofitting aging bridges in India and across Europe presents considerable economic benefits. In India, the implementation of the Indian Bridge Management System (IBMS) and guidelines by the Indian Roads Congress highlight efforts for bridge assessments and reparations, which are crucial given the low number of bridges rehabilitated to date and staff shortages. European countries employ various Bridge Management Systems that integrate Bridge Information Modelling and Digital Twins for efficient lifecycle management, potentially reducing maintenance costs and extending bridge lifespans. Proactive bridge rehabilitation can prevent catastrophic failures, preside over safety, and ensure uninterrupted connectivity, thereby safeguarding against economic losses from potential operational disruptions.

2. Methodology

The railway bridges are dynamically loaded structures that experience complicated loads that fluctuate with different amplitudes. As a result, it is necessary to perform a fatigue assessment to find the damage and remaining life of the bridge. Rehabilitation of steel bridge involves the following steps which are discussed below

1. Inspection and Condition Assessment
2. Fatigue Analysis and Service Life Forecasting

This section explains the fatigue analysis design methodology as per European standards through the example of a truss bridge. The focus is squarely on the fatigue assessment and service life evaluation, thus details on the inspection of the bridge's current state are omitted. The methodology describes a systematic approach to quantify the fatigue strength of the truss bridge components under repetitive stress cycles, crucial for ensuring long-term structural integrity and safety.

Design Methodology

Step 1: Inspection and Condition Assessment The assessment commences with an exhaustive inspection to evaluate the bridge's structural damages. By identifying structural damages and citing repair over replacement where viable, adherence to responsible practices that reduce waste, and resource consumption, and reduce overall cost.

Step 2: Fatigue Analysis and Service Life Forecasting: After the damages are rectified, the life span of the bridge needs to be assessed. For this, a fatigue analysis is performed. Detailed fatigue analysis is performed in accordance with Eurocode EN 1993-1-9 (European Standard, 2005) to accurately measure the progressive deterioration caused by repetitive stress cycles on bridge structures, hence determining the remaining service life of the structural element with greater accuracy. Utilizing "Rain-flow counting", in line with ASTM E 1049-85 guidelines (ASTM Standards, 2017), proves crucial in interpreting the fatigue damage, leading to better-informed decisions based on the damage due to fatigue over time.

For illustration, an example of a fatigue assessment on a steel truss bridge is explained.

A typical railway steel truss bridge as shown in Figure. ***1*** , consists of compression steel members on top of the bridge and tension chords on the bottom. Additionally, wind bracing is used to connect left and right truss systems. The Rail track is supported by the bottom members.

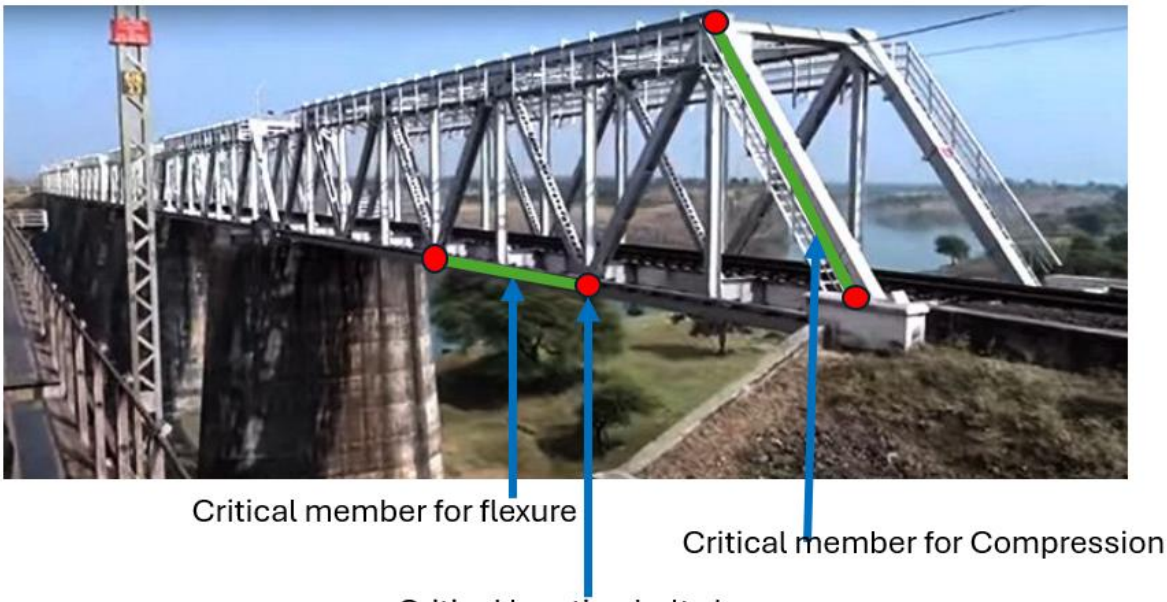

Figure. 1: A typical steel truss

The calculation starts with finite element modeling of the bridge based on the existing drawing as shown in Figure. *2*. This finite element (FE) model will be used for further analysis.

