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Review

Vibration diagnostics of beam bridges for serviceability assessment: a comparative analysis of international practice

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Abstract. Vibration-based methods are widely used in bridge assessment, yet their engineering interpretation for serviceability evaluation remains inconsistent across studies and national practice. This paper comparatively analyzes international practice in the vibration diagnostics of beam bridges with a focus on how measured dynamic response is translated into conclusions about operational suitability. The analysis covers field-oriented studies and review sources and compares excitation strategies, sensor layouts, measured parameters, interpretation routes, and links between diagnostic results and engineering decisions. Across the reviewed studies, the most frequently used indicators are natural frequencies, mode shapes, damping characteristics, and vibration response levels, since these quantities are sensitive to changes in stiffness, boundary conditions, and structural deterioration. The comparison also shows that these indicators are not equally informative across all field conditions and do not, by themselves, provide a uniform basis for serviceability assessment. Their practical value depends on the test organization, signal interpretation, and the extent to which vibration data are combined with structural models, inspection context, or baseline states. The paper identifies the most transferable findings from international practice and highlights considerations relevant to bridge networks that require practical, selective, and reproducible assessment procedures, including those in Kazakhstan.

Keywords: beam bridges, serviceability assessment, vibration diagnostics, operational modal analysis, bridge monitoring, structural health monitoring.

1. Introduction

The assessment of bridge serviceability cannot be reduced to simply recording the presence or absence of damage. In engineering terms, serviceability refers to a structure's ability to sustain operational actions at prescribed traffic speeds while maintaining an acceptable technical condition, reliability, and stability throughout its service life. For beam bridges, this means that the superstructure must remain fit for normal operation without unacceptable deformation, excessive vibration, accelerated deterioration, or loss of functional performance. A bridge may therefore retain sufficient load-carrying capacity while already exhibiting behavior that is unsatisfactory in routine service [1].

This issue becomes especially important when serviceability is interpreted only through deformation-based checks. The Federal Highway Administration (FHWA) study [2] on steel girder bridges showed that, within American AASHTO LRFD practice, deflection limits under the Service I load combination were historically used to control both excessive bridge vibrations and deformation-related damage, even though a single deflection criterion is insufficient for both tasks. The same report noted that criteria based on natural frequency reflect excessive vibration more adequately than deflection limits alone, whereas deterioration of the reinforced concrete deck is better represented by strain-related indicators [2]. This suggests that if serviceability is interpreted only as a deflection problem, part of the actual structural behavior remains outside the assessment framework.

For beam bridges, this is particularly relevant because changes in stiffness, support conditions, and operational regime are often reflected rather quickly in the dynamic response.

Under these conditions, vibration diagnostics has become increasingly important in bridge assessment. Vibration-based structural health monitoring studies [3] show that a structure's dynamic response can provide information about its actual condition. In bridge applications, this response reflects the effects of traffic, wind, impact, and other dynamic actions, while the most commonly used diagnostic parameters include natural frequencies, mode shapes, and damping ratios. These quantities are valuable because they are sensitive to changes in stiffness, mass distribution, boundary conditions, and structural deterioration. At the same time, they do not automatically translate into an engineering judgment on serviceability, since interpretation depends on structural context, field conditions, and the purpose of the investigation [3].

The engineering value of vibration diagnostics is also shaped by methodological diversity. Saidin et al. [3] distinguish between forced vibration testing and ambient vibration testing, that is, between tests with artificially introduced excitation and tests based on uncontrolled operational loading. The same review notes that the choice of testing strategy depends on structural size, access conditions, available equipment, and inspection objectives. In practice, bridge diagnostics is rarely performed under fully controlled conditions, so the usefulness of a method depends not only on sensitivity but also on reproducibility, labor demand, and compatibility with in-service operation.

At the same time, vibration diagnostics occupies an intermediate position between conventional inspection, load testing, and full-scale permanent structural health monitoring systems [3]. Unlike purely visual assessment, it provides access to the structure's actual dynamic behavior. Unlike permanent Structural Health Monitoring (SHM), however, it can also be applied as a one-time or periodic instrumented investigation, which is especially important for bridge networks where continuous monitoring of every structure is neither technically nor economically justified [3], [4].

Beam bridges are particularly suitable for comparative analysis because they are widely used and sufficiently repetitive in structural form to enable meaningful comparison of diagnostic approaches. In the reviewed literature, beam and girder systems frequently serve as the basis for operational assessment: the FHWA report analyzed a dataset of 195 steel girder bridges [2], while the Kazakhstan-based publication on the safe operation of artificial structures [1] directly considers vibration diagnostics for beam bridge superstructures. In that publication, the first natural frequency, the relative damping coefficient, and the relative midspan deformation or stress are proposed as informative parameters for technical-condition assessment. These indicators are important because they connect a measurable dynamic response with an engineering interpretation of structural condition.

Despite the growing number of studies in bridge monitoring and vibration-based assessment, the literature remains uneven in scope and emphasis. The review by Saidin et al. [3] focuses on vibration-based SHM, modal identification, and dynamic testing. In contrast, the review by Deng et al. [4] covers a much broader spectrum of bridge monitoring technologies, including sensors, computer vision, warning systems, and data processing. Both are useful, but neither is centered specifically on the comparative international practice of vibration diagnostics for beam-bridge serviceability assessment [3], [4]. By contrast, the FHWA report [2] is more directly connected to engineering decision-making, since it shows that the relationship between vibration, deformation, and deterioration is more complex than conventional code limits may suggest. The Kazakhstan-based publication [1] is also practice-oriented, but it does not extend to a structured comparison of international approaches, implementation conditions, or interpretation strategies. As a result, bridge vibration monitoring is well studied in general terms, whereas fewer works examine how vibration measurements are actually translated into serviceability-related engineering conclusions across different practical contexts [1], [3], [4].

