Periodic Ambient Vibration Testing to Evaluate Bridge Integrity: PR204 Red River Lift Span Bridge

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Abstract

In collaboration with the Ministry of Transportation and Infrastructure of Manitoba, this study presents a novel structural health monitoring (SHM) framework based on periodic ambient vibration testing (AVT) to evaluate the integrity of aging bridge infrastructure. While dynamic SHM offers significant advantages over traditional visual inspection, current approaches often struggle to localize damage or account for seasonal environmental variability. This paper addresses these limitations by utilizing high-density, synchronized wireless sensing and compares measured 3D mode shapes against a broad database of bridge typologies to enable objective damage detection and quantification. The framework was applied to the PR204 Red River Selkirk Bridge, a seven-span 90-year-old steel truss structure, through four periodic campaigns conducted between August 2024 and January 2026. Data was collected at 132 locations using high-resolution sensors to establish seasonal dynamic baselines spanning temperatures from +23°C to -23°C. The results demonstrate that 3D mode-shape analysis successfully evaluated the effectiveness of the June 2025 bottom-chord repair in Span 4 by capturing changes in its dynamic properties before and after rehabilitation. Additionally, the framework localized ongoing structural anomalies, including progressive substructure flexibility at Pier SU2, persistent fixed-bearing malfunctions in Spans 2 and 6, and localized superstructure deterioration. Conducting periodic one-day AVTs enables the tracking of structural deterioration rates over time. This provides bridge owners with data-driven insights to effectively plan for future rehabilitation or replacement. Distinguished from traditional inspections and permanent SHM systems, this approach offers a robust, scalable solution that eliminates the need for long-term installations or existing structural drawings. Ultimately, the proposed approach supports targeted maintenance and performance-based asset management, helping to extend service life and improve decision-making in bridge infrastructure management.

Keywords: Ambient vibration testing, Bridge health monitoring, Data-driven structural analysis, 3D mode shapes, Periodic testing, Repair validation, Cold-climate engineering.

Introduction

Canada's aging bridge infrastructure presents a significant asset-management challenge. Many highway bridges were constructed several decades ago and are increasingly affected by material deterioration, growing traffic demand, and severe environmental exposure[1]. Their condition has traditionally been evaluated through visual inspections, supported by assumption-based theoretical models[2,3]. Although visual inspection remains indispensable for identifying observable defects, it can be labour-intensive, subjective, and limited to accessible bridge components[4]. Its effectiveness depends on inspector judgement, inspection conditions, and physical access to the structure. These limitations are particularly relevant for bridges over water, where foundations, substructure elements, and bearing regions may be difficult to access. Numerical models can supplement inspections by estimating structural behaviour; however, their predictions depend on assumptions regarding material properties, connection behaviour, boundary conditions, and the extent of deterioration, which may differ from the actual in-service condition of an aging bridge[5,6]. Where further investigation is required, destructive testing and localized

non-destructive evaluation techniques, such as ultrasonic testing and ground-penetrating radar, may be used to characterize individual components or material conditions[7,8]. Although these methods are valuable for confirming localized defects, they generally do not provide a direct assessment of the global structural integrity and dynamic behaviour of the entire bridge system[8]. There is, therefore, a growing need for efficient, repeatable, and non-invasive techniques to evaluate the "as-is" behaviour of bridges.

Vibration-based SHM has emerged as a promising complement to conventional inspection because it enables non-destructive tracking of dynamic properties, principally natural frequencies, mode shapes, and modal damping ratios, that are related to mass distribution, boundary conditions, and structural stiffness[9,10]. Numerous studies have demonstrated the ability of AVT to extract these modal properties from operational bridge vibrations without interrupting traffic[11,12]. Static monitoring systems, including strain gauges, displacement transducers, environmental sensors, and corrosion sensors, also provide useful information but are commonly restricted to instrumented locations and can require extensive cabling, installation effort, and maintenance[13,14]. Dynamic SHM can provide a more global perspective; nevertheless, its practical application remains challenging. Reliable modal identification depends on high-resolution sensors, accurate synchronization, adequate spatial sensor density, and robust signal-processing methods[15,16,17,18]. Furthermore, dynamic parameters are influenced by environmental and operational variability, particularly temperature, and modal changes cannot always be uniquely associated with a specific physical defect without complementary engineering interpretation[19,20]. These limitations highlight the importance of periodic measurements, seasonally comparable baselines, dense three-dimensional (3D) mode-shape measurements, and quantitative indicators capable of distinguishing environmental variability from deterioration-related structural changes.