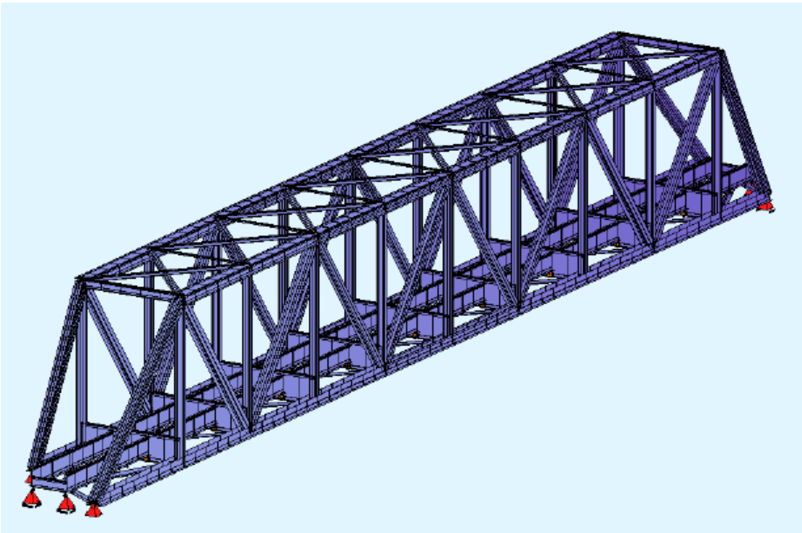

Figure. 2 : Model idealization using FEM software

Then to find the damage caused due to all traffic run to date, sensor data is required which records the time history of the stress developed on the bridge over the years. For many old bridges, this information is absent. So, standard trains and traffic data given by the rail authority are used for the fatigue analysis. So, fatigue train loads are applied as shown in the following Figure 4.

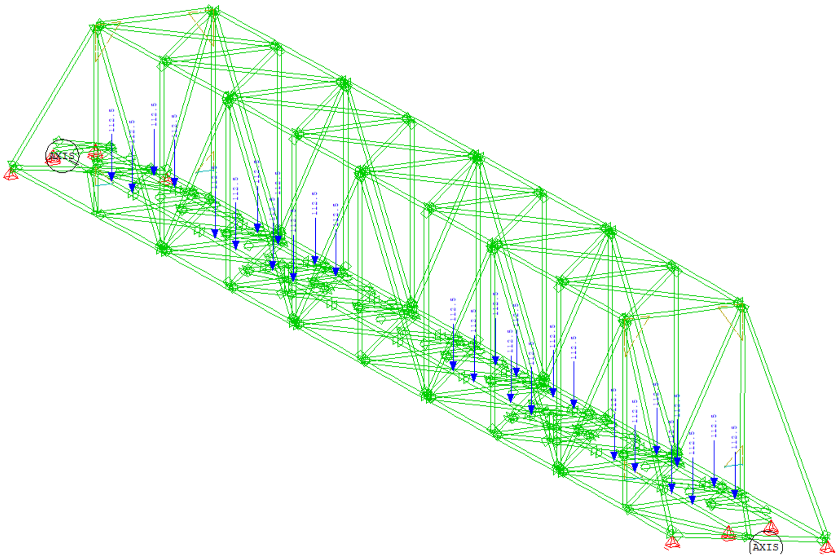

Figure. 3 : Running live load (Fatigue trains) for generating time histories

After performing live load analysis, internal forces time histories are obtained which include (moments, shear, and axial forces). These forces along with cross-sectional values are used to derive flexural and shear stress (in bolts) time histories. These stress time histories are used for further analysis.

The fatigue assessment process follows a step-by-step cumulative damage method outlined in NS-EN 1993-1-9 Annex C (European Standard, 2005) as shown in Figure 4. Initially, the stress time history is read and then transformed into a sequence of peaks and valleys. These stress variations are then translated into cycle counts using the Rain flow method. The next phase involves employing the S-N curve to quantify the damage sustained by each cycle, culminating in net damage assessment as per the Palmgren-Miner rule.

