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Integrated framework for the sustainable conservation and rehabilitation of Nepal's historic bridges

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Abstract: Nepal's historic bridges, including timber, stone masonry, and early suspension typologies, are vital components of both the national mobility network and the cultural heritage landscape. However, progressive material deterioration, environmental exposure, increasing service demands, and the lack of standardized conservation frameworks have increased their vulnerability. This study develops an integrated multi-criteria decision framework that jointly evaluates structural condition and cultural significance to support systematic conservation planning. Seven structural and four cultural indicators were identified and weighted using the analytic hierarchy process (AHP) based on responses from 191 experts. Material degradation (0.193) and structural deformation (0.153) emerged as the most influential structural indicators, while local cultural importance (0.295) and historic age (0.276) dominated the cultural dimension. The weighted indicators are combined into a composite scoring model with defined decision thresholds on a ten-point scale: scores below 2.883 indicate replacement, values between 2.883 and 6.289 require retrofitting, and scores above 6.289 support continued use with minor intervention. The framework links each decision range with heritage-sensitive strengthening strategies, providing a transparent and reproducible methodology for balancing structural safety and cultural preservation. The proposed model offers a scalable reference for sustainable management of historic bridge infrastructure in Nepal and similar heritage contexts.

Keywords: historic bridge; heritage conservation; analytic hierarchy process; structural assessment; sustainable rehabilitation; Nepal

1 Introduction

There are more than 6 000 rivers flowing from the high Himalaya in the north to the low plains in the south of Nepal. Numerous bridges have been constructed since ancient times, including traditional timber bridges, stone arch bridges, and early suspension bridges. Dating back several centuries, many of these structures represent remarkable examples of indigenous engineering and craftsmanship, utilizing locally available materials [1]. These bridges embody regional traditions, artisanal knowledge, and social symbolism that reflect the evolution of settlement and transportation systems in mountain environments [2]. As important elements of civil engineering cultural heritage, these historic bridges should be conserved and protected.

Bridges have long been a defining element of Nepal's cultural and infrastructural identity, connecting remote settlements and enabling trade, mobility, and cultural exchange across its rugged terrain [3–4]. Many of these structures, dating back several centuries, represent remarkable examples of indigenous engineering and craftsmanship, utilizing locally available materials such as timber, stone, and wrought iron [1]. Beyond their functional role, historic bridges in Nepal embody regional traditions, artisanal knowledge,

and social symbolism that reflect the evolution of settlement and transport systems in mountain environments [2]. However, the combined effects of climatic stress, inadequate maintenance, seismic vulnerability, and unregulated urban expansion have placed these structures under increasing threat [1]. Despite their historical and functional significance, the conservation of Nepal's historic bridges remains constrained by fragmented institutional responsibilities and the absence of comprehensive technical frameworks for preservation and rehabilitation [5].

Existing studies and conservation initiatives in Nepal have largely concentrated on the structural integrity of bridges, particularly modern reinforced concrete (RC) structures, while seldom integrating engineering safety and heritage value within a unified methodology for historic bridges [6]. This lack of integration has frequently resulted in interventions that either prioritize safety at the expense of authenticity or preserve aesthetics while overlooking structural stability. To address this gap, the present study develops a comprehensive framework for the conservation and rehabilitation of Nepal's historic bridges that combines structural assessment, cultural valuation, and sustainability considerations. The framework defines measurable indicators encompassing deformation, scour, corrosion, material degradation, craftsmanship, and his-

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torical significance. By synthesizing these indicators, bridge condition and heritage importance can be objectively assessed, enabling systematic prioritization of conservation needs across diverse typologies. The approach promotes balanced decision-making between engineering safety and cultural preservation, moving beyond subjective or ad hoc maintenance practices.

In addition to methodological development, this study conducted field investigations across the Kathmandu Valley, where prevalent deterioration mechanisms, including moisture ingress, vegetation growth, mortar loss, foundation scour, and drainage deficiencies, were examined. Based on these findings, the study recommends practical repair and strengthening measures for heritage as well as old historic bridges. These techniques demonstrate how traditional materials and craftsmanship can be effectively integrated with modern strengthening technologies to ensure structural stability while maintaining cultural authenticity. The literature review and field synthesis reveal that while advanced economies have developed holistic frameworks for heritage bridge rehabilitation, developing contexts like Nepal continue to face challenges due to the absence of systematic surveys, standardized documentation, and adequate technical capacity. A national-level methodology for prioritizing and managing historic bridge assets remains largely undeveloped, resulting in inconsistent and sometimes incompatible conservation practices.

The integrated framework presented in this study addresses these institutional and technical gaps by merging multi-criteria evaluation with empirical field validation and lessons from international practice. By linking qualitative assessments of heritage value with quantitative measures of structural performance, the framework establishes a foundation for heritage-sensitive and technically reliable conservation planning. The outcomes demonstrate that such integration enhances the efficiency of resource allocation, improves maintenance planning, and supports the sustainable management of heritage bridge infrastructure. Ultimately, this study contributes to the development of a replicable model for the conservation and rehabilitation of Nepal's historic bridges, ensuring that structural resilience and cultural authenticity advance together within a sustainable and adaptive infrastructure management system.

2 Brief introduction of Nepal's historic bridges

2.1 Timber bridges

The earliest forms of bridges in the Himalayan region were timber structures (Fig. 1), often constructed by projecting wooden beams from both riverbanks until they met at mid-span. Although precise construction dates of the earliest bridges are difficult to verify due to limited historical documentation, traditional timber bridges found in various mountain regions demonstrate sophisticated indigenous engineering knowledge [7]. These bridges utilized



Fig. 1 Traditional timber bridge over Marsyangdi River in Syange, Lamjung, Nepal.

locally available materials such as timber and were well adapted to narrow gorges and steep river valleys. Structurally, timber cantilever bridges transfer loads through compression and bending in projecting beams anchored into rock or masonry abutments. Beyond their structural function, they also reflect local craftsmanship, cultural identity, and community-based construction practices that have been transmitted across generations.

2.2 Stone arch bridges

Stone arch bridges represent another important historic typology in Nepal. Constructed primarily in regions where stone masonry was readily available, these bridges rely on compressive arch action to transfer loads into abutments. The arch mechanism provides durability and long service life, making such bridges structurally efficient in mountainous terrain. Although fewer in number compared to suspension trail bridges, stone arch bridges remain important cultural heritage structures. Their construction required skilled masonry workmanship and precise stone cutting, demonstrating advanced knowledge of geometry and load transfer principles in historic civil engineering practice.

2.3 Suspension bridges: From vine to wrought iron cables

Suspension-type bridges (Fig. 2) have historically been the most suitable solution for crossing deep Himalayan gorges. Early indigenous crossings consisted of tree vines, bamboo elements, and rope systems stretched across rivers. Similar primitive suspension systems have been documented throughout Himalayan regions and are described in historical bridge literature [8]. Over time, these systems evolved into iron-chain and eventually steel cable suspension bridges. During the twentieth century, especially after the 1960s, systematic development of trail suspension bridges was initiated with governmental and international technical support. By the early twenty-first century, more than 6,000 trail suspension bridges had been constructed across Nepal, significantly improving rural accessibility and socio-economic connectivity. These bridges generally consist of steel wire rope main cables supporting a suspended deck system through vertical hangers. The deck structures typically comprise timber planks or steel grating supported by steel cross-beams and longitudinal members, while the main cables are anchored into massive masonry or reinforced concrete anchor blocks constructed on stable ground. Depending on topography and river width, the span length of these bridges commonly ranges from about 40 m to over 150 m. These suspension bridges are particularly suited to Nepal's topography because they require minimal intermediate supports and can span wide rivers with relatively lightweight construction. In addition to their structural efficiency, they have become symbolic elements of rural connectivity and community resilience.