Figure 1. Lift Span Bridge on PR204 over the Red River in Selkirk, Manitoba



Accordingly, this study presents a periodic AVT framework for evaluating bridge integrity. The framework is demonstrated through a case study of a seven-span Lift Span Bridge on PR204 over the Red River in Selkirk. Recent inspection reports identified visible deterioration, including severe corrosion and perforations in the south bottom chord of Span 4, as well as missing anchor bolts at fixed bearings in Spans 2 and 6. Four AVT campaigns, comprising two summer and two winter tests, were conducted between August 2024 and January 2026 using Sensequake's Larzé sensors[21] and a dense sensing layout with 132 measurement locations (792 channels) in each test configuration. The study establishes seasonal modal baselines and compares the bridge's modal frequencies and 3D mode shapes, with particular emphasis on the dynamic response of Span 4 before and after the June 2025 repair of its south bottom chord. The

methodology combines rapid one-day field deployments, high-resolution synchronized measurements, operational modal analysis, and comparative modal indicators to assess the bridge's structural behaviour. While the primary focus is the rehabilitation assessment of Span 4, the framework also enables identification of other bridge-level anomalies, including deterioration-related support flexibility and bearing irregularities. The case study demonstrates how periodic AVT can complement visual inspection by providing objective, evidence-based information on the dynamic effectiveness of rehabilitation measures and the need for continued monitoring.

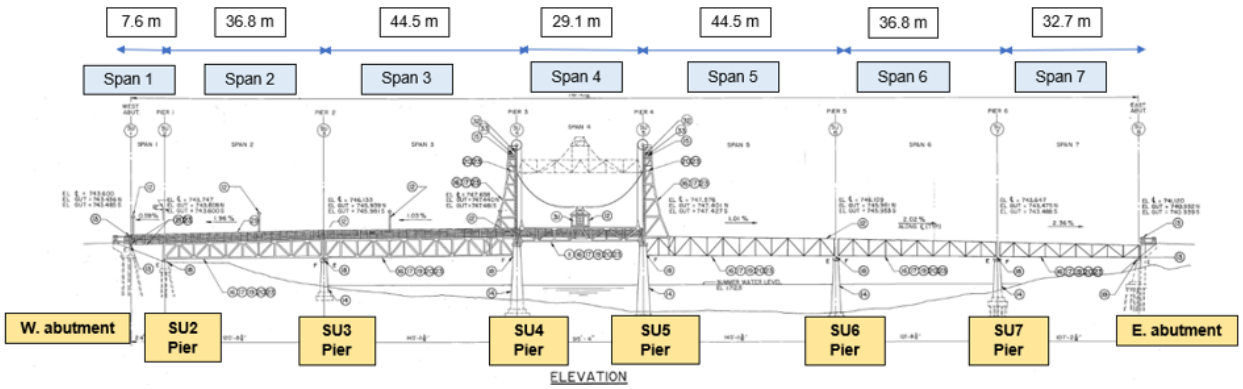
Bridge Description

Constructed in 1935, the Lift Span Bridge on PR204 over the Red River in Selkirk (hereafter, the Selkirk Bridge) carries Provincial Road 204 and crosses the Red River in Selkirk, Manitoba, Canada (**Figure 1**). The structure has a total deck length of 232 m and an overall deck width of 7.3 m, with a current posted load limit of 33 tonnes. The bridge comprises one concrete approach span (Span 1) and six steel through-truss spans (Spans 2 through 7), numbered from west to east. The substructure consists of the West Abutment (SU1), six intermediate piers (SU2 through SU7), and the East Abutment (SU8). The naming scheme illustrated in **Figure 2** and is consistently followed throughout this paper.

Span 1 is a concrete approach span between the West Abutment (SU1) and Pier SU2, with considerably higher natural frequencies (10-18 Hz) than the steel truss spans (4-14 Hz). Spans 2 and 6 share similar structural geometry and boundary conditions, as do Spans 3 and 5, enabling comparative analysis between similar spans as an internal reference for global deterioration assessment. Span 4 is a distinct intermediate span whose structural behaviour is influenced by its coupling to adjacent spans; it exhibits a unique coupled torsional mode not observed in other spans. Span 7 is the easternmost truss span.

The bearing system is central to several key findings. Spans 2 and 6, and Span 7, employ rocker-type fixed bearings at one end. A 2023 visual inspection confirmed missing anchor bolts at the fixed bearings of Spans 2 and 6. No specific bearing anomaly was reported for Span 7 during visual inspection.

Figure 2. Span and pier naming convention used throughout this study



