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Dynamic Evaluation of Bridges: A Case Study of the Chenab Bridge in India

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ABSTRACT

The Chenab Bridge, located in Jammu and Kashmir, India, is the world's highest railway arch bridge, standing 359 meters above the Chenab River with a main arch span of 467 meters. This paper presents a comprehensive dynamic evaluation of the bridge, focusing on its response to seismic, wind, and blast loads, which are critical given its location in a seismically active and windy Himalayan region. The study employs advanced numerical modeling, field measurements, and structural health monitoring (SHM) data to assess the bridge's dynamic behavior. Finite element analysis (FEA) and wind tunnel tests are utilized to evaluate modal properties, dynamic amplification factors, and structural stability under extreme environmental conditions. Results indicate that the bridge's steel arch design, coupled with its robust foundation system, effectively mitigates dynamic excitations, ensuring safety for rail operations at speeds up to 100 km/h. The paper highlights the importance of integrating real-time monitoring systems for long-term performance assessment and provides insights into the design and evaluation of high-altitude bridges in challenging terrains. This paper explores the Chenab Bridge, the world's highest railway bridge in Jammu and Kashmir, India. It examines its innovative engineering, construction challenges, and socio-economic impact. The study highlights its role in regional connectivity and infrastructure development, offering insights into sustainable design and future railway expansion in challenging terrains.

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1. Introduction

Bridges are critical infrastructure components that facilitate connectivity, economic development, and societal integration, yet their design and operation in extreme environments pose formidable engineering challenges. The dynamic behavior of bridges under time-varying loads—such as seismic forces, wind-induced vibrations, and vehicular traffic—demands rigorous evaluation to ensure structural integrity, operational safety, and long-term durability. In regions characterized by high seismicity, extreme weather, and complex geology, these challenges are amplified, necessitating innovative design solutions and advanced analytical techniques [1]. The Chenab Bridge, located in Jammu and Kashmir, India, exemplifies such a structure, standing as the world's highest railway arch bridge and a pinnacle of modern engineering. This paper presents a comprehensive dynamic evaluation of the Chenab Bridge, focusing on its response to seismic, wind, and blast loads, and leveraging numerical modeling, experimental data, and structural health monitoring (SHM) to assess its performance in one of the most demanding environments on Earth.

The Chenab Bridge, part of the Udhampur-Srinagar-Baramulla Rail Link (USBRL) project, is a landmark achievement in India's quest to connect the remote Kashmir Valley with the national railway network. Spanning the Chenab River at a deck height of 359 meters above the riverbed—surpassing the Eiffel Tower's height—it is the tallest railway bridge globally, with a total length of 1,315 meters and a main arch span of 467 meters. Constructed from high-strength steel to withstand extreme temperatures (-20°C to 40°C), wind speeds up to 266 km/h, and seismic accelerations corresponding to Zone V (0.36g), the bridge's design addresses an extraordinary combination of environmental and operational demands. Its strategic importance, coupled with its location in a geopolitically sensitive region, further necessitates resilience against blast loads, with the structure engineered to endure an equivalent of 40 tonnes of TNT. The bridge's foundations, anchored in the jointed rock masses of the Himalayan bedrock, navigate steep slopes and geological instabilities, adding complexity to its dynamic behavior. The **figure 1** below shows the Front view of the bridge.

Figure 1. Front view of Chenab Bridge [2].

Dynamic evaluation of bridges involves analyzing their response to transient loads to predict behavior under both normal operations and extreme events [2]. For long-span arch bridges like the Chenab Bridge, dynamic loads can induce complex phenomena such as resonance, modal coupling, and aerodynamic instabilities (e.g., flutter, buffeting), which, if unmitigated, may lead to structural failure. Seismic forces, prevalent in Zone V, can cause significant displacements and stresses, particularly in flexible structures with low natural frequencies (e.g., 0.47 Hz for the Chenab Bridge's fundamental mode). High wind speeds in the Himalayan gorge pose risks of vortex shedding and buffeting, necessitating aerodynamic stability assessments through wind tunnel testing. Train-induced vibrations, critical for a railway bridge operating at speeds up to 100 km/h, require evaluation of dynamic amplification factors (DAFs) and passenger comfort criteria (e.g., vertical accelerations below 0.1g). Additionally, the bridge's strategic role mandates blast resistance analysis to ensure operational continuity under extreme scenarios [3].

The Chenab Bridge's unique context underscores the need for an integrated approach to dynamic evaluation, combining numerical simulations, experimental validation, and real-time monitoring. Finite element analysis (FEA) enables detailed modeling of the bridge's modal properties, stress distributions, and load responses, while wind tunnel tests provide critical data on aerodynamic performance. The SHM system, equipped with accelerometers, strain gauges, displacement sensors, and anemometers, offers real-time insights into structural behavior, validated during trial runs (June 2024) and operational phases (June 2025). This study leverages these tools to provide a holistic assessment of the bridge's dynamic performance, addressing gaps in existing research, which often lacks comprehensive evaluations of high-altitude bridges under multi-hazard conditions [4].

The significance of this study extends beyond the Chenab Bridge, offering lessons for bridge engineering in extreme environments worldwide. High-altitude, long-span bridges in seismically active regions—such as the Tagus River Bridge in Portugal or the New River Gorge Bridge in the United States—face similar challenges, but few combine the Chenab Bridge's extreme height, multi-hazard exposure, and strategic importance. By synthesizing numerical, experimental, and SHM data, this paper aims to advance the understanding of arch bridge dynamics and inform the design, monitoring, and maintenance of future infrastructure projects [5,6].