For Kazakhstan, this issue has direct practical relevance. According to current official data, 1,335 bridge structures are in operation on republican roads, of which 735 are in good technical condition, 547 are assessed as satisfactory, and 53 require repairs of varying complexity (Figure 1). In terms of construction period, 341 bridges were built before 1980, 534 were commissioned between

1980 and 2015, and 460 were built after 2015 (Figure 2). By structure type, 1,144 bridges cross rivers and other water barriers, 151 are road overpasses, 21 are railway overpasses, and 19 are dry bridges (Source: JSC NC «KazAvtoZhol», official letter dated 03.03.2026). This bridge stock includes structures of different generations, designed under different regulatory conditions and operating under different service demands. Under such conditions, selective and technically interpretable diagnostic methods that can be applied when needed become especially valuable.

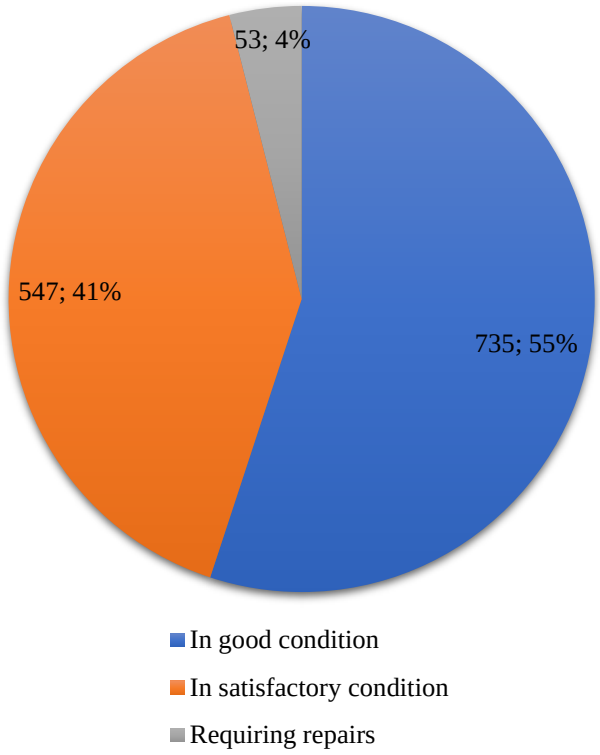


Figure 1 – Distribution of bridge structures on republican roads in Kazakhstan by technical condition

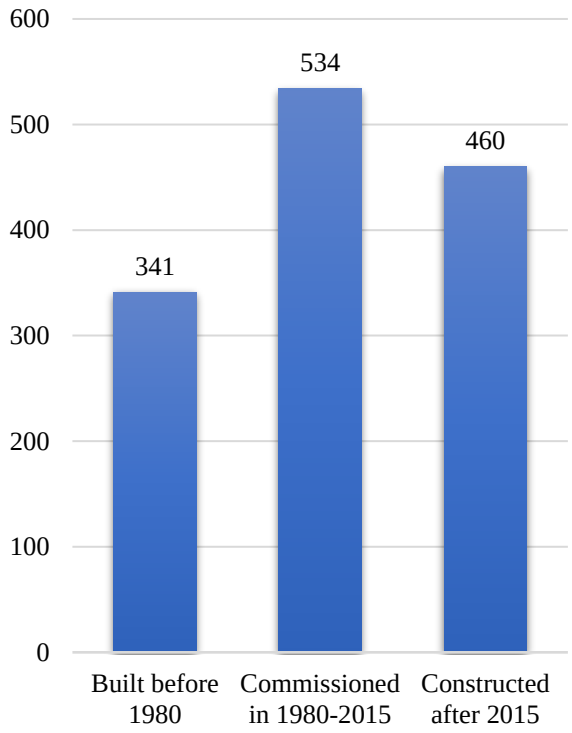


Figure 2 – Distribution of bridge structures on republican roads in Kazakhstan by construction period

Based on the above, this study aims to analyze international practices in vibration diagnostics of beam bridges and identify transferable diagnostic approaches, indicators, and interpretation strategies that can support practical serviceability assessment and maintenance decision-making for bridge structures.

2. Methods

This study employs a comparative analytical framework to examine international practices in vibration-based diagnostics for beam bridges. The primary objective is to evaluate how dynamic data is collected, processed, and translated into meaningful indicators of structural serviceability across different engineering traditions.

The literature was sourced from major engineering databases (including Scopus, Web of Science, ScienceDirect, and ASCE Library) covering the period from 2000 to 2025. This timeframe was chosen to capture the transition from traditional field-based modal testing to modern automated, output-only monitoring techniques.

The search strategy utilized targeted keyword combinations focusing on the intersection of bridge dynamics, modal analysis, and serviceability assessment. To ensure a comprehensive dataset, the initial search was supplemented by a backward reference check of seminal papers and case studies. The specific criteria for inclusion are detailed in Table 1.