Overall, the development of Nepal's historic bridges can be broadly categorized into: (i) Pre-recorded and early indigenous crossings using timber and vines; (ii) masonry arch construction



Fig. 2 The 567 m long suspension bridge linking Baglung and Parbat (Image source: Nepal Press).

during organized settlement periods; (iii) engineered suspension systems introduced and refined during the modern development era. This progression reflects technological adaptation to environmental constraints, availability of materials, and evolving transportation demands.

3 Methodology

The flowchart (Fig. 3) clearly presents the overall methodology adopted for decision-making regarding retrofitting and prioritizing conservation actions for Nepal's historic bridges using the Analytic Hierarchy Process (AHP). The process begins with a comprehensive state-of-the-art review of Nepal's historic bridges to understand their existing typologies and prevailing degradation patterns. Based on this review, structural and cultural indicators are defined to quantify the current condition of the bridges. Those indicators are compared with each other using the AHP method to derive the weight of each indicator. Within the AHP framework, the methodology involves constructing pairwise comparison matrices using comparison scores obtained from respondents through a questionnaire survey. These matrices are then normalized to derive indicator weights, followed by a consistency check to ensure the reliability of the judgments. Ultimately, weights are derived for each factor under the structural and cultural categories, along with the overall (collective) weights of these categories. Furthermore, the decision-making ranges, whether to keep as-is, retrofit, or replace are also derived from the questionnaire survey using the AHP framework. Based on these derived weights and criteria, the methodology establishes clear thresholds for selecting one of

the three possible conservation actions: keep as-is, retrofit, or replace.

3.1 Literature review, contextual foundation, and field-based condition assessment

The study commenced with a comprehensive review of Nepal's historic bridge typologies, construction techniques, deterioration mechanisms, and institutional maintenance practices to establish a clear understanding of the current state-of-the-art condition of these structures. Particular emphasis was placed on timber cantilever bridges, stone masonry arch bridges, and early suspension or cable-supported pedestrian bridges. The review incorporated academic literature, heritage conservation guidelines, governmental reports, and archival documents to understand both structural characteristics and prevailing degradation patterns. To broaden the technical perspective, relevant international case studies from Europe, Japan, and Bhutan were examined, focusing on reversible strengthening techniques, corrosion protection strategies, lifecycle-based maintenance planning, and structural health monitoring approaches. This knowledge base was further substantiated through field investigations conducted on representative historic bridges in the Kathmandu Valley. Using a standardized inspection protocol, detailed observations were made regarding surface deterioration, cracking patterns, biological growth, drainage deficiencies, geometric distortions, and foundation exposure.

3.2 Analytical hierarchy process (AHP)

Two sets of indicators are defined to evaluate the condition and significance of Nepal's historic bridges, as summarized in Table 1. The structural indicator set comprises seven parameters that represent the engineering integrity and durability of the bridges, while the cultural indicator set includes four parameters reflecting their historical significance and community value. Following the literature review and field-based condition assessment, the AHP proposed by Saaty [9] was implemented through a structured questionnaire survey administered to 191 respondents. The respondents were selected using purposive expert sampling to ensure representation from both technical bridge engineering practice and heritage-informed academic expertise. Participants included university professors and researchers specializing in structural engineering, transportation infrastructure, and heritage conservation; practicing professionals engaged in bridge design, construction, supervision, retrofitting and maintenance; experts serving in technical review or advisory committees; and retired senior professionals with extensive institutional experience. All respondents possessed a minimum of five years of professional experience, with many having substantially longer involvement in bridge engineering, infrastructure management, or academic research. This diversity ensured that the weighting process incorporated perspectives from theoretical research, field implementation, policy review, and long-term professional practice, thereby strengthening the reliability and applicability of the derived AHP weights. All respondents were requested to provide pairwise comparison judgments using Saaty's 1-9 scale (including reciprocal values) to express the relative importance of defined structural and cultural indicators. The questionnaire was systemat-

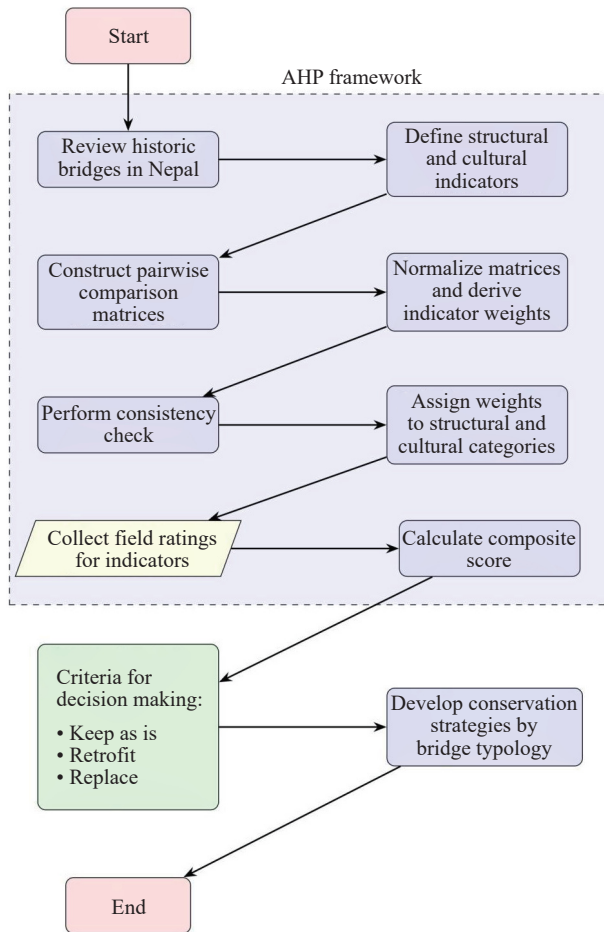


Fig. 3 Methodological Framework for prioritizing conservation actions for Nepal's historic bridges, illustrating the Analytic Hierarchy Process (AHP) steps, decision-making criteria, and tailored conservation strategies by bridge typology.

Table 1 Structural and cultural indicators considered.

SN	Structural indicators	SN	Cultural indicators
	Indicator		Indicator
1	Material degradation	1	Historic age
2	Foundation/scour vulnerability	2	Traditional construction method
3	Structural deformation	3	Architectural uniqueness
4	Joint condition	4	Local cultural importance
5	Deck integrity		
6	Live load response		
7	Environmental exposure		

ically organized to capture grouped judgments for each indicator pair, enabling the computation of aggregated priorities using the geometric mean method. The same expert pool also provided inputs for determining the decision thresholds corresponding to the three conservation actions: keep as-is, retrofit, or replace. The collected responses were processed using a consistency-controlled AHP framework, ensuring that all derived weights satisfied the acceptable consistency ratio ($R_c \leq 0.10$) before proceeding to the final prioritization and decision analysis.