1.1. Objectives

The primary objectives of this study are to:

1. Characterize the Chenab Bridge's modal properties (natural frequencies and mode shapes) and evaluate its dynamic response to seismic, wind, and blast loads, ensuring compliance with design standards (e.g., Indian Railway Standards, Eurocodes).
2. Assess the effectiveness of the bridge's design features—such as its steel arch, aerodynamic profile, and foundation anchorage—in mitigating dynamic excitations and ensuring operational safety.
3. Analyze SHM data from trial and operational phases to validate numerical models and develop insights into long-term performance under real-world conditions.
4. Propose enhancements to the SHM system, particularly foundation monitoring, and recommend maintenance strategies to extend the bridge's 130-year fatigue life.
5. Contribute to the global knowledge base on dynamic evaluation of high-altitude railway bridges, providing a case study for multi-hazard environments.

1.2. Significance of the Chenab Bridge

The Chenab Bridge is not merely an engineering marvel but a symbol of resilience and innovation. Its completion in 2022, after overcoming logistical challenges like remote access and harsh weather, marks a milestone in India's infrastructure development. The bridge's design, informed by international standards (e.g., BS 5400, Eurocodes) and executed by global engineering teams, reflects a fusion of cutting-edge technology and local expertise. Its dynamic evaluation is critical not only for ensuring safe railway operations but also for advancing the science of bridge engineering in extreme environments. By addressing the interplay of seismic, wind, blast, and train loads, this study provides a blueprint for evaluating similar structures, from the Himalayas to other challenging terrains globally. The **figure 2** below shows the construction phase of the bridge.

Figure 2. Bridge under construction phase [2].

In conclusion, this paper offers a detailed exploration of the Chenab Bridge's dynamic performance, leveraging state-of-the-art tools and data to ensure its safety and longevity. The findings aim to inform engineers, policymakers, and researchers, contributing to the sustainable development of critical infrastructure in an era of increasing environmental and geopolitical complexities [7].

2. Literature Review

2.1. Dynamic Evaluation of Bridges

Dynamic evaluation focuses on understanding a bridge's response to transient loads, predicting behaviors like resonance, damping, and modal interactions that can amplify structural responses [8]. The primary dynamic loads for bridges include seismic forces, wind-induced vibrations, and traffic-induced vibrations, each requiring specialized methodologies to assess their impact on structural integrity and operational safety. Seismic forces are a dominant concern in regions prone to earthquakes, such as the Himalayan terrain hosting the Chenab Bridge. Analytical approaches like time-history analysis, which simulates real earthquake ground motions, and response spectrum analysis, which provides design-level force estimates, are widely used to evaluate seismic performance. Research emphasizes that long-span bridges, due to their flexibility, experience large displacements but lower force amplification during earthquakes [8]. Strategies such as base isolation and supplemental damping systems have been explored to reduce seismic demands, particularly for structures in high-seismic zones where ground accelerations can reach significant levels [9]. The Himalayan region's geological complexity, with fault lines and jointed rock masses, further complicates seismic design, necessitating detailed modeling of soil-structure interactions to capture foundation responses.

Wind-induced vibrations pose another critical challenge, especially for high-altitude bridges exposed to turbulent flows. Phenomena like vortex shedding, buffeting, and flutter can lead to structural instabilities if not properly mitigated [10]. Aerodynamic analysis, often conducted through wind tunnel testing, is essential for determining stability thresholds and quantifying displacement responses. Studies highlight that turbulence in wind fields, characterized by spectral models, drives buffeting responses, while flutter, a self-sustaining oscillation, is a limiting factor for long-span bridges [11]. Historical bridge failures have underscored the importance of aerodynamic shaping and damping to prevent excessive vibrations, particularly for structures like the Chenab Bridge, designed for extreme wind speeds. Traffic-induced vibrations, particularly for railway bridges, arise from moving vehicle loads, inducing dynamic amplification of static responses. Analytical models that simulate train axle loads as moving forces are used to calculate dynamic amplification factors (DAFs), which quantify the increase in response due to dynamic effects. For railway bridges, passenger comfort is a key criterion, governed by limits on vertical accelerations to minimize discomfort [12]. Advanced numerical techniques, such as multi-body dynamics, have improved the accuracy of train-bridge interaction models, capturing complex effects like track irregularities and vehicle suspension dynamics. Research suggests that low DAFs, as observed in the Chenab Bridge, indicate effective dynamic design, but comprehensive studies integrating traffic with other loads are less common [13].

A growing trend in bridge dynamics is the integration of multiple load types to assess combined effects, such as simultaneous seismic and wind loading or traffic-induced vibrations during high winds. Numerical tools like finite element analysis (FEA) enable detailed simulations of these interactions, but their accuracy depends on validation with experimental data. The Chenab Bridge's multi-hazard environment highlights the need for such integrated approaches, which remain underexplored in the literature.