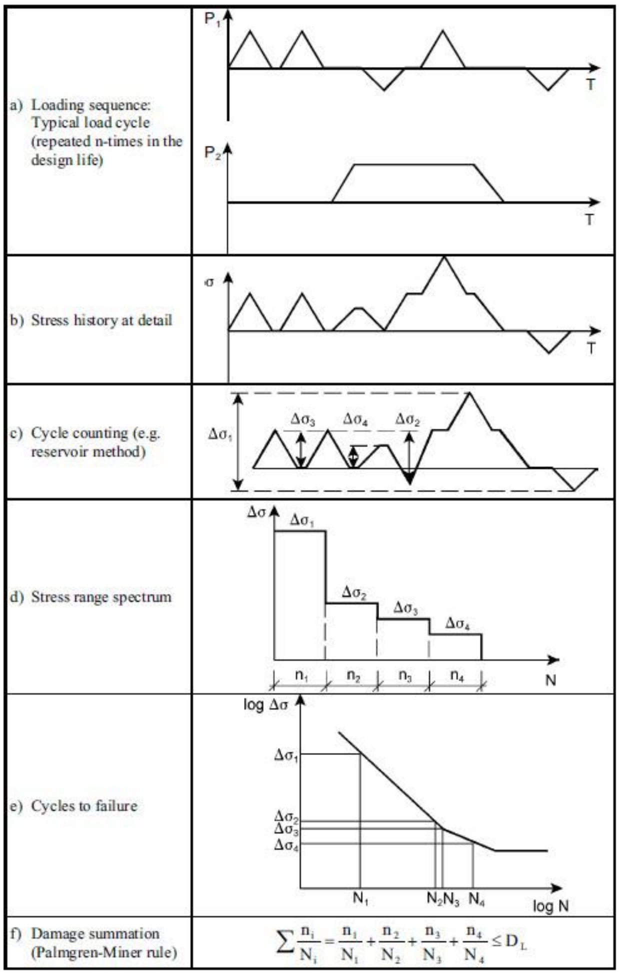

Figure A.1: Cumulative damage method

Figure 4 : Workflow of fatigue analysis

Rain flow counting and cumulative damage calculation

Step 3.1: Reading stress time history:

The analysis begins with the collection of stress data that a component experiences over time. This data can be obtained through direct measurements on a physical prototype with sensors, derived from a Finite Element Analysis (FEA) simulation. A typical stress time history is shown in Figure 5.

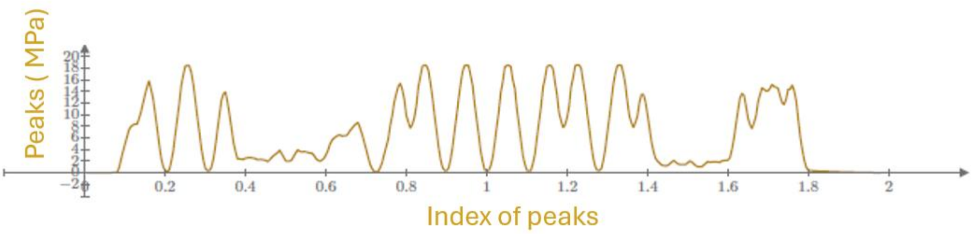

Figure 5 : Stress time history

Step 3.2: generating peaks and valleys

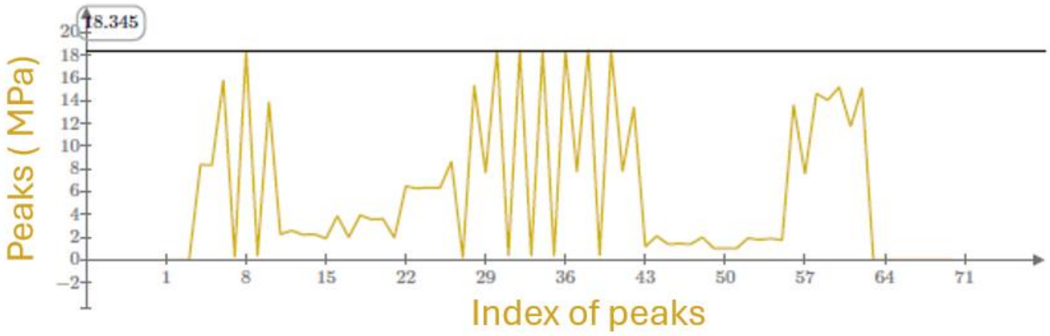

Figure. 6 : Peaks and valleys

Once the stress time history is recorded, the next step is to identify the stress reversal points in the stress time history, known as peaks and valleys.