To quantify the relative importance of these indicators, pairwise comparison matrices $A = [a_{ij}]$ are constructed separately for the structural and cultural sets. Each matrix is square with dimensions matching the number of indicators (i.e., 7×7 for structural and 4×4 for cultural indicators), and satisfies the properties:

$$a_{ii} = 1, a_{ji} = \frac{1}{a_{ij}} \quad (1)$$

Eq. (1) ensures that each indicator is equally important to itself and that reciprocal consistency is maintained between comparisons.

The values a_{ij} represent expert judgments on the relative importance of indicator i over indicator j , and are assigned according to the standard AHP fundamental scale of relative importance shown in Table 2. This scale provides a systematic framework for translating subjective assessments into numerical values ranging from equal importance to extreme importance, with intermediate values allowing nuanced distinctions.

Table 2 AHP fundamental scale of relative importance (source: Saaty [9]).

Value	Description
1	Equal importance
3	Moderate importance of one over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the above judgments

3.2.1 Normalization and weight derivation

Once the pairwise comparison matrices are constructed based on expert judgments, they are normalized column-wise as follows:

$$n_{ij} = \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad (2)$$

where, a_{ij} is the element of the pairwise comparison matrix; n is its order.

The relative weight w_i for each indicator i is then calculated by averaging the normalized values across the corresponding row:

$$w_i = \left(\frac{1}{n} \right) \sum_{j=1}^n n_{ij} \quad (3)$$

These weights represent the relative importance of each indicator within its domain, as derived from the AHP process.

3.2.2 Consistency check

The pairwise comparison matrices are constructed based on expert judgments following the Analytic Hierarchy Process (AHP) methodology, where each entry a_{ij} reflects the relative importance of indicator i compared to indicator j . To ensure logical coherence of these judgments, a consistency check is performed using the Consistency Index (I_c) and Consistency Ratio (R_c):

$$I_c = \frac{\lambda_{\max} - n}{n - 1}, R_c = \frac{I_c}{I_R} \quad (4)$$

where, $\lambda_{\max}$ is the principal eigenvalue of the matrix; n is its order; I_R is the random index value. R_c value of 0.10 or less is generally accepted as indicating consistent judgments. If R_c exceeds this threshold, the pairwise comparisons are reassessed and revised to

improve consistency.

3.2.3 Category-level weighting and decision rule

To integrate structural and cultural considerations into the final decision-making process, category-level weights are denoted by α (structural) and β (cultural). These weights are derived through the Analytic Hierarchy Process (AHP) based on expert judgment and pairwise comparisons between the two domains. The derived values of α and β , satisfying:

$$\alpha + \beta = 1 \quad (5)$$

Eq. (5) constrains the relative importance weights of the two domains in the overall conservation prioritization framework. Based on the final composite score D derived from the AHP-based evaluation of structural and cultural indicators, conservation decisions are made using defined score thresholds. The score range is divided into three zones corresponding to recommended actions: minimal intervention or use as is, strengthening or retrofitting, replacement. These thresholds are determined systematically to reflect condition severity while balancing structural safety and heritage significance. These decision rule ranges were derived by asking each of the 191 respondents to specify the maximum threshold for replacement and the maximum threshold for retrofitting on a scale of 0 to 10.

3.3 Formulation of strengthening strategies

The strengthening and conservation strategies were formulated through a structured methodology that systematically linked identified defects with appropriate retrofitting interventions. Based on the previously established structural and cultural indicators derived from the literature review, field investigations, and expert consultations, major deterioration mechanisms and vulnerabilities in traditional pedestrian bridges were identified. These included material degradation, joint distress, foundation instability, structural deformation, and culturally sensitive architectural elements. Bridges were then classified into three principal typologies: timber, stone masonry, and early suspension or cable supported systems, and typical defect patterns were mapped for each typology.

For each identified defect category, technically feasible and heritage-compatible strengthening measures were suggested through a critical evaluation of international conservation practices, documented performance studies of strengthening materials, and precedent retrofitting projects in comparable environmental and cultural contexts. The selection of interventions was guided by structural effectiveness, compatibility with original materials such as lime-based systems instead of incompatible cementitious materials where appropriate, reversibility, durability, and minimal visual impact. The proposed strategies were subsequently refined and validated through expert review and organized in a structured tabular framework according to bridge typology and indicator classification, ensuring practical applicability and alignment with heritage conservation principles.

4 Results and discussions

4.1 Field-identified deterioration mechanisms

Field inspections of twenty bridges in Kathmandu and Lalitpur, including two historic masonry bridges (Sankhamul and Thapathali), revealed consistent patterns of deterioration associated with environmental exposure, inadequate maintenance, and material aging.

4.1.1 Vegetation-induced damage

Vegetation growth (Fig. 4) was the most prevalent deterioration mechanism. Observations show that over 90% of bridges exhibited vegetation growth. Among them, approximately 10%–20% displayed vegetation-induced cracking and localized material loss, in-

dicating early structural vulnerability. Vegetation growth, water stagnation, and biological deposits were observed as common deterioration mechanisms in historic bridges, as shown in Fig. 4. These processes were particularly apparent along spandrel walls and pier bases, where trapped moisture created favorable growth conditions.



Fig. 4 Deterioration observed in the Sanepa Suspension Bridge (Teku–Sanepa Bridge), a Rana-period suspension bridge constructed in 1940 AD with masonry piers and abutments supporting an early cable suspension system. (a) Tree root growth causing cracking in the masonry elements of the bridge and; (b) grass growth at the base of the parapet, illustrating vegetation-induced deterioration in this historic bridge structure.

4.1.2 Moisture ingress and drainage deficiency

At Sankhamul Bridge, significant water stagnation (Fig. 5) was observed on the deck, accompanied by moss growth and persistent dampness near pier foundations. Inadequate drainage allowed moisture to penetrate masonry cores, promoting mortar softening, surface scaling, and vegetation establishment. Prolonged dampness also increased lateral pressures on abutments and walls. These findings confirm that drainage deficiency is one of the primary drivers of material decay in Nepal's heritage bridges.



Fig. 5 Water stagnation observed on the deck surface of the Sankhamul Bridge, an old reinforced concrete T-beam bridge.

4.1.3 Foundation settlement and erosion

Signs of differential settlement were recorded at several sites, including minor distortion of masonry, separation of joints, and uneven deck alignment. Localized erosion around foundations likely triggered by monsoon flow variability indicated vulnerability to scour. In some cases, fine material loss was evident around pier bases, suggesting reduced bearing capacity and increased susceptibility to displacement during flood events.

4.1.4 Overloading effects on historical bridges

Although historical bridges were originally designed for pedestrian or light animal traffic, many now accommodate informal vehicular loading. Field observations revealed cracking near the intrados, keystone deformation, and loosening of masonry joints symptoms (Fig. 6) consistent with overstressed arch rings. Increased vertical loads have also contributed to outward thrust, pro-

ducing minor bulging in several spandrel walls. These findings align with well-documented global challenges in overloaded heritage bridges.