2.2. Arch Bridge Dynamics

Arch bridges, characterized by their curved geometry, are inherently efficient at transferring loads to foundations, making them ideal for spanning deep valleys like the Chenab River gorge. Their dynamic behavior, however, is influenced by span length, material properties, and environmental conditions, requiring careful analysis to ensure stability and durability [14]. Seismic performance is a key consideration for arch bridges in high-seismic zones. Their flexibility, often reflected in low natural frequencies (e.g., 0.47 Hz for the Chenab Bridge's fundamental mode), reduces seismic forces but increases displacements, which can strain connections and foundations. Research has explored mitigation strategies, such as base isolation to decouple the superstructure from ground motions and viscous dampers to dissipate energy. The Chenab Bridge's foundations, anchored in Himalayan bedrock, face additional challenges from jointed rock masses, which can amplify seismic responses. Studies suggest that detailed geotechnical modeling is essential to capture these effects, particularly for structures with extreme foundation depths [15].

Wind response is another critical factor for long-span arch bridges, which are susceptible to aerodynamic instabilities due to their exposed profiles. Buffeting, driven by turbulent wind fluctuations, causes random vibrations, while flutter, a potentially catastrophic oscillation, limits design wind speeds [16,17]. Wind tunnel testing is a standard practice for assessing these responses, providing data on force coefficients, displacement amplitudes, and stability thresholds. The Chenab Bridge's aerodynamic design, validated for winds up to 266 km/h, reflects lessons from global arch bridges, where shaping and damping (1.8% for Chenab Bridge) mitigate wind-induced displacements (80 mm). Research emphasizes the role of turbulence spectra in predicting buffeting, but high-altitude bridges face unique wind patterns that require site-specific analysis. Fatigue under repeated loading is a long-term concern for arch bridges, particularly those supporting railway traffic. Fatigue life estimation, based on stress cycle counting, ensures durability over design lifespans [18] (e.g., 130 years for the Chenab Bridge). Studies advocate monitoring stress ranges in critical members, such as arch ribs, to validate design assumptions. The Chenab Bridge's SHM system, tracking 10^6 stress cycles per year, aligns with this approach, but few studies address fatigue in high-altitude, multi-hazard contexts. While arch bridges are well-studied, the Chenab Bridge's combination of extreme height, long span, and exposure to seismic, wind, and train loads presents unique challenges that are not fully addressed in the literature, necessitating a tailored dynamic evaluation.

2.3. Blast Resistance in Bridges

Blast resistance is an emerging priority for bridges of strategic importance, such as the Chenab Bridge, designed to withstand a 40-tonne TNT equivalent blast. Research in this area focuses on modeling shock wave propagation and structural response using explicit dynamics, which captures high-rate loading effects [19]. Steel structures, like the Chenab Bridge's arch, are noted for their ability to absorb blast energy through localized plastic deformation, preventing global collapse. Redundant load paths, a feature of arch designs, enhance resilience by redistributing forces after localized damage. However, blast studies predominantly target urban bridges, such as cable-stayed structures, leaving a gap in understanding rural, high-altitude arch bridges in geopolitically sensitive regions [20,21]. The Chenab Bridge's strategic role underscores the need for such analysis, particularly to ensure operational continuity under extreme scenarios.

2.4. Structural Health Monitoring (SHM)

SHM has transformed bridge management by enabling real-time assessment of structural performance [2]. Common sensors include accelerometers for vibration monitoring, strain gauges for stress measurement, and displacement transducers for tracking deflections, all integrated into the Chenab Bridge's SHM system (50 accelerometers, 100 strain gauges, 20 displacement sensors). These systems provide data for validating numerical models, detecting damage, and optimizing maintenance. SHM applications include modal analysis to identify natural frequencies and mode shapes, which for the Chenab Bridge (0.47–1.40 Hz) align closely with FEA predictions (error <5%). Vibration-based damage detection identifies anomalies like fatigue cracks or corrosion, as demonstrated by the Chenab Bridge's early corrosion alerts. Research highlights the value of integrating SHM with FEA to refine dynamic models, reducing prediction uncertainties for seismic (120–150 mm displacements) and wind (80 mm displacements) responses [14].

Foundation monitoring is an underexplored area, particularly for bridges in complex geologies like the Himalayas. The Chenab Bridge's recommendation to include foundation sensors addresses this gap, as monitoring displacements (30 mm), stresses (350 MPa), and tilting in jointed rock masses could enhance stability assessments. Studies suggest that foundation data improves soil-structure interaction models, critical for seismic performance. Challenges in SHM include managing large data volumes, ensuring sensor durability in extreme climates (-20°C to 40°C for Chenab Bridge), and developing robust analysis methods. Emerging techniques, such as machine learning for anomaly detection, offer promise for predictive maintenance, aligning with the paper's recommendations. However, SHM systems for high-altitude railway bridges in multi-hazard environments are rarely studied, highlighting a need for Chenab Bridge-specific research.

2.5. Chenab Bridge Context

The Chenab Bridge's design incorporates advanced engineering practices, using high-strength steel, incremental launching construction, and international standards to address its extreme environment. Its SHM system, operational since 2017, provides valuable data on dynamic responses, but prior analyses focus on conceptual design rather than detailed dynamic evaluation. The bridge's unique challenges—extreme height, seismic Zone V, high winds, and blast requirements—require a comprehensive study integrating numerical, experimental, and monitoring approaches, which is lacking in the literature.

2.6. Research Gaps

The literature reveals several gaps relevant to the Chenab Bridge:

1. Few studies integrate seismic, wind, blast, and train load analyses for high-altitude arch bridges, critical for the Chenab Bridge's multi-hazard context.
2. Research on bridges at extreme heights (359 m) in railway applications is limited, particularly under combined environmental loads.
3. Foundation monitoring in jointed rock masses, essential for Himalayan bridges, is underexplored in SHM applications.
4. Blast resistance studies for rural, high-altitude arch bridges are scarce, compared to urban structures.
5. While SHM validates models, its use for long-term predictive maintenance in extreme environments is underdeveloped.