Table 1 – Literature search and selection criteria

Criterion	Specification
Review type	Comparative analytical review
Methodological basis	PRISMA-inspired structured selection
Scope of structures	Reinforced concrete and steel beam bridges
Databases	Scopus, Web of Science, ScienceDirect, SpringerLink, ASCE Library, IEEE Xplore, TRID
Time window	2000–2026
Search fields	Title, abstract, keywords, plus backward reference checking
Main query groups	beam bridge and vibration diagnostics; bridge serviceability and modal analysis; vibration-based assessment and bridge; operational modal analysis and beam bridge; bridge monitoring and frequency and serviceability

To facilitate consistent comparisons across diverse studies, a standardized data-extraction protocol was used. Each publication was analyzed based on:

- Technical parameters: sensor configurations, excitation methods, and identified dynamic characteristics (frequencies, damping, mode shapes);
- Operational context: bridge material, span length, and regional environmental conditions;
- Engineering interpretation: the logic used to correlate vibration data with serviceability limits, maintenance decisions, and structural integrity.

This review treats vibration diagnostics as a continuous workflow – extending from raw measurement to final engineering judgment. Rather than viewing monitoring and manual inspection as competing domains, this study assumes they are complementary. Consequently, the evidence base includes both long-term monitoring systems and one-time diagnostic investigations, provided they offer actionable insights into the structure's operational state.

The methodology acknowledges several challenges inherent in this field. These include the inconsistent use of the term «serviceability» across different jurisdictions, a prevalent research focus on damage detection over operational assessment, and the fact that much practical experience remains locked in project-specific reports rather than standardized academic literature.

3. International experience and measurement strategies in vibration diagnostics of beam bridges

3.1 From modal testing to operational diagnostics: how international practice has evolved

International practice in bridge vibration diagnostics has evolved from controlled modal testing toward measurements under real operating conditions and, increasingly, toward operational modal analysis (OMA), in which modal parameters are identified from structural response to unknown input excitation [3], [5]. This shift reflects practical engineering constraints: for in-service bridges, controlled excitation is often expensive, labor-intensive, and only partially compatible with normal traffic, whereas output-only approaches and long-term monitoring enable measurements under actual service conditions.

In the reviewed European studies, vibration diagnostics is most often associated with long-term observation, environmental normalization, and statistical interpretation. On the Westend Bridge in Berlin, continuous monitoring was used to remove temperature-related effects from modal frequencies and to track possible prestress loss [6]. The Ponte Moesa Campagnola campaign in Switzerland combined ambient and forced vibration data on a prestressed concrete bridge with controlled artificial damage [7]. Taken together, these studies suggest that European practice often develops vibration diagnostics within a broader SHM framework rather than as a one-time extraction of a limited set of modal parameters [6], [7].

The North American line in the reviewed literature is defined less by the number of cases than by the structure of the diagnostic workflow. In the long-term VBSHM review, the Confederation Bridge is presented as a reference example of extended automated monitoring, including modal estimation, mode tracking, and sensor self-diagnostics [5]. Another influential direction is the development of deployable wireless systems. This is reflected in the Nine Wells Rail Bridge study, where measurements from a wireless accelerometer network were used directly for structural identification based on Finite Elements (FE) [8]. In this type of framework, vibration testing is not treated as an isolated measurement exercise, but as part of a model-supported engineering interpretation [5], [8].

The reviewed Asian studies are more strongly oriented toward field practicality and operational applicability. On the Sungai Raia UHPC bridge in Malaysia, ambient vibration testing was carried out under normal traffic conditions and was combined with FE model updating and serviceability verification [9]. In Japan, measurements were performed from an under-bridge maintenance walkway without traffic closure using a wireless system based on Microelectromechanical Systems (MEMS) [10]. The Indonesian case of the A.P. Pettarani Flyover Bridge represents a simpler but practically relevant configuration based on permanently installed accelerometers and processing with Fast Fourier Transform/Stochastic Subspace Identification (FFT/SSI) [11]. In this part of the literature, the emphasis is less on large-scale permanent SHM and more on feasible measurement schemes for bridges in regular service [9], [10], [11].

An important comparative observation is that the algorithms themselves do not primarily define international differences. The more meaningful distinction lies in what each study treats as the central engineering task: long-term interpretation, rapid field deployment, or minimal interference with bridge operation [6], [8], [10]. For comparative analysis, this distinction is more informative than a simple inventory of signal-processing methods.

3.2 Excitation methods, sensor layouts, and measurement campaign parameters

With respect to excitation, international practice shows clear recurring patterns. For in-service bridges, ambient and traffic-induced vibrations dominate, as they enable measurements without heavy excitation equipment or major traffic disruption [5], [8], [9], [10]. This is evident in the Sungai Raia bridge [9], the Nine Wells Rail Bridge [9], and the Japanese under-walkway system [10], where operational traffic served as the main excitation source. The broader review of long-term vibration-based SHM similarly emphasizes that the value of such systems lies in their ability to operate under real-world service uncertainty rather than under artificially controlled laboratory conditions [5].

Forced excitation remains relevant, but mainly in validation-oriented or benchmark studies. The Ponte Moesa campaign is a representative example in which both ambient and forced vibrations were recorded after artificial damage was introduced to a real prestressed concrete bridge [7]. Such campaigns are highly valuable for testing the sensitivity of diagnostic features, but they are too demanding for routine bridge-network assessment [7].