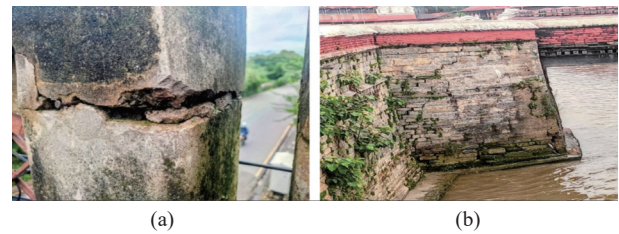


Fig. 6 Field observations photographs. (a) Cracks developed in parapet wall of Sankhamul Bridge; (b) Displacement and cracking of masonry in the abutment of a historical bridge.

4.1.5 Material degradation and mortar loss

Widespread degradation of mortar joints was observed across both historical and non-historical masonry structures. Weathering, moisture exposure, and microbial action resulted in disintegration of lime mortar, increasing permeability and reducing masonry interlock. In severely affected areas, material loss had created open joints and detachment of stone units, directly compromising structural stiffness and water resistance.

4.2 Multi-criteria decision framework

4.2.1 Structural condition assessment indicators

Table 3 outlines a set of structural indicators that this study suggests for assessing the condition of Nepal's historic pedestrian bridges, particularly traditional types such as wooden cantilever, stone slab, and early suspension structures. These indicators have been selected for their relevance to typical forms of deterioration observed in aging bridges, and because they can be realistically applied in field settings with limited resources. For instance, deterioration of materials, loosening of joints, and deck damage are likely to affect the safety and usability of these bridges. Likewise, signs of scour, foundation movement, or deck misalignment can point to more serious structural concerns. This study propose simple, low-tech methods such as visual inspection, hammer tests, string line measurements, and basic loading checks, which are feasible even in remote areas.

4.2.2 Cultural significance assessment indicators

Table 4 presents a set of cultural significance indicators that are recommended for evaluating the heritage value of Nepal's historic bridges, going beyond their structural role. These suggestions are based on a review of existing heritage frameworks and have been adapted to fit the social and cultural context of rural Nepal. Indicators such as the age of the bridge, traditional construction techniques, and unique architectural features help capture the visible aspects of indigenous engineering. In addition, many bridges hold symbolic or ritual importance within their communities, whether through association with festivals, oral traditions, or spiritual meaning. These cultural values can be explored through local interviews, community discussions, and comparative analysis. Including these indicators in the assessment process allows for a more respectful and balanced approach, ensuring that bridges with cultural importance are not overlooked or unnecessarily replaced even if they are structurally sound.

4.2.3 Application of AHP for multi-criteria decision framework

This section presents the consolidated results derived from the structured questionnaire survey and the subsequent application of the AHP. Based on pairwise comparison responses from 191 domain experts, aggregated judgment matrices were constructed for both structural and cultural indicators. Consistency ratios were

Table 3 Structural condition assessment indicators for historic bridges.

SN	Indicator	Description	How to assess	Why it matters
1	Material degradation	Decay of timber, cracking of stone, corrosion of connectors or cables	Visual inspection, hammer sound test, photo documentation	Indicates aging or unsafe materials
2	Deck integrity	Damage to the walking surface or deck beams	Walk-through inspection, measure deflection or gaps	Core to user safety and comfort
3	Foundation/scour vulnerability	Signs of erosion, tilting, undermining of abutments or piers	Check for scour holes, exposed foundations, tilt or settlement marks	Determines long-term stability
4	Structural deformation	Warping, sagging, or misalignment of beams or decks	Use level string lines, photographic comparison over time	Early sign of structural failure
5	Joint and connection condition	State of wooden joinery, lashing, bolts, or pinned joints	Visual check for looseness, corrosion, or missing elements	Affects load transfer and overall stability
6	Live load response	Observable behavior under normal pedestrian load	Dynamic bounce test or temporary live loading observation	Helps estimate current capacity
7	Environmental exposure risk	Proximity to riverbank erosion, flood debris, or landslide-prone slopes	Mapping and visual observation of surrounding hazards	Anticipates future hazard threats

Table 4 Cultural significance assessment indicators for historic bridges.

SN	Indicator	Description	How to assess	Why it matters
1	Historic age	Age since original construction	Archive search, community memory, program records	Older structures are often more heritage-worthy
2	Traditional construction method	Use of local joinery, stone dressing, timber shaping, cantilever technique	Field observation, craft interview, photos	Signifies indigenous engineering practices
3	Architectural uniqueness	Distinctive design, proportions, or ornamentation	Compare with regional typologies	Unique forms deserve higher conservation priority
4	Local cultural importance	Ritual use, symbolism, association with festivals or oral history	Focus group, local interview, observation	Culturally anchored bridges enhance place identity

verified to ensure methodological reliability before computing normalized priority weights. In addition, expert-defined decision thresholds for conservation actions, namely keep as-is, retrofit, or replace, were integrated into the overall decision-support framework.

Psychological Distribution of Structural Indicators: Fig. 7 illustrates the psychological judgment intensity matrix for the structural indicators. A clear pattern emerges in the concentration of responses within the moderate importance range of the Saaty scale, particularly values 2 to 4 and their reciprocals. Extreme dominance levels such as 8 and 9 account for less than 3% of responses in most comparisons. This distribution indicates analytical caution among experts and recognition of the interdependent behavior of structural components in historic bridges.

A dominant preference is observed in favor of Material Degradation. In comparisons with Foundation or Scour Vulnerability, 64.4% selected value 3, while 56.02% selected value 4 when compared with Deck Integrity. Similarly, 47.64% selected value 3 when compared with Joint Condition. In several pairings, more than 70% of responses leaned toward material degradation as the more influential factor. This confirms that progressive decay, corrosion, and aging are perceived as the most critical structural risks in Nepal's historic bridges.

Foundation or Scour Vulnerability also shows consistent prioritization. When compared with Live Load Response, nearly 46% of respondents favored foundation vulnerability, and similar clustering between values 2 and 4 appears in comparisons with Environmental Exposure. In contrast, comparisons involving Environ-

mental Exposure and Live Load Response exhibit more dispersed and reciprocal patterns, suggesting that experts interpret environmental exposure as an underlying driving condition that amplifies deterioration rather than acting as an independently dominant parameter. Overall, the psychological distribution reflects an emphasis on progressive and irreversible deterioration mechanisms over transient operational effects. The clustering around moderate values further confirms that experts perceive structural indicators as interconnected rather than hierarchically absolute.

Psychological Distribution of Cultural Indicators: Fig. 8 presents the corresponding judgment intensity matrix for cultural indicators. Similar to the structural case, responses are concentrated within moderate importance levels, with extreme dominance values remaining minimal. This indicates that experts view cultural attributes as layered and mutually reinforcing components of heritage significance.

Comparative trends reveal that Historic Age and Local Cultural Importance frequently dominate pairwise judgments. While Historic Age often shows moderate preference over Traditional Construction Method and Architectural Uniqueness, the comparison between Historic Age and Local Cultural Importance shifts noticeably. More than 45% of respondents favored Local Cultural Importance over Historic Age, indicating that community relevance and living cultural function often outweigh chronological age.