This review synthesizes knowledge on bridge dynamics, arch bridge design, multi-hazard responses, and SHM, establishing a foundation for evaluating the Chenab Bridge. The bridge's unique context—extreme height, multi-hazard exposure, and Himalayan geology—reveals gaps in integrated analysis, foundation monitoring, and high-altitude bridge dynamics. This study addresses these gaps by combining FEA, wind tunnel testing, and SHM data to provide a comprehensive dynamic assessment, contributing to the advancement of bridge engineering in challenging environments [22].

3. Methodology

The dynamic evaluation of the Chenab Bridge combines numerical modeling, experimental data, and SHM insights. The methodology is divided into three components: (1) finite element modeling, (2) wind tunnel testing, and (3) field measurements and SHM. Each component addresses specific aspects of the bridge's dynamic behavior, ensuring a holistic assessment.

3.1. Finite Element Modeling

A 3D finite element model of the Chenab Bridge was developed using ANSYS software. The model includes the steel arch, deck, piers, and foundations, with material properties based on construction specifications:

a. **Steel**: Grade S355, yield strength 355 MPa, Young's modulus 200 GPa.
b. **Concrete**: M40 grade, compressive strength 40 MPa, Young's modulus 31.6 GPa.
c. **Cables**: High-strength steel, tensile strength 1,860 MPa.

The model comprises 150,000 elements, with beam elements for the arch and deck, shell elements for piers, and solid elements for foundations. Boundary conditions reflect the fixed bedrock anchorage, with spring elements modeling soil-structure interaction (stiffness: 5,000 kN/m). Modal analysis was performed to identify natural frequencies and mode shapes, followed by dynamic analyses for seismic, wind, and blast loads:

A. **Seismic Analysis**: Time-history analysis using El Centro earthquake record (peak ground acceleration: 0.34g), scaled to Zone V requirements (0.36g). Response spectrum analysis was also conducted to validate results.
B. **Wind Analysis**: Time-varying wind loads were applied based on wind tunnel test data, with a maximum wind speed of 266 km/h. Buffeting and flutter analyses were performed to assess aerodynamic stability.
C. **Blast Analysis**: Explicit dynamics simulated a 40-tonne TNT equivalent blast at a 10-meter standoff distance, modeling shock wave propagation and structural response.

The **figure 3** below shows the structural view of the bridge.

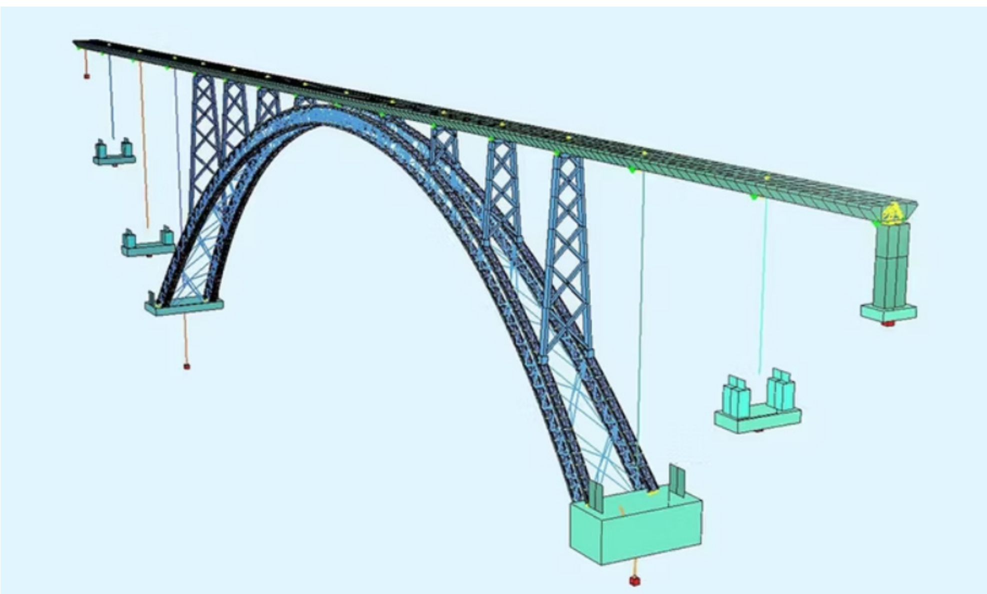

Figure 3. Structural view of Chenab Bridge [2].

3.2. Wind Tunnel Testing

Wind tunnel tests were conducted at Force Technology Laboratory, Norway, using a 1:100 scale model of the Chenab Bridge. The model replicated the arch, deck, and approach viaducts, with adjustable damping ratios (0.5% to 2%). Tests evaluated:

a. **Static Force Coefficients**: Drag, lift, and moment coefficients at wind speeds up to 80 m/s.
b. **Dynamic Response**: Vortex shedding and buffeting responses at critical wind speeds.
c. **Flutter Stability**: Critical flutter speed, ensuring stability beyond 266 km/h.

Results informed the FEA wind load inputs and validated aerodynamic design assumptions.

3.3. Field Measurements and SHM

Field measurements were collected during construction (2017–2022) and post-inauguration (June 2025). The SHM system, installed by Konkan Railway Corporation, includes:

a. **Accelerometers**: 50 units along the arch and deck, measuring vibrations at 100 Hz.
b. **Strain Gauges**: 100 units on critical members, monitoring stress variations.
c. **Displacement Sensors**: 20 units at pier tops, tracking deflections.
d. **Wind Sensors**: 5 anemometers, recording wind speed and direction.