Impact-based express methods occupy a separate niche. In Bondar's method for railway beam bridges, the main diagnostic criterion is the first-mode vibration period, while excitation is introduced by a small impulse at midspan [12]. This approach is intended for periodic instrumental diagnostics rather than continuous monitoring. Its main advantage is operational simplicity, while its limitation is that it primarily captures the global structural response rather than a more complete modal portrait of the bridge.

Sensor layouts vary as much as excitation strategies. The reviewed studies range from compact short-session arrangements to dense long-term monitoring systems. Some cases rely on relatively moderate instrumentation, while others use larger sensor networks, higher sampling rates, and repeated-measurement configurations [12]. This variation does not point to a single "correct" instrumentation scale; rather, it indicates that the measurement configuration is selected based on the objective of the investigation.

To illustrate these differences, Figure 3 compares the instrumentation scale adopted in selected international case studies of vibration-based bridge diagnostics. The figure highlights the considerable variation in sensor deployment across different monitoring programs.

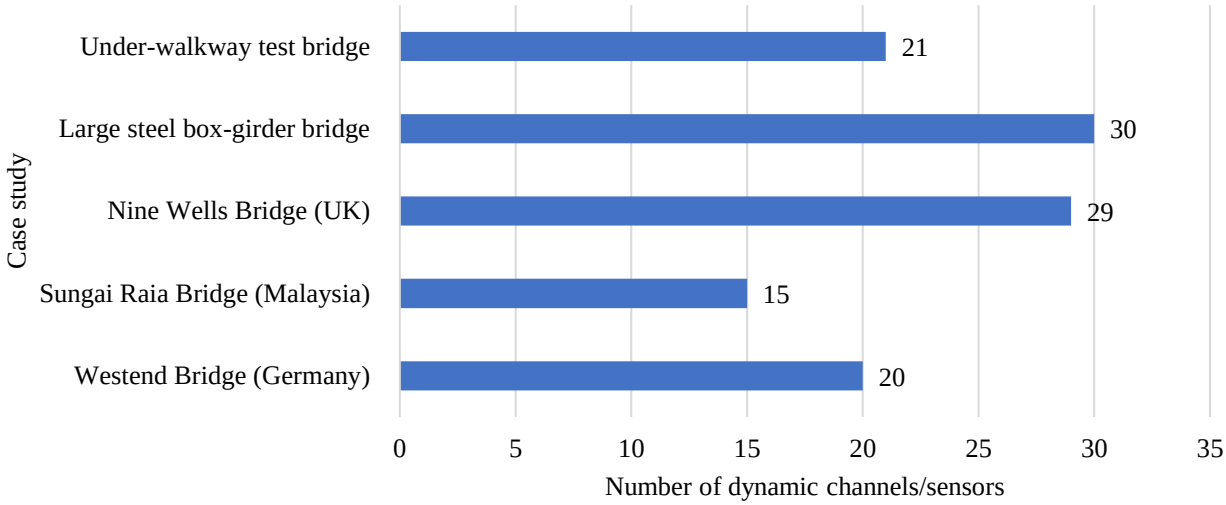


Figure 3 – Instrumentation scale in selected international case studies of vibration diagnostics for beam bridges

A similar pattern is observed in sampling frequency and record duration. As shown in Figure 4, the reviewed studies employ a wide range of sampling frequencies, reflecting differences in monitoring objectives, expected vibration characteristics, and data-processing requirements.

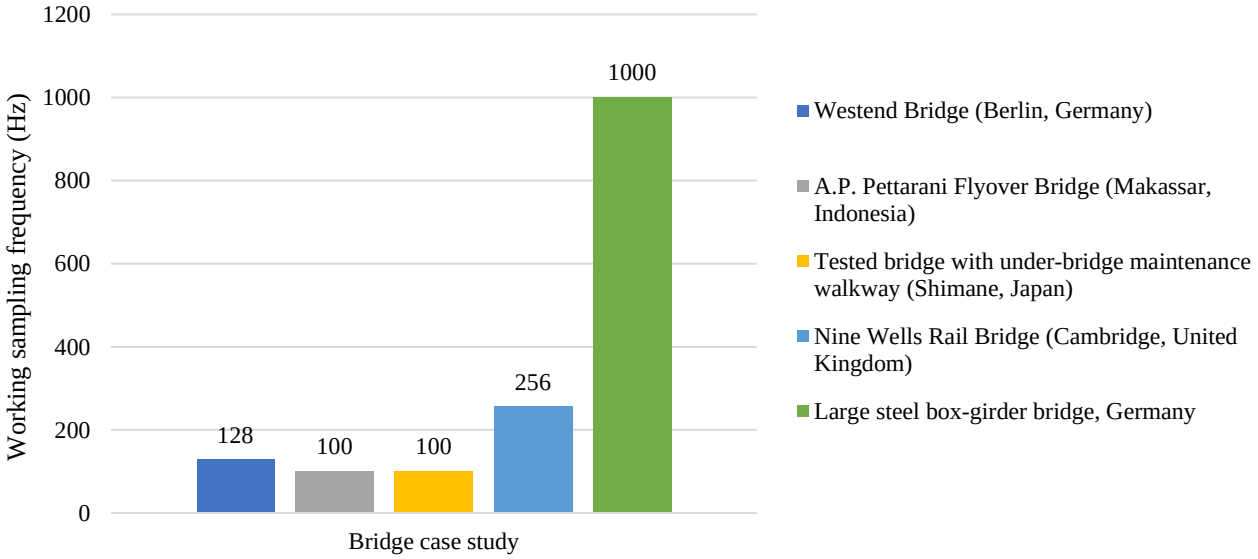


Figure 4 – Sampling frequency in selected bridge vibration-monitoring case studies

A compact comparison of the most informative case studies is presented in Table 2. The comparison indicates that the most informative diagnostic configuration is not necessarily the one with the largest number of sensors. In several studies, the key contribution lies in the clear link between measurement, signal processing, and engineering interpretation. This can be observed in the Sungai Raia bridge study, where the measured frequencies were validated against an updated FE model and serviceability criteria [11]. A similar approach was adopted in the German steel box-girder bridge case, where the identified modal properties were used to refine the numerical model and improve the interpretation of structural behavior [13].