Activities in this step include:

- Identifying the maximum and minimum stress levels within each loading cycle.
- Removing extraneous data that do not affect the fatigue life, simplifies the stress history.

Step 3.3: Rain Flow counting: (Stress cycles)

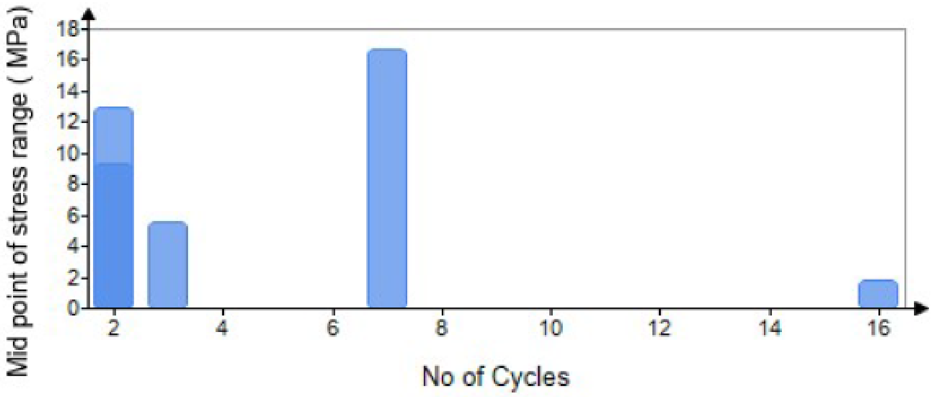

Figure. 7 : Result of rain flow counting.

In the present stage number of stress cycles is counting and method use is called rain-flow counting. Rain flow counting is a method used to simplify complex stress histories into a series of simple, fully reversed stress cycles that can be used to predict fatigue life. The rain flow counting used in the analysis is as per ASTM E1049-85 (ASTM Standards, 2017)

Activities in this step include:

- Breaking down the stress history into a series of half-cycles.
- Sorting these half-cycles into bins according to their amplitude and mean stress.

Step 4: Damage calculation

The final step is to calculate the cumulative damage that the component has experienced due to the applied stress cycles. This is typically done using a damage model such as the Palmgren-Miner rule, which assumes that each cycle of stress contributes a certain amount of damage, and when the cumulative damage reaches a critical value (typically set to 1), failure is expected.

Activities in this step include:

- Applying fatigue life models (e.g., S-N curves etc as shown in Figure. .) that relate stress amplitude and mean stress to the number of cycles to failure.
- Summing the damage of each cycle to predict the life.

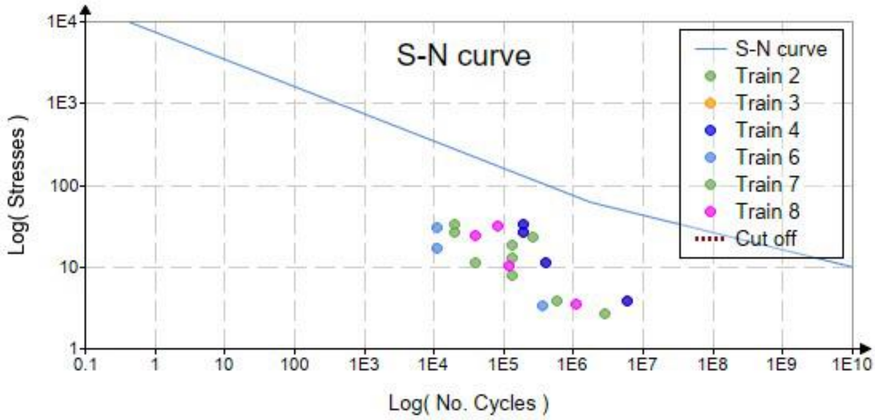

Figure. 8 : Typical SN curve used for damage calculation

Step 5: Residual service life prediction

Following the assessment of damage to individual components, the residual service life is determined. Should this duration fall short of the targeted lifespan, a replacement component is suggested to prolong the bridge's overall longevity.

The following equation is the simple version to calculate the remaining life of the structure.

$$RemainingLife\ (\ years) = (1 - damagedOccured\ till\ date\ )/(Damage\ to\ occur\ per\ year)$$

In cases where the estimated remaining service life is below the projected requirement, for instance 20 years, those specific elements will be subject to replacement. A representative diagram (refer Figure 8) is provided to illustrate the components earmarked for replacement, corresponding to their remaining service life calculations

Figure 8 : Service life of each member

This approach demonstrates that rail authorities need only replace select portions of the bridge that have diminished service life rather than undertake a complete overhaul. Adopting such measures contributes to the aim of sustainability.