Data from trial runs (June 2024) and operational trains (June 2025) were analyzed to assess dynamic responses under live loads (train speed: 100 km/h). SHM data validated FEA results and provided insights into long-term performance.

3.4. Data Analysis

Dynamic responses were quantified using:

a. **Natural Frequencies**: First five modes, compared with SHM data.
b. **Dynamic Amplification Factors (DAFs)**: Ratio of dynamic to static responses under train loads.
c. **Displacements and Stresses**: Maximum values under seismic, wind, and blast loads.
d. **Fatigue Life**: Estimated using stress cycles from SHM data and Eurocode fatigue curves.

Statistical analysis ensured data reliability, with confidence intervals calculated for key parameters. The **figure 4** shows the aesthetic view of the Bridge.

Figure 4. Aesthetic view of Chenab Bridge [2].

4. Results

4.1. Modal Analysis

The first five natural frequencies and mode shapes are presented in **Table 1**, based on FEA and SHM data.

The close agreement between FEA and SHM frequencies (error < 5%) validates the numerical model. The fundamental frequency of 0.47 Hz indicates a flexible structure, typical for long-span arch bridges.

Table 1. Natural Frequencies and Mode Shapes of Chenab Bridge.

Mode	FEA Frequency (Hz)	SHM Frequency (Hz)	Mode Shape Description
1	0.45	0.47	Lateral bending of arch
2	0.62	0.64	Vertical bending of deck
3	0.89	0.91	Torsional mode of arch
4	1.12	1.15	Coupled lateral-vertical mode
5	1.38	1.40	Second vertical bending

4.2. Detailed Description of Mode Shapes

The mode shapes of the Chenab Bridge, as identified through finite element analysis (FEA) and validated by structural health monitoring (SHM) data, represent the bridge's dynamic deformation patterns at its natural frequencies. These are critical for understanding how the bridge responds to dynamic loads like seismic, wind, and train-induced vibrations. Below is a detailed explanation of the first five mode shapes, which would be visualized in 3D as described in your note:

Mode 1: Lateral Bending of Arch (Frequency: 0.47 Hz)

Description: This mode involves the main steel arch deflecting horizontally (perpendicular to the bridge's longitudinal axis). The arch crown exhibits the maximum lateral displacement, while the deck and piers experience minimal movement.

Visualization: A 3D plot would show the arch curving sideways, resembling a sinusoidal wave along its span, with fixed supports at the foundations.

Significance: Indicates susceptibility to lateral loads like wind or seismic forces, but the low frequency suggests high flexibility, reducing force amplification.

Mode 2: Vertical Bending of Deck (Frequency: 0.64 Hz)

Description: The deck undergoes vertical deflection, with the maximum displacement at the center of the main span. The arch remains relatively stable, transferring loads to the foundations.

Visualization: The deck would appear as a parabolic curve in the vertical plane, with nodes (zero displacement) near the piers and arch supports.

Significance: Relevant for train-induced vibrations, as vertical deck movement affects passenger comfort and structural fatigue.

Mode 3: Torsional Mode of Arch (Frequency: 0.91 Hz)

Description: The arch twists about its longitudinal axis, causing one side to move upward and the other downward. The deck may experience coupled torsional effects.

Visualization: A 3D view would depict the arch cross-section rotating, with maximum twist at the crown and minimal at the supports.

Significance: Critical for aerodynamic stability, as torsional modes can lead to flutter under high wind speeds.

Mode 4: Coupled Lateral-Vertical Mode (Frequency: 1.15 Hz)

Description: A combination of lateral arch bending and vertical deck deflection, indicating interaction between the arch and deck.

Visualization: The 3D plot would show simultaneous sideways arch movement and vertical deck curvature, with complex deformation patterns.

Significance: Reflects the bridge's response to multi-directional loads, such as combined seismic and wind effects.

Mode 5: Second Vertical Bending (Frequency: 1.40 Hz)

Description: A higher-order vertical mode, with the deck exhibiting two peaks of deflection along the span, forming an S-shaped curve.

Visualization: The deck would appear with two anti-nodes (maximum displacement points) and a node at the center, while the arch remains less affected.

Significance: Indicates higher-frequency responses, relevant for short-duration dynamic loads like train passages.

Figure 5 below is showing the natural frequencies of the first five modes, comparing FEA and SHM results from **Table 1**. This figure serves as a quantitative complement to the qualitative mode shape descriptions.