Table 2 – Comparative characteristics of selected international vibration-diagnostic bridge case studies for condition assessment

Case study	Bridge type	Measurement setup	Key result
Westend Bridge, Germany [6]	Prestressed concrete box-girder bridge	20 vertical velocity sensors; 128 Hz; 32 s setup	Frequently excited modes at about 2.5, 3.4, 4.9, 7.8, and 8.9 Hz; long-term analysis was used to detect possible prestress loss.
Nine Wells Rail Bridge, UK [8]	Three-span prestressed reinforced-concrete bridge	29 accelerometers; 256 Hz	16 mode shapes were reconstructed, of which 10 were used for structural identification and FE updating
Sungai Raia UHPC Bridge, Malaysia [9]	Single-span UHPC bridge, 50 m	15 single-axis accelerometers; ambient vibration test	After model updating, the discrepancy for the first five frequencies was < 5%; the first dominant frequency was 3.348 Hz
Large steel box-girder bridge, Germany [14]	Steel box-girder bridge	30-channel system; 1000 Hz; 60 min per setup	9 modes were identified; the first five frequencies were 0.85, 2.03, 2.61, 4.22, and 4.76 Hz
Ponte Moesa Campagnola, Switzerland [7]	Three-span prestressed concrete bridge	7 triaxial accelerometers; 200 Hz; ambient + forced vibrations	4-day benchmark campaign after artificial damage; forced vibration level was about one order of magnitude higher than the ambient response
Underneath maintenance walkway wireless test, Japan [10]	In-service bridge tested from below	21 acceleration channels; 100 Hz; 5 min records	The dominant vertical frequencies were 2.34, 4.10, 10.30, 14.45, and 18.75 Hz; the deck–girder response comparison proved more informative.

3.3 What the International Experience Shows for Reinforced-Concrete and Steel Beam Bridges

The reviewed international experience shows that reinforced-concrete and steel beam bridges are not interpreted in the same way in vibration diagnostics.

For reinforced-concrete beam bridges, the dominant approach is to use vibration data to assess global structural behavior and support FE model refinement. This is evident in the Westend Bridge [6], the Nine Wells Rail Bridge [9], and the Sungai Raia UHPC bridge [9], where vibration measurements were interpreted primarily in terms of stiffness-related behavior and consistency with structural models. In these cases, vibration diagnostics is used less as a direct damage detector and more as a means of evaluating whether the bridge behaves as expected under service conditions [6], [8], [9].

For steel beam and box-girder systems, the reviewed studies indicate a greater need for detailed spatial interpretation and caution when evaluating frequency changes. On a large steel box-girder bridge in Germany, identified modal properties were used not only to validate but also to refine the numerical model [13]. Similarly, in the Japanese deck-damage study, the most valuable information was obtained not from frequency shifts alone but from comparing the relative responses of the bridge deck and the main steel girders [12]. These examples suggest that, for steel bridge systems, vibration diagnostics often relies on component-level assessment, environmental-effect filtering, and careful distinction between local and global structural responses [12].

An important conclusion from this section is that the reviewed literature does not support the existence of one universal measurement strategy for all beam bridges. For reinforced-concrete systems, the reviewed studies more often emphasize global stiffness behavior, FE calibration, and serviceability-oriented interpretation [6], [10]. For steel systems, they more often highlight the importance of relative-response comparison when local deterioration is not clearly reflected in a limited set of global frequencies [12].

Accordingly, for one-time inspection of beam bridges, the engineering value of a vibration-diagnostic approach appears to depend less on instrumentation density alone than on a balanced combination of excitation type, rational sensor layout, appropriate signal processing, and comparison with either a baseline state or a numerical model. For some railway and short-span structures under restricted-access conditions, a period-based express approach, such as Bondar's method, may also remain relevant [12]. In practical terms, international experience points not to one preferred measurement scheme, but to the need to match diagnostic depth to structural type and engineering objective.

4. Diagnostic indicators, serviceability interpretation, and transferability of approaches to Kazakhstan

4.1 Vibration-based diagnostic indicators and their interpretation in terms of serviceability

Among the indicators used in vibration diagnostics of beam bridges, natural frequency and vibration period remain the most consistently applied. Both are directly related to global structural stiffness, and their variation is commonly interpreted as a sign that the overall structural behavior of the span has changed. In the review on modal-based damage detection, frequency is described as a practically convenient global indicator because it is relatively easy to extract and compare. At the same time, in Bondar's Kazakhstan-oriented methodology, the principal evaluation criterion is explicitly defined as the vibration period of the first mode of a girder span [12]. In the UHPC bridge study from Malaysia, the first dominant frequency after FE-model updating was 3.348 Hz, and the discrepancy between the updated model and the first five measured frequencies was less than 5%, which allowed this parameter to be interpreted not only as a modal characteristic but also as an indicator relevant to serviceability assessment [9].