Similarly, Architectural Uniqueness tends to be preferred over Traditional Construction Method, and Local Cultural Importance frequently prevails in direct comparisons with both factors. These patterns collectively suggest that experts prioritize socially embed-

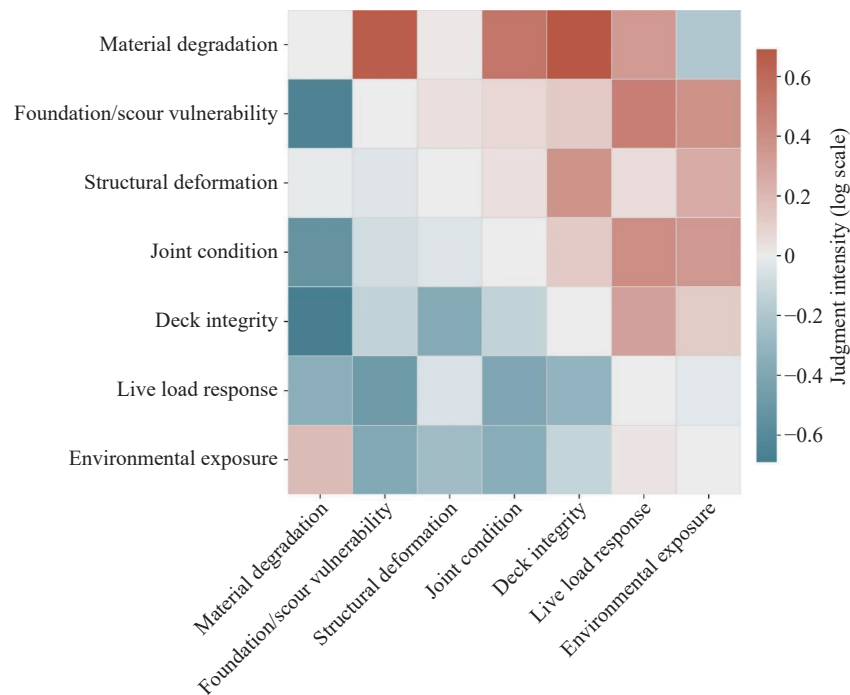


Fig. 7 Psychological judgment intensity matrix for structural indicators.

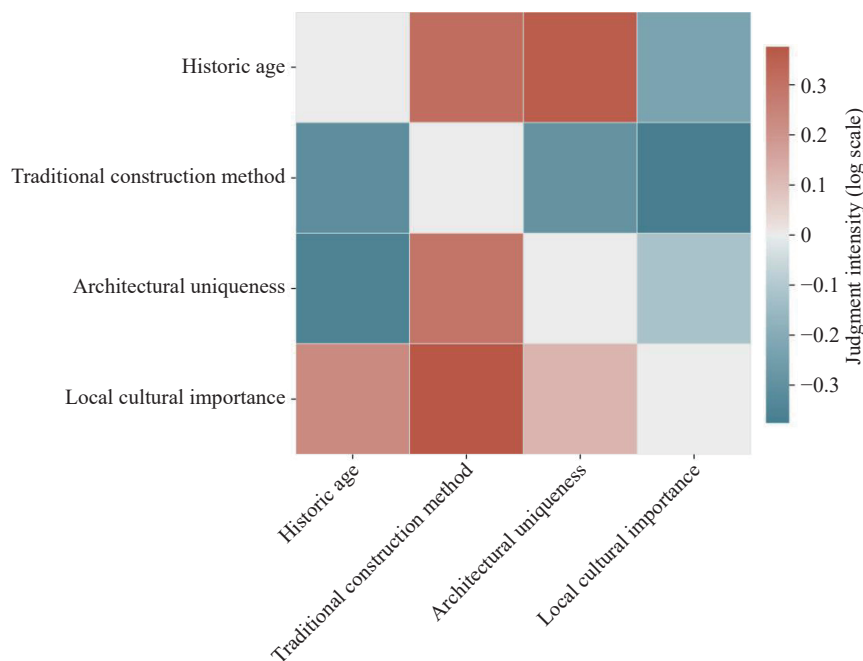


Fig. 8 Psychological judgment intensity matrix for cultural indicators.

ded and identity-related attributes over purely technical or stylistic considerations. The distribution reflects a conservation perspective in which historic bridges are understood as active cultural infrastructure rather than static artifacts.

Finalized Indicator Weights: The normalized priority weights derived from the aggregated AHP matrices are presented in Fig. 9. These values represent the finalized relative importance of each indicator after consistency validation.

Within the structural category, Material Degradation receives the highest weight at 0.1933, representing 19.33% of total structural priority. Structural Deformation follows at 15.29%, closely aligned with Foundation or Scour Vulnerability at 14.96%. Together, these three indicators account for nearly 49.6% of the structural weight-

ing, confirming that stability and deterioration mechanisms dominate technical assessment. Joint Condition accounts for 14.38%, Environmental Exposure for 12.60%, and Deck Integrity for 12.28%. Live Load Response receives the lowest structural weight at 11.14%. The distribution demonstrates that experts prioritize long-term deterioration and structural integrity over short-term loading effects.

In the cultural category, Local Cultural Importance emerges as the highest weighted factor at 29.55%, followed by Historic Age at 27.63%. Architectural Uniqueness accounts for 23.58%, while Traditional Construction Method receives 19.25%. Combined, Local Cultural Importance and Historic Age contribute over 57% of total cultural weighting, underscoring the dominance of social relev-

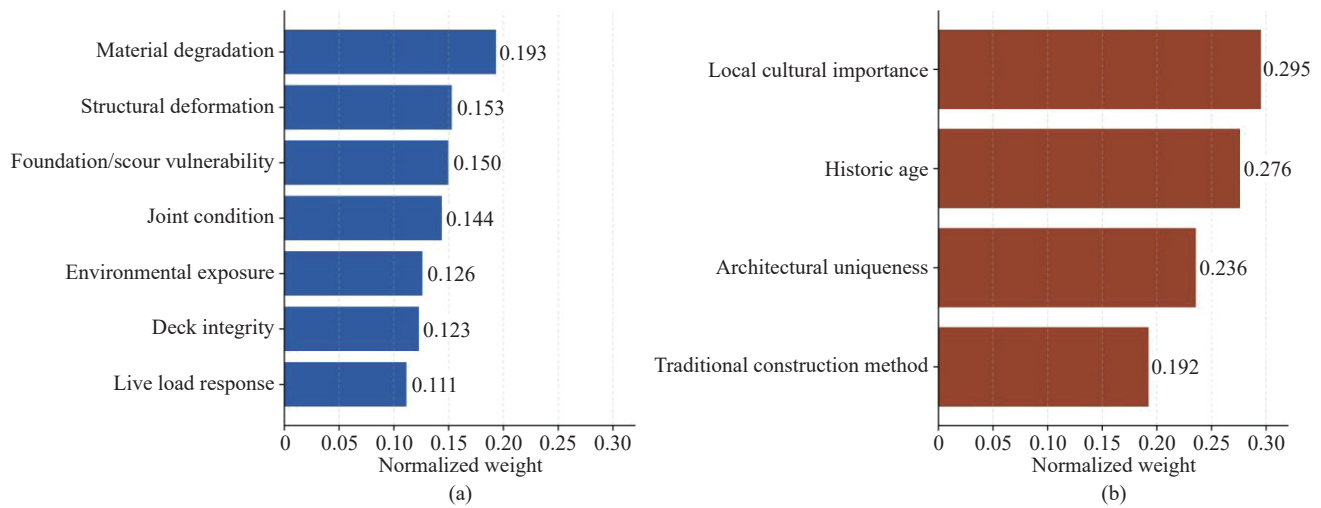


Fig. 9 Integrated compact weights. (a) structural indicator weights; (b) cultural indicator weights derived from the AHP analysis of 191 expert responses.

ance and historical continuity in conservation prioritization. Therefore, psychological distributions and finalized weights reveal a coherent decision logic among experts. In the structural domain, priority is assigned to progressive deterioration and stability-related mechanisms. In the cultural domain, social embeddedness and historical continuity prevail over purely technical craftsmanship considerations.