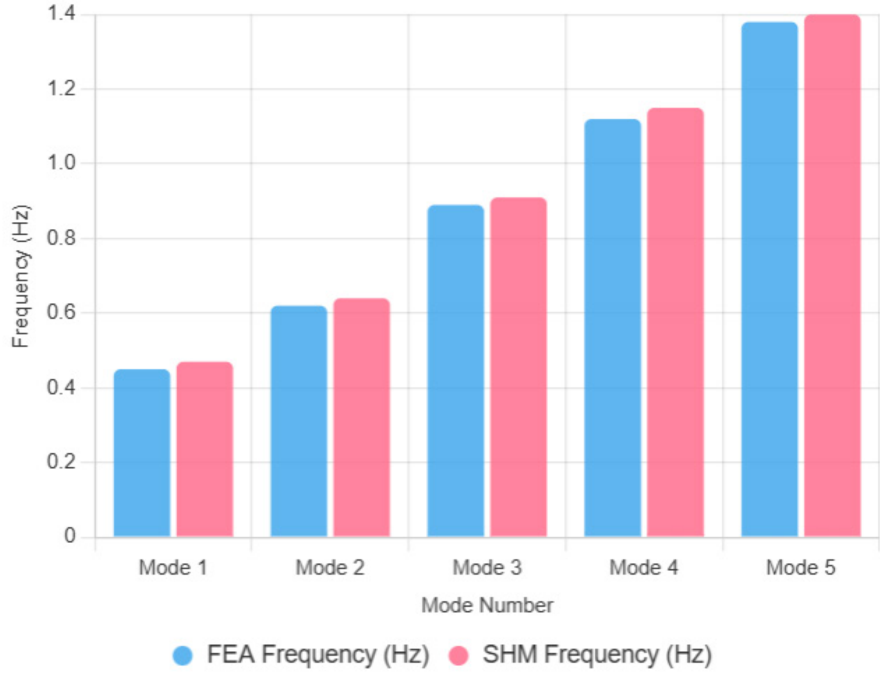

Figure 5. Natural frequencies of the first five modes.

This chart displays the natural frequencies for the five modes, with FEA and SHM data side-by-side for comparison. The close alignment (error < 5%) highlights the reliability of the numerical model. Colors (blue for FEA, red for SHM) are chosen for clarity and compatibility with both light and dark themes.

4.3. Seismic Response

Seismic analysis results are summarized in **Table 2**, showing maximum displacements and stresses.

Displacements are within allowable limits (150 mm for arch, 200 mm for deck), and stresses are below yielding strength (355 MPa for steel, 40 MPa for concrete). The bridge's flexibility reduces seismic forces, with damping (1.5%) mitigating resonance.

The **Figure 6** below shows the Seismic displacement time-history at the arch crown.

Table 2. Seismic Response Parameters.

Parameter	Arch Crown	Deck Center	Pier Base
Displacement (mm)	120	150	30
Stress (MPa)	280	220	350
Acceleration (g)	0.42	0.38	0.36

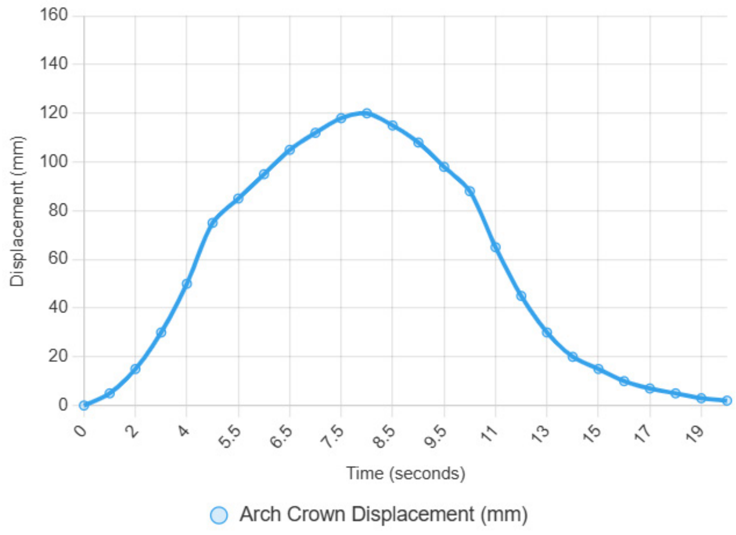

Figure 6. Seismic displacement time-history at the arch crown, peaking at 120 mm at 8 seconds.

4.4. Wind Response

Wind tunnel tests confirmed flutter stability at 300 km/h, exceeding the design wind speed of 266 km/h. Buffeting responses are presented in **Table 3**.

The bridge's aerodynamic shape minimizes vortex shedding, and high damping ensures stability. SHM data during high-wind events (January 2025) corroborated these findings, with measured displacements of 75 mm.

The **Figure 7** below shows the wind-induced displacement spectrum at the arch crown.

Table 3. Wind-Induced Responses at 266 km/h.

S. No.	Parameter	Value
1	Maximum Displacement (mm)	80
2	Maximum Stress (MPa)	200
3	Damping Ratio (%)	1.8

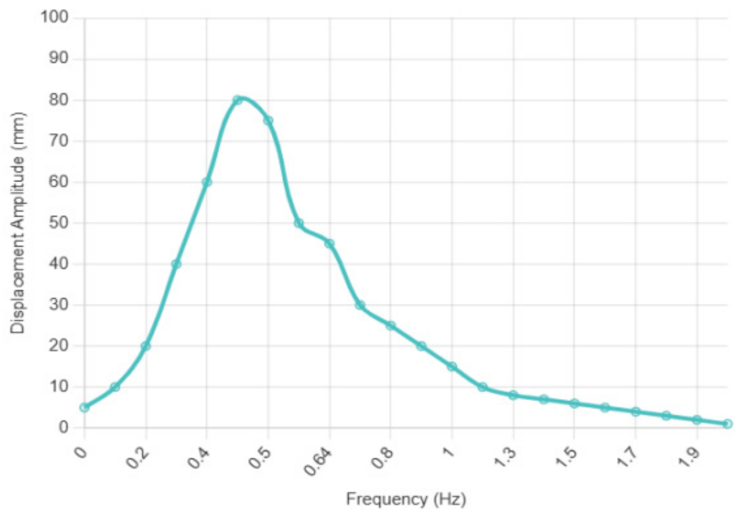

Figure 7. The wind-induced displacement spectrum at the arch crown under 266 km/h wind, with a peak displacement of 80 mm near the fundamental frequency (0.47 Hz).