At the same time, frequency and period are useful only up to the point where the task shifts from identifying that a deviation exists to explaining what that deviation means structurally. Their main strength lies in their sensitivity to changes in global stiffness. Their main limitation is that local deterioration may have only a limited influence on the global modal response. As a result, the same indicator that performs well in rapid screening may be insufficient for an engineering judgment about the actual mechanism of deterioration [15].

Interpretation becomes more reliable when frequency is considered together with mode shapes and their consistency with the numerical model. In the field study of a simple beam bridge, the identified modal parameters were used to update the FE model after a relatively short instrumented campaign [13]. In the UHPC bridge study, model validation was additionally strengthened through the Modal Assurance Criterion (MAC), with the minimum MAC value exceeding 90% after updating [9]. This type of interpretation is more robust than relying on a single frequency because it compares not a single measured value but a set of dynamic characteristics against the expected structural behavior [13], [16].

Damping must be treated more cautiously. In principle, it reflects the dissipation of vibration energy and may therefore contain information about structural condition. In bridge testing practice, however, damping estimates are more sensitive than frequency to the identification method, signal quality, and excitation conditions. For this reason, in local studies on railway transport structures, damping is proposed not as an independent diagnostic criterion, but as one of several parameters together with the first frequency or period and relative midspan deformation or stress [1], [17]. This combined use is methodologically more realistic than any attempt to rely on a single modal indicator [1], [17].

The engineering meaning of serviceability-oriented interpretation becomes clearest when vibration-based indicators are compared with external performance criteria. In the UHPC bridge study, the identified dominant frequency was evaluated against serviceability requirements, and the authors concluded that it fell within the admissible range. However, the same study also demonstrated that serviceability limits depend on span configuration [11]. The relationship between natural

frequency and span length, together with the corresponding admissible serviceability range, is illustrated in Figure 5.

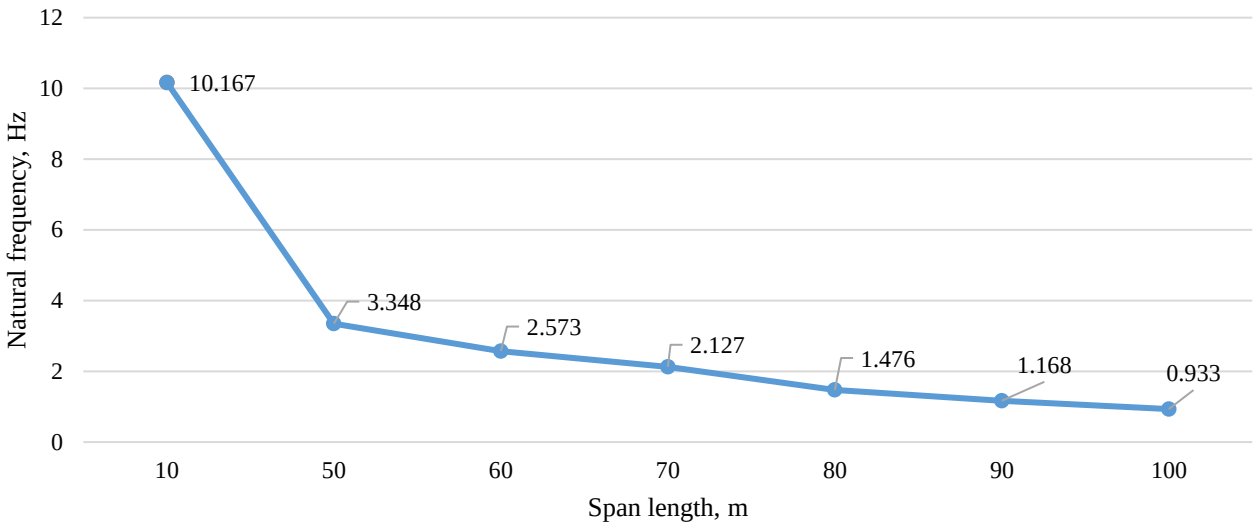


Figure 5 – Relationship between natural frequency and span length for the UHPC bridge, with the admissible serviceability range [9]

The FHWA report based on 195 steel girder bridges leads to an even more important engineering conclusion: a single deflection limit is insufficient, because excessive vibration is better controlled by a criterion based on natural frequency, whereas deterioration of the concrete deck is better represented by flexural tensile strain [2]. Bridge serviceability, in the dynamic sense, therefore, cannot be reduced to a single parameter. In most cases, it requires at least two lines of interpretation: one related to vibration behavior and another related to deformation-induced deterioration [2], [11].

4.2 Limits of interpretation and the integration of vibration diagnostics with inspection, load testing, and FE modeling.

The main limitation of vibration-based diagnostics is not that it fails to detect change, but that it cannot always explain that change reliably on its own. In review [15], this boundary is formulated through Rytter's damage-detection levels: when only vibration data are used, it is realistic to expect detection, localization, and partial assessment of damage, but not a reliable prediction of remaining service life without a sufficiently developed numerical and engineering framework. This is a fundamental limitation because it dispels the misleading assumption that a single set of modal parameters can replace inspection, structural analysis, and engineering judgment [15].