Category-Level Weight Derivation - Structural vs Cultural Importance: To determine the relative importance between the two principal categories, structural and cultural, respondents were asked to assign pairwise judgments using the Saaty scale. In this comparison, values greater than 1 indicate preference toward structural importance over cultural importance, while reciprocal values less than 1 indicate preference toward cultural importance over structural importance.

Fig. 10 presents the psychological distribution of responses across the Saaty scale. The distribution demonstrates a noticeable tendency toward reciprocal judgments. While 13.09% of respondents selected value 1, indicating equal importance, a significant proportion favored cultural importance over structural importance. Specifically, 17.8% selected 1/3 and 16.23% selected 1/2, together accounting for over 34% of responses leaning toward cultural dominance. Additional clustering at 1/4 and 1/5 further reinforces this tendency.

In contrast, direct structural dominance values show comparatively lower concentration at higher intensity levels. Although 16.23% selected value 2 and 9.95% selected value 3, responses sharply decrease beyond value 4, with extreme dominance values such as 7, 8, and 9 each remaining close to or below 1%. This

asymmetry indicates that respondents were more confident in moderately favoring cultural importance than in strongly prioritizing structural considerations.

Overall, the distribution reveals a balanced but slightly culture-oriented perception. The aggregation of pairwise judgments through the AHP process resulted in a finalized normalized weight of 0.5205 for Cultural indicators and 0.4795 for Structural indicators. This corresponds to approximately 52.05% importance assigned to cultural considerations and 47.95% to structural considerations in the overall conservation prioritization framework. Although the difference is not extreme, the results demonstrate that experts marginally prioritize cultural values over purely structural performance when making holistic conservation decisions for Nepal's historic bridges. This outcome aligns with the earlier indicator-level findings, where socially embedded attributes such as Local Cultural Importance and Historic Age received substantial weighting. At the same time, the near-balanced distribution confirms that structural integrity remains nearly equally critical, reflecting an integrated conservation perspective that recognizes both technical stability and heritage significance as co-dependent dimensions of decision-making.

Derivation of Decision Thresholds for Conservation Actions: To operationalize the composite scoring framework, respondents were asked to define threshold values on a 10-point scale indicating the upper limits for replacement and retrofitting decisions. The aggregated responses were processed using the AHP-based normalization procedure to derive final decision boundaries. The resulting upper limit for Replacement was calculated as 2.883, while the upper limit for Retrofitting was determined as 6.289. Composite scores ex-

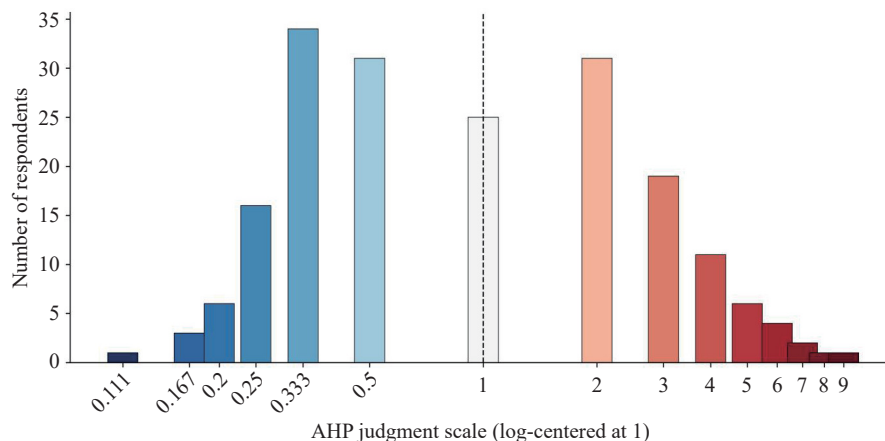


Fig. 10 AHP Psychological Distribution for category-level comparison between structural and cultural importance.

ceeding 6.289 indicate that the bridge may be retained for use with only minor interventions and routine maintenance.

Fig. 11 illustrates the decision spectrum mapping derived from respondent inputs. For the replacement threshold, a strong clustering is observed at value 3, selected by 53.4% of respondents, fol-

lowed by 15.71% at value 4 and 9.95% at value 2. This concentration around the lower-middle range indicates a shared perception that bridges scoring below approximately 3 on the composite scale are structurally or culturally deficient to a degree warranting full replacement.

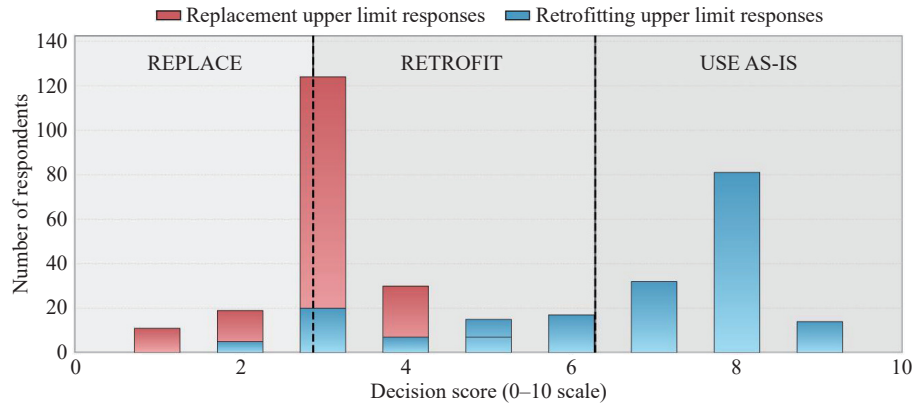


Fig. 11 Decision spectrum mapping showing composite score ranges for replacement, retrofitting, and continued use.

For the retrofitting threshold, responses are more widely distributed but display a dominant peak at value 8, selected by 42.41% of respondents. Additional clustering occurs at values 6 and 7, collectively accounting for more than 25% of responses. This distribution suggests that experts perceive retrofitting as appropriate for bridges within a broad intermediate performance range, extending from moderate deficiency to near-acceptable condition. The aggregation of these judgments resulted in a normalized retrofitting upper limit of 6.289, establishing a transition zone between major intervention and minor maintenance. Overall, the decision spectrum reflects a structured and experience-based consensus among experts. Bridges scoring below 2.883 fall within the replacement zone, those between 2.883 and 6.289 require retrofitting interventions of varying intensity, and those above 6.289 can remain in service with limited corrective measures. The relatively clear clustering of responses around central threshold values confirms the robustness of the derived decision boundaries and enhances the practical applicability of the proposed multi-criteria decision framework for conservation planning of Nepal's historic bridges.