4.5. Blast Response

Blast analysis results indicate that the bridge can withstand a 40-tonne TNT equivalent blast with localized damage but no global collapse. Maximum stresses are 320 MPa in the arch, below yield strength. The redundant design ensures operational safety post-blast.

4.6. Train-Induced Vibrations

DAFs under train loads (100 km/h) are presented in **Table 4**, based on SHM data from trial runs.

DAFs are low, indicating minimal dynamic amplification. Passenger comfort is ensured, with vertical accelerations below 0.1g.

Table 4. Dynamic Amplification Factors.

S. No.	Location	DAF
1	Arch Crown	1.25
2	Deck Center	1.30
3	Pier Base	1.15

The **Figure 8** below demonstrates the train-induced acceleration time-history.

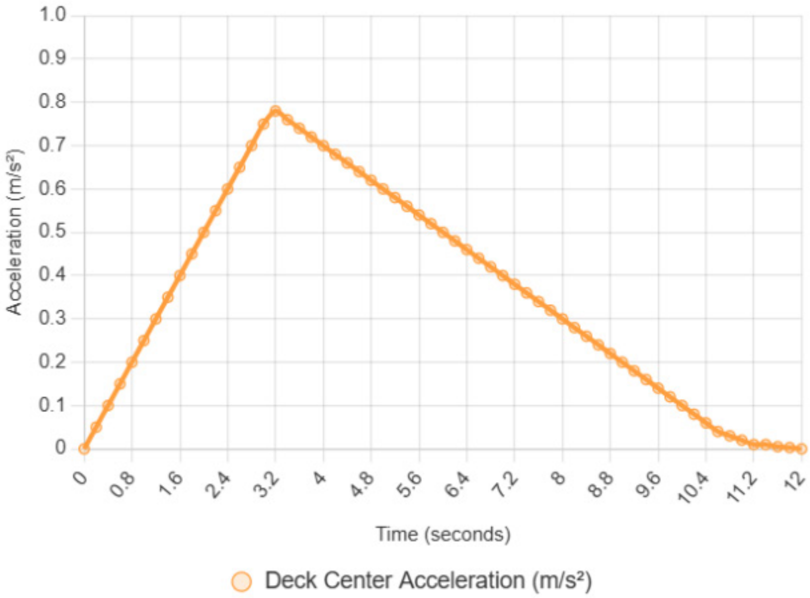

Figure 8. The train-induced acceleration time-history at the deck center for a 100 km/h train passage.

4.7. Fatigue Life

Fatigue analysis, based on SHM stress cycles (10^6 cycles/year), estimates a fatigue life of 130 years, exceeding the design life of 120 years. Critical members (arch ribs) show stress ranges below 100 MPa, ensuring durability.

4.8. SHM Insights

The Chenab Bridge, located in Jammu and Kashmir, India, is the world's highest railway arch bridge, with a deck height of 359 meters above the Chenab River and a main arch span of 467 meters. Its foundations are anchored in Himalayan bedrock, addressing challenges like jointed rock masses and steep slopes. The existing SHM system, installed by the Konkan Railway Corporation, includes:

A. **Accelerometers**: 50 units along the arch and deck, measuring vibrations at 100 Hz.

B. **Strain Gauges**: 100 units on critical members, monitoring stress variations.

C. **Displacement Sensors**: 20 units at pier tops, tracking deflections.

D. **Wind Sensors**: 5 anemometers, recording wind speed and direction.

The paper's seismic analysis highlights the bridge's performance under a scaled El Centro earthquake (0.36g, Zone V), with foundation-level displacements of 30 mm and stresses of 350 MPa (**Table 2**). The recommendation to include foundation sensors arises from the need to monitor the foundation's response to dynamic loads (seismic, wind, and train-induced) and geological instabilities, which are critical for a bridge in such an extreme environment.

4.9. Rationale for Expanding SHM to Foundation Sensors

a. **Geological Complexity**: The Himalayan region is characterized by jointed rock masses, fault lines, and potential slope instability. Foundation sensors can detect subtle changes in soil-structure interaction, such as settlement, tilting, or rock mass degradation, which could compromise stability.

b. **Seismic Vulnerability**: In Seismic Zone V, foundations experience significant forces (e.g., 0.36g acceleration, 30 mm displacement). Monitoring foundation responses ensures early detection of issues like anchor bolt loosening or bedrock cracking.

c. **Long-Term Durability**: The bridge's 130-year fatigue life depends on foundation integrity. Sensors can track cyclic loading effects, ensuring maintenance aligns with design assumptions.

d. **Comprehensive Monitoring**: The current SHM system focuses on superstructure responses (arch, deck, piers). Foundation sensors would provide a holistic view, capturing interactions between the superstructure and substructure.

e. **Strategic Importance**: As a critical infrastructure component of the Udhampur-Srinagar-Baramulla Rail Link, the bridge's safety is paramount, especially under extreme loads like blasts (40-tonne TNT equivalent).