Accordingly, in well-designed field studies, vibration testing is rarely conducted in isolation from finite-element modeling. In the study of a simple beam bridge, a numerical model was used prior to field measurements to identify expected modes, select reference points, and design the sensor layout [13], [18]. This type of workflow is particularly informative for one-time inspections: the field test remains relatively short, but its interpretation is grounded in the actual structural scheme rather than in an isolated set of spectral peaks [13].

In more complex cases, the role of engineering context becomes even more important. For the retrofitted bridges B1 and B2 in Central Italy, ambient vibration tests were performed after the interventions to verify whether the post-retrofit dynamic behavior of the structures was consistent with the engineering intent of the strengthening scheme [19]. In this context, OMA does not function as a universal "damage detector," but as a tool for checking whether the bridge behaves as expected after repair or modification [19].

A separate but equally important issue is the influence of the environment, especially temperature. The review on temperature effects states explicitly that temperature-induced changes in modal properties may be comparable to, or even larger than, those caused by damage; if such effects

are not accounted for, vibration-based diagnostics may produce both false positives and false negatives [20]. The West End Bridge provides a clear long-term example of this problem. In that study, modal features were extracted from continuous measurements, temperature effects were filtered using multiple linear regression, and interpretation was based on a health index derived from residual trends rather than on raw frequency shifts alone [6]. This is an important methodological point: once environmental variability becomes significant, the condition of the structure can no longer be interpreted through a single frequency value. Only a normalized trend relative to the bridge's own baseline remains meaningful [6], [20].

Even after such normalization, one more limitation remains: the scale of damage. This leads to an important practical conclusion. Vibration diagnostics works well when the task is to detect a system-level change in structural behavior. However, when the problem concerns local corrosion, crack opening, bearing condition, or a defensible prediction of remaining life, reliable interpretation usually cannot be achieved without combining vibration data with inspection, deformation measurements, and a numerical model [16].

4.3 Transferability of international approaches to Kazakhstan and criteria for method selection under local conditions

For Kazakhstan, the key question is not whether international experience in vibration diagnostics can be used, but which elements of that experience can be transferred in a technically realistic and economically justified way. Since the national bridge stock is heterogeneous in age, technical condition, structural configuration, and likely also in the completeness of available design and maintenance records, the direct transfer of one uniform monitoring strategy to all bridges would be methodologically weak. What is needed instead is a differentiated selection of diagnostic approaches according to bridge type, expected deterioration mechanism, availability of reference data, and the level of engineering decision required.

Table 3 – Comparative evidence on vibration-based diagnostic indicators, serviceability interpretation, and applicability to Kazakhstan

Bridge/sample	Main indicator(s)	Key result and serviceability interpretation	Relevance for Kazakhstan
UHPC single-span bridge [9]	Natural frequency, MAC, FE updating	The difference between the updated FE and the measured first five frequencies was <5%; the minimum MAC was 90%.	Suitable for one-time assessment when a benchmark FE model is available.
195 steel girder bridges [2]	Natural frequency, deck tensile strain	Deflection alone was found insufficient; natural frequency was proposed for vibration comfort, while flexural tensile strain was proposed for deck deterioration.	Useful as a framework for separating vibration-related serviceability from structural deterioration.
Westend Bridge, Berlin (2000–2013) [6]	Frequency trends, normalized novelty index, tendon strain	Baseline was built from the first year; NI indicators increased after 2008; tendon strain changed from 85.29 to −43.99 μmm/mm. Interpretation was based on deviation from a normalized baseline.	Appropriate for strategically important bridges, but too complex for routine network-wide use.
Two retrofitted multi-span prestressed RC bridges (B1, B2) [19]	OMA, frequencies, mode shapes	AVTs used 30 min records at 2048 Hz; 6 tests for B1 and 8 for B2; identified frequencies were 2.04–6.31 Hz for B1 and 1.05–4.44 Hz for B2. Dynamic testing was used for post-retrofit verification.	Relevant for bridges after repair, strengthening, or bearing replacement.
Railway girder spans [12]	Vibration period under small impulse action	Express diagnostics is based on the response to "a person's jump"; the main criterion is the vibration period of the first mode.	Highly relevant for low-cost periodic assessment of typical beam spans.
Railway bridges under operational loads [1], [17]	First frequency or period, relative damping, midspan deformation/stress	Condition assessment is based on comparing measured dynamic and deformation parameters with those of a defect-free model.	Directly relevant to Kazakhstan because it aligns with local railway monitoring practices.

As shown in Table 3, the reviewed studies differ not only in the indicators they use, but also in the engineering logic through which vibration results are translated into serviceability decisions. This distinction is especially important for Kazakhstan, where typical beam spans, repaired bridges, and strategically important structures cannot reasonably be assessed with the same diagnostic depth.

For a large and heterogeneous bridge network, the more realistic option is not the most technologically complex SHM scenario, but periodic instrumental inspections based on a limited yet interpretable set of indicators. This logic is clearly reflected in Bondar's methodology, where express diagnostics of reinforced-concrete and steel girder railway spans is performed using a small impulse excitation and the first-mode vibration period as the main evaluation criterion [12]. This scheme does not address every diagnostic problem, but for typical beam spans, it is considerably closer to engineering reality than permanent continuous monitoring at every structure.

Local Kazakhstan-oriented publications move in a similar direction, though in a somewhat more explicitly engineering form. In studies [17], the proposed technical-condition parameters include the first natural frequency or period, the relative damping ratio, and the relative midspan deformation or stress. Condition assessment is based not on a single measured number alone, but on a comparison between field-test results and the calculated parameters of a defect-free structural model. For Kazakhstan, this appears to be one of the most practically transferable diagnostic logics: first, a rapid vibration-based inspection, then comparison with a numerical scheme, and only after that a decision on whether deeper investigation is required [1], [17].