4.3 Application of proposed framework: Study of Sankhamul Bridge

To demonstrate the practical application of the proposed AHP-based multi-criteria decision framework, the methodology was applied to the Sankhamul Bridge as a case study (Table 5). The case study illustrates how expert-derived indicator weights and decision thresholds can be translated into a transparent conservation de-

cision through a structured evaluation process. The bridge was evaluated using seven structural indicators and four cultural indicators, each scored on a ten-point scale based on observed condition and heritage relevance. The assigned marks were multiplied by their respective AHP-derived weights to obtain weighted indicator values. These were aggregated to produce structural and cultural subtotals, which were then combined using category-level weights to compute the final composite score used for decision-making.

4.3.1 Structural condition evaluation

The structural assessment indicates moderate performance with localized deterioration but overall functional stability. A relatively low score for material degradation reflects visible aging and weathering effects accumulated over long-term exposure, significantly influencing the structural subtotal due to its high weight. In contrast, foundation or scour vulnerability and structural deformation received higher scores, suggesting stable substructure behavior and acceptable geometric integrity without critical displacement. The joint condition was evaluated as moderate, indicating partial deterioration at connection points requiring maintenance interventions. Deck integrity received a lower rating due to surface wear and serviceability concerns, while live load response scored comparatively higher, confirming adequate load-carrying performance under current usage. Environmental exposure was assessed as moderate, recognizing ongoing environmental effects that may accelerate deterioration if not addressed through preventive measures. Overall, the structural subtotal reflects a bridge that is serviceable but

Table 5 Summary of the application of the proposed AHP framework for decision-making on whether to replace, retrofit, or use the Sankhamul Bridge as is.

	Indicator	Weightage (w_i)	Marks (M_i)	Final Marks ($M_{Fi}=w_iM_i$)
Structural marking	Material degradation	0.193	3	0.580
	Foundation / scour vulnerability	0.150	7	1.048
	Structural deformation	0.153	7	1.070
	Joint condition	0.144	5	0.719
	Deck integrity	0.123	3	0.368
	Live load response	0.111	7	0.780
	Environmental exposure	0.126	6	0.756
	$\sum M_{Fsi}$ (Sum of all FM_i of structural marking)			5.322
Cultural marking	Historic age	0.276	5	1.381
	Traditional construction method	0.192	7	1.347
	Architectural uniqueness	0.236	5	1.179
	Local cultural importance	0.295	8	2.364
	$\sum M_{Fci}$ (Sum of all FM_i of cultural marking)			6.271
$\text{Combined Marking } (\alpha \sum M_{Fsi} + \beta \sum M_{Fci})$			5.816	
Decision			Retrofit	

Note: α and β are structural weightage and cultural weightage.

requires rehabilitation to address progressive deterioration.

4.3.2 Cultural significance evaluation

The cultural assessment demonstrates strong heritage value. The bridge obtained a moderate score for historic age, indicating meaningful historical continuity. A higher score for traditional construction method reflects preservation of original construction characteristics contributing to authenticity. Architectural uniqueness received a moderate evaluation, while local cultural importance achieved the highest score, highlighting the bridge's continued social relevance and community association. Due to the higher weighting of cultural indicators, these attributes substantially strengthened the overall evaluation outcome.

4.3.3 Composite score and decision outcome

The structural and cultural subtotals were combined using the respective category weights to produce the composite score. The resulting value falls within the predefined retrofitting range established by expert-derived decision thresholds. This classification indicates that, although deterioration is present, the bridge retains sufficient structural capacity and cultural significance to justify rehabilitation rather than replacement or minimal intervention.

4.3.4 Framework applicability

The Sankhamul Bridge case study demonstrates the practical functionality of the proposed framework in integrating engineering assessment with heritage valuation. The step-by-step scoring, weighting, and aggregation process provides a transparent and reproducible methodology that can be directly applied to other historic bridges by assigning indicator scores based on field evaluation. The approach therefore offers a consistent decision-support tool for balancing structural safety and cultural preservation in historic bridge conservation planning.

4.4 Conservation and strengthening strategies preserving heritage integrity

The conservation of traditional pedestrian bridges in Nepal requires a careful balance between structural safety and heritage preservation. In the context of recognized heritage bridges, interventions must prioritize minimal intervention, material compatibility, and reversibility, in accordance with established conservation principles. Therefore, this study primarily focuses on condition-based stabilization, localized repair, and traditional material rehabilitation for three prevalent typologies: timber cantilever bridges, stone

masonry slab or arch bridges, and early suspension or cable-supported footbridges. The recommended measures are derived from literature review and the past experience from field investigations and the authors' structural assessments. Emphasis is placed on preserving original structural systems, retaining historic fabric, and enhancing durability through compatible techniques such as improved drainage, biological growth removal, selective member replacement, joint rehabilitation, anchorage stabilization, and protective treatments. For historic bridges that are not formally designated as protected heritage structures, limited structural upgrading may be considered where necessary to ensure user safety; however, such interventions should remain visually unobtrusive and materially compatible. By tailoring conservation strategies to specific bridge typologies and aligning them with heritage protection principles, this study provides a context-sensitive framework for safeguarding Nepal's historic bridges while maintaining their structural authenticity and cultural significance.

4.4.1 Strengthening of timber bridges

Traditional timber bridges are particularly vulnerable to defects associated with material degradation, joint failure, and deck integrity loss. [Table 6](#) summarizes applicable defects, and corresponding strengthening techniques.

4.4.2 Rehabilitation of stone masonry bridges

Stone slab and arch bridges are particularly vulnerable to defects such as scour-induced foundation instability, material erosion, and deformation of arch geometry. [Table 7](#) outlines rehabilitation methods that address both structural integrity and heritage sensitivity.

4.4.3 Retrofitting early suspension bridges

Suspension and simple cable-supported pedestrian bridges often built with indigenous materials like timber decks, stone anchors, or manually tensioned cables are susceptible to deck flexibility, anchor instability, and cable deterioration. [Table 8](#) outlines compatible retrofitting strategies that maintain both structural safety and cultural authenticity.

5 Conclusion

Historic bridges in Nepal represent an important intersection of transportation infrastructure and cultural heritage, yet systematic tools for evaluating both structural condition and heritage significance have remained limited. This study developed an integrated as-

Table 6 Retrofitting strategies for timber bridges based on structural indicators.

SN	Defect (indicator)	Retrofitting measure
1	Material Degradation (e.g. rotting timber, loss of section, insect damage)	Embed GFRP rods or strips longitudinally in tension zones of timber beams using groove bonding and adhesive injection. Enhances bending and shear capacity by 30%–50% with minimal visual impact.
2	Deck Integrity Loss (loose planks, gaps, weakened transverse members)	Replace degraded decking with treated timber of similar species; reinforce underneath using FRP grid panels or stainless-steel stiffeners. Use concealed fasteners to preserve original appearance.
3	Joint and Connection Deterioration (loosened lashings, corroded fasteners)	Insert concealed stainless-steel plates, dowels, or threaded rods within traditional joints. Re-secure with reversible mechanical fastening. Align grain orientation and match finishes for visual continuity.
4	Structural Deformation (sagging beams, lateral misalignment)	Install CFRP textile-reinforced mortar (TRM) bands on arch or girder surfaces. Carbon or basalt mesh embedded in lime-based mortar improves stiffness and reduces mid-span deflection.
5	Live Load Deflection or Vibrations	Introduce supplemental hidden transverse braces or stiffening beams beneath deck. Optionally use prestressed GFRP bars across girders to control deflection and dynamic response.

Table 7 Retrofitting strategies for stone masonry bridges based on structural and heritage indicators.

SN	Defect (indicator)	Retrofitting measure
1	Foundation/Scour Vulnerability (undermined piers, settlement cracks)	Inject lime-based grout (1–3 MPa pressure) through systematically drilled boreholes to fill internal voids and restore footing stability. Grout must match original mortar porosity to avoid internal stress buildup.
2	Structural Deformation (arch sagging, joint separation)	Drill and insert stainless-steel threaded rods or tensioned tendons across arch barrels. Preload within elastic range to improve load transfer and seismic resilience, fully hidden within stone mass.
3	Environmental Exposure Risk (riverbank erosion, flood impact)	Apply textile-reinforced mortar (TRM) to spandrel walls or wing walls using carbon or basalt grids and lime-based mortar. Enhances lateral and shear capacity while compatible with historic aesthetics.
4	Material Degradation (stone weathering, surface flaking)	Treat exposed stone with ethyl silicate consolidants after testing absorption and reaction compatibility. Restores surface cohesion and resistance to future moisture cycles without sealing the surface.
5	Architectural Uniqueness (decorated stone, local dressing patterns)	Use stone stitching or dutchman repair using reclaimed or locally sourced similar stone blocks to preserve visual consistency and original craftsmanship. Avoid surface epoxy or non-reversible techniques.

Table 8 Retrofitting measures for early suspension/cable-supported bridges.

SN	Defects (indicators)	Retrofitting measures
1	Deck flexibility or uneven response under dynamic pedestrian loading (Live Load Response, Deck Integrity)	Installation of lightweight inverted portal stiffening frames beneath the deck. Steel or treated bamboo frames improve stiffness, control vibration, and distribute pedestrian loads more uniformly.
2	Aging, rusted, or slack main cables or vertical hangers (Material Degradation, Structural Deformation)	Replacement or wrapping of hangers using CFRP or hybrid CFRP-steel strands. These retain slenderness and preserve aesthetics while restoring tensile strength. Anchoring maintained in existing housings.
3	Anchor instability or partial detachment from abutment blocks (Foundation/Scour Vulnerability, Local Cultural Importance)	Concealed addition of baseplates and braced cross-frames embedded into stone or timber anchor zones. Local stone facades or cultural symbols are retained.
4	Structural misalignment or sagging at mid-span (Structural Deformation, Traditional Construction Method)	Re-tensioning of cables using calibrated turnbuckles or installing mid-span saddle supports. All interventions are carried out respecting traditional suspension geometry.

assessment framework that jointly evaluates these dimensions using a dual-indicator system comprising seven structural and four cultural indicators. Based on pairwise comparisons from 191 experts and the Analytic Hierarchy Process (AHP), normalized weights were derived to compute a composite score representing overall bridge condition and heritage value. The framework further establishes intervention thresholds on a ten-point scale to classify bridges into replacement, retrofitting, or continued-use categories and links these decisions with compatible conservation and strengthening strategies. Based on the analysis, the following key findings are obtained:

(1) Expert judgment responses show a strong concentration within moderate importance levels of the Saaty scale (values 2–4), while extreme dominance levels (8–9) accounted for less than 3% of responses in most structural comparisons.

(2) Among structural indicators, Material Degradation received the highest normalized weight (0.1933), followed by Structural Deformation (0.1529) and Foundation or Scour Vulnerability (0.1496). Together, these three factors account for approximately 49.6% of the total structural priority.

(3) Other structural indicators received comparatively lower weights, including Joint Condition (14.38%), Environmental Exposure (12.60%), Deck Integrity (12.28%), and Live Load Response (11.14%). This distribution indicates that long-term deterioration processes are considered more critical than short-term loading effects in the assessment of historic bridges.

(4) Within cultural indicators, Local Cultural Importance received the highest weight (29.55%), followed by Historic Age (27.63%), Architectural Uniqueness (23.58%), and Traditional Construction Method (19.25%). The combined contribution of Local Cultural Importance and Historic Age exceeds 57% of the total cultural weighting, highlighting the dominant role of community relevance and historical continuity in heritage evaluation.

(5) Category-level comparison between structural and cultural criteria produced a nearly balanced prioritization, with Cultural indicators receiving a normalized weight of 0.5205 (52.05%) and Structural indicators receiving 0.4795 (47.95%). This result demonstrates a slightly culture-oriented conservation perspective while maintaining strong emphasis on structural safety.

(6) Expert-derived decision thresholds established a structured intervention spectrum on the composite 10-point evaluation scale. Bridges scoring below 2.883 fall within the replacement category, scores between 2.883 and 6.289 indicate the need for retrofitting interventions, and scores above 6.289 allow continued use with minor maintenance measures.

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Author contribution statement

Arun Paudel: conceptualization, data curation, methodology, software, formal analysis, investigation, visualization, resources, writing-original draft, writing-review & editing. Kabin Lamichhane: data curation, methodology, software, formal analysis, investigation, writing-original draft. Bijaya Jaishi: data curation, writing review & editing. Baochun Chen: conceptualization, data curation, review & editing. Avimanyu Lal Singh: writing-review & editing. Krishna Shrestha: data curation, methodology, investigation, writing-review & editing. Garima Gauli: data curation, methodology, software, writing-original draft, formal analysis, investigation, visualization, resources.

Data availability statement

All data used in this research will be made available upon reasonable request to the corresponding author.

Use of AI statement

During the preparation of this manuscript, the authors used ChatGPT and other AI models solely for language editing, grammar correction, and improvement of readability. The tool was not used for content generation, data analysis, interpretation of results, or development of scientific ideas. All technical content, analyses, and conclusions presented in this study were developed entirely by the authors. After using this tool, the authors have carefully reviewed and revised the manuscript and take full responsibility for the accuracy and integrity of the published work.

References

- [1] Bhandari SB, Shahi PB, Sharma RR, et al. Bridges in Nepal: Enhancing connectivity and economic development. *The Open Transportation Journal*, 2025(19): e26671212357746.
- [2] Bhandari SB, Shahi PB, Shrestha RN. Overview of rural transportation infrastructures in Nepal. *Eurasia Journal of Earth Science & Civil Engineering*, 2012(1): 1–14.
- [3] Murton G. Border corridors: Mobility, containment, and infrastructures of development between Nepal and China. University of Colorado at Boulder, 2017.
- [4] Budha PB, Joshi BR. An assessment of operation and maintenance of trail bridges for sustainable mobility in Nepal. *Himalayan Journal of Applied Science and Engineering*, 2022, 3(1): 1–7.
- [5] Adhikari SH. Developing criteria for priority ranking of bridges: A case study of Bagmati Province. Pulchowk Campus, 2020.
- [6] Wagle MS, Khakurel S, Poudel S. Development of bridge management system for existing bridge in Nepal using analytical hierarchy process. 12th IOE Graduate Conference, 2022: 1536–1543.
- [7] Pradhan P. Construction of trail suspended bridges in Nepal: an application of traditional technology. Tokyo: United Nations University, 1981.
- [8] Blockley D. Bridges: the science and art of the world's most inspiring structures. Oxford: Oxford University Press, 2010.
- [9] Saaty TL. Decision making with the analytic hierarchy process.