3. Discussions

Rehabilitation bridge in India so far

Since 2015, India has implemented the Indian Bridge Management System (IBMS). The Ministry introduced the IBMS to perform evaluations of the condition of all bridges and structures within the National Highway Network. This encompasses both inventory and inspection, employing Mobile Bridge Inspection Units and locally developed software. Additionally, in 2019, the Indian Roads Congress (IRC) released guidelines on methods for repairing and rehabilitating bridges, encapsulated in two documents: IRC: SP 40- 2019 (Indian Road Congress, Guidelines on Repair, Strengthening and Rehabilitation of Concrete bridges (IRC:SP:40-2019), 2019), which focuses on general repair and rehabilitation techniques, and IRC: SP:74-2007 (Indian Road Congress, Guidelines for Repair and Rehabilitation of Steel bridges (IRC:SP:74-2007), 2007), which specifically addresses steel bridges. While IRC: SP:74-2007 (Indian Road Congress, Guidelines for Repair and Rehabilitation of Steel bridges (IRC:SP:74-2007), 2007), does not provide detailed guidance on fatigue analysis, the Steel Bridge Code (Railway Board, 2017) from RDSO does offer a comprehensive procedure for it.

The Railway Review Report (Railway board , 2019) presented the following insights:

- According to Para No. 10 of the report, the number of railway bridges that have undergone rehabilitation is significantly low in relation to the total number of existing or aging bridges.

- There is a notable shortage of maintenance personnel, with only 40% of the necessary staff currently employed, as indicated by Para No 8, which could contribute to the overall shortfall.
- Visual assessments are primarily used to evaluate the condition of bridges; therefore, the implementation latest technology like satellite imagery for inspection purposes is advocated within the report.

In reference to the Steel Bridge Code (Railway Board, 2017), specifically Appendix G explains the fatigue assessment and cycles counting for the analysis. To summarize, there exists comprehensive technical literature addressing both rehabilitation and fatigue assessment for bridges in India. The main challenge is the manpower and lack of equipment to monitor the structure.

Bridge management system in Europe:
Based on the IABSE conference (Vanessa Saback de Freitas Bello, Cosmin Popescu , Thomas Blanksvärd, & Björn Täljsten, 2021) , Europe has a set of different Bridge management system (BMS) as shown below:

- Denmark - DANBRO,
- Finland - HiBris & HankeSiha
- France - LAGORA ,
- Germany - SIB-Bauwerke,
- Norway - Brutus,
- Sweden - BatMan,
- Switzerland - KUBA, UplaNS
- UK - SMIS.

These BMS have advanced the development of Bridge Information Modelling (BrIM) and Digital Twins. These methods facilitate the effective administration throughout a bridge's entire lifecycle. Resulting of these developments, a model for an ideal BMS has been suggested, which aims for the automated and intelligent management of bridges.

4. Conclusion

In India, fatigue analysis can be integrated into the rehabilitation strategies for aging railway bridges as part of the Indian Bridge Management System (IBMS). It involves detailed inspections, condition assessments, and the use of advanced technologies such as finite element modelling and real-time monitoring. While the framework for fatigue analysis exists within India's infrastructure management, challenges like limited manpower and outdated monitoring equipment need to be addressed to fully realize its potential.

- Increased funding for systems like Integrated Bridge Management Systems (IBMS) is essential for transitioning to advanced Bridge Information Modelling (BrIM) and Digital Twins. These innovative methods facilitate comprehensive bridge life cycle management. Drawing from these results, a conceptual framework for an optimal Bridge Management System (BMS) is recommended to realize autonomous and intelligent bridge administration.

- Create more detailed Recordings of the traffic through the various railway line so that it can be used for fatigue analysis.
- Expand the sensor network installed on bridges to capture a more detailed picture of structural responses, aiding in comprehensive fatigue evaluations.

Fatigue analysis in bridge rehabilitation aligns with several UN Sustainable Development Goals (SDGs). It helps create sustainable cities and communities (Goal 11) by allowing for bridge repairs without disrupting traffic or daily life. It promotes responsible consumption and production (Goal 12) by reducing the resources required for bridge projects. Contributing to climate action (Goal 13), it lessens the environmental footprint of construction. Lastly, it supports life below water (Goal 14) by ensuring that the maintenance of bridges over water bodies doesn't harm aquatic ecosystems.

This holistic approach ensures that infrastructure development can coexist harmoniously with environmental preservation, fostering a sustainable future for urban growth and transportation networks

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