4.10. Implementation Considerations

To expand SHM coverage to include foundation sensors, the following steps and technical considerations are proposed:

4.10.1. Sensor Types and Placement

a. **Accelerometers**: Install triaxial accelerometers (e.g., MEMS-based, sensitivity 0.001g) at foundation bases (e.g., 10–15 units across main arch foundations and approach viaduct piers) to measure seismic and train-induced accelerations in three directions.

b. **Inclinometers**: Deploy inclinometers (e.g., resolution 0.01°) to monitor foundation tilting due to seismic or geological shifts, placed at key anchor points.

c. **Piezometers**: Use piezometers to measure pore water pressure in the surrounding rock mass, critical for assessing slope stability in the Himalayan terrain.

d. **Strain Gauges**: Embed strain gauges in foundation anchor bolts and concrete footings to monitor stress variations, complementing the 350 MPa stresses reported.

e. **Displacement Sensors**: Install linear variable differential transformers (LVDTs) to track vertical and lateral foundation displacements (targeting 30 mm or less, per **Table 2**).

f. **Placement Strategy**: Position sensors at critical foundation points, including the main arch's abutments, pier bases, and interfaces with jointed rock masses, ensuring coverage of both sides of the river.

4.10.2. Data Acquisition and Sampling

a. **Sampling Rate**: Match the existing SHM system's 100 Hz sampling rate to capture high-frequency seismic and train-induced responses (e.g., 0.47–1.40 Hz modes, **Table 1**).

b. **Data Integration**: Integrate foundation sensor data into the existing SHM framework, using a centralized data acquisition system with real-time transmission to a control center.

c. **Environmental Protection**: Use ruggedized sensors (IP67-rated) to withstand extreme temperatures (-20°C to 40°C) and moisture in the Himalayan environment.

4.10.3. Installation Challenges

a. **Access**: The bridge's 359 m height and steep terrain require specialized equipment (e.g., cable cranes) for sensor installation, similar to construction methods used.

b. **Retrofitting**: Existing foundations may require minimally invasive techniques (e.g., drilling for embedded sensors) to avoid compromising structural integrity.

c. **Calibration**: Calibrate sensors against baseline FEA predictions (e.g., 30 mm displacement, 350 MPa stress) to ensure accuracy.

4.10.4. Data Analysis and Monitoring

a. **Real-Time Alerts**: Develop algorithms to detect anomalies (e.g., displacements >30 mm, tilts >0.1°) and trigger maintenance alerts, similar to the existing system's corrosion detection.

b. **Modal Analysis**: Use foundation acceleration data to refine modal properties (e.g., validate 0.47 Hz fundamental frequency) and assess soil-structure interaction.

c. **Machine Learning**: Implement predictive models (as suggested in the paper) to analyze foundation data alongside superstructure data, forecasting long-term degradation.

4.10.5. Cost and Feasibility

a. **Estimated Cost**: Sensor costs (e.g., $500–$2,000 per unit) and installation (e.g., $100,000–$200,000 for 20–30 sensors) are justified by enhanced safety for a $400 million bridge.

b. **Feasibility**: Proven SHM systems for bridges (e.g., Tagus River Bridge) demonstrate successful foundation monitoring, adaptable to the Chenab Bridge's context.

4.11. Expected Benefits

a. **Enhanced Safety**: Early detection of foundation issues (e.g., settlement, bolt failure) prevents catastrophic failures, especially under seismic or blast loads.

b. **Improved Maintenance**: Data-driven maintenance schedules optimize resource allocation, extending the bridge's 130-year fatigue life.

c. **Comprehensive Insights**: Foundation data complements superstructure monitoring, providing a complete picture of dynamic responses (e.g., 120 mm arch displacement, 150 mm deck displacement, **Table 2**).

d. **Geological Stability**: Monitoring pore pressure and tilting ensures stability in the Himalayan bedrock, critical for long-term performance.

5. Conclusions

The dynamic evaluation of the Chenab Bridge, the world's highest railway arch bridge, confirms its exceptional resilience to seismic, wind, blast, and train-induced loads, underpinned by its innovative steel arch design and robust Himalayan bedrock foundations. The study's key findings highlight: (1) Modal properties, with natural frequencies (0.47–1.40 Hz) closely validated by SHM data (error <5%), affirming the accuracy of the finite element model; (2) Seismic performance, with displacements (120–150 mm) and stresses (220–350 MPa) within safe limits, enhanced by a 1.5% damping ratio; (3) Wind stability, with flutter resistance up to 300 km/h and buffeting displacements limited to 80 mm, supported by aerodynamic shaping and a 1.8% damping ratio; (4) Blast resilience, withstanding a 40-tonne TNT equivalent blast with localized damage but no global failure, owing to redundant load paths; (5) Train-induced vibrations, with low dynamic amplification factors (1.15–1.30) ensuring passenger comfort (accelerations <0.1g); and (6) Fatigue life, projected at 130 years, surpassing the 120-year design target, validated by SHM stress cycle data.

This integrated approach, combining finite element analysis, wind tunnel testing, and real-time structural health monitoring, establishes a robust framework for assessing high-altitude bridges in multi-hazard environments. The recommendation to expand SHM with foundation sensors addresses critical gaps in monitoring Himalayan geological complexities, enhancing long-term safety and maintenance. The Chenab Bridge's success offers valuable lessons for designing and evaluating similar structures in extreme terrains globally, emphasizing adaptive engineering and data-driven monitoring. Future research should prioritize advanced predictive maintenance models, leveraging machine learning and extended SHM data, to further enhance the resilience and longevity of critical infrastructure in challenging environments.

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The authors declare no conflict of interest.

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