This directly leads to the criteria for method selection. For typical short and medium beam spans, when the task is screening and identifying possible signs of stiffness loss, a rapid scheme based on the first frequency or period, with a minimal sensor set and subsequent comparison against a benchmark or analytical model, appears rational [12], [13], [17]. For strategic or already problematic bridges, where tracking of slow deterioration is critical, long-term monitoring with temperature normalization and statistical indices is justified – but only as a selective scenario, not as a universal practice for the whole network [6].

Ultimately, international experience is most transferable to Kazakhstan not as a single ready-made technology, but as a hierarchy of approaches. At the lower level, frequency or period serves as a rapid indicator of a general change in structural behavior. At the next level, mode shapes and FE modeling are added when it becomes necessary to understand not only that a deviation exists, but what it means structurally. Only at the upper level does long-term SHM with temperature normalization and statistical pattern recognition become justified, and then only where the structure truly warrants it. For local bridge practice, this three-level logic appears more realistic and useful than any attempt to force all serviceability problems into a single universal monitoring scheme.

5. Discussion

The comparative analysis shows that international experience in the vibration diagnostics of beam bridges remains methodologically heterogeneous rather than fully unified. Different practical lines coexist in the current literature, including one-time field testing, long-term vibration-based monitoring, operational modal analysis, and, more recently, indirect and AI-assisted approaches [5], [21], [22], [23], [24], [25]. At the same time, one stable pattern is evident across the reviewed studies: frequency-based interpretation and OMA-based analysis remain central to practical bridge vibration diagnostics [8]. Serviceability is rarely measured directly. In most cases, it is inferred through changes in modal parameters, stiffness-related response, or the degree of consistency between measured vibration behavior and an expected structural model [5], [26].

From an engineering perspective, vibration diagnostics should not be treated as a self-sufficient decision tool. Its main strength lies in the ability to detect and interpret changes in structural behavior under operational conditions. Its main limitation is that such changes do not always explain themselves. For this reason, the reviewed studies repeatedly show that reliable serviceability assessment requires not only vibration data, but also structural context, inspection results, and, where necessary, FE-supported interpretation [26].

This is also why the most practically useful distinction in the reviewed literature is not between traditional and advanced algorithms, but between different levels of diagnostic purpose. Some studies are aimed at rapid field screening, others at post-repair verification, and others at long-term tracking of deterioration under environmental and operational variability [5], [19]. These are not interchangeable tasks, and they should not be forced into one universal monitoring scheme. A method that is sufficient for identifying a possible change in stiffness may still be insufficient for explaining a local defect, evaluating the effect of repair, or supporting maintenance prioritization.

Indirect and AI-assisted approaches are promising, especially for rapid screening of large bridge stocks, but their current engineering role remains limited [23], [24], [25]. Indirect monitoring is operationally attractive because it reduces the need for bridge-mounted instrumentation, yet extracting bridge-specific information from vehicle responses remains sensitive to vehicle–bridge interaction and road roughness [23], [24]. Similarly, AI-based methods are likely to become more useful for serviceability-oriented bridge assessment only if they become more interpretable, more robust to incomplete and noisy field data, and more transferable across bridge types and operational conditions [25]. At present, such methods are better viewed as supplementary tools rather than as replacements for measurement-based engineering interpretation.

The reviewed studies also indicate that future progress in beam-bridge vibration diagnostics depends less on increasing data volume alone than on improving the interpretability and reproducibility of the full diagnostic chain. This includes baseline definition, resistance to environmental and operational variability, automated but controllable mode tracking, and a clearer relationship between measured dynamic response and engineering decisions [5], [25], [27], [28]. In practical terms, the main methodological challenge is not simply to detect a dynamic deviation, but to establish when that deviation is meaningful for serviceability assessment and when it is not.

Overall, the review leads to several conclusions. First, international practice does not support one universal vibration-diagnostic scheme for all beam bridges. The engineering value of vibration measurements depends not only on the identified parameters but also on how they are interpreted in relation to structural behavior, inspection findings, baseline state, and numerical modeling [5], [26]. Second, reinforced-concrete and steel beam bridges require partly different diagnostic emphases: the former are more often assessed through global stiffness-related behavior and model consistency, whereas the latter more often require environmental filtering, denser spatial interpretation, or relative-response comparison [1], [17]. Third, for bridge networks such as those considered in this article, the most realistic strategy is not universal continuous monitoring, but a selective hierarchy of approaches ranging from rapid frequency- or period-based screening to OMA- and FE-supported assessment and, where justified, long-term SHM [6], [12].

For Kazakhstan, this conclusion is particularly important. The most transferable international experience is not a single ready-made technology, but a differentiated diagnostic logic matched to the bridge type, the expected deterioration mechanism, and the required decision level [1], [17]. For typical short- and medium-beam spans, rapid instrumental assessment based on the first frequency or period may be sufficient for screening. For repaired or modified bridges, OMA combined with FE support is more appropriate. For strategically important or already problematic structures, long-term monitoring with environmental normalization may be justified, but only selectively [6], [17]. In this sense, the practical future of vibration diagnostics lies not in methodological expansion alone, but in the development of reproducible, engineering-oriented procedures that can be adapted to real bridge networks and operating conditions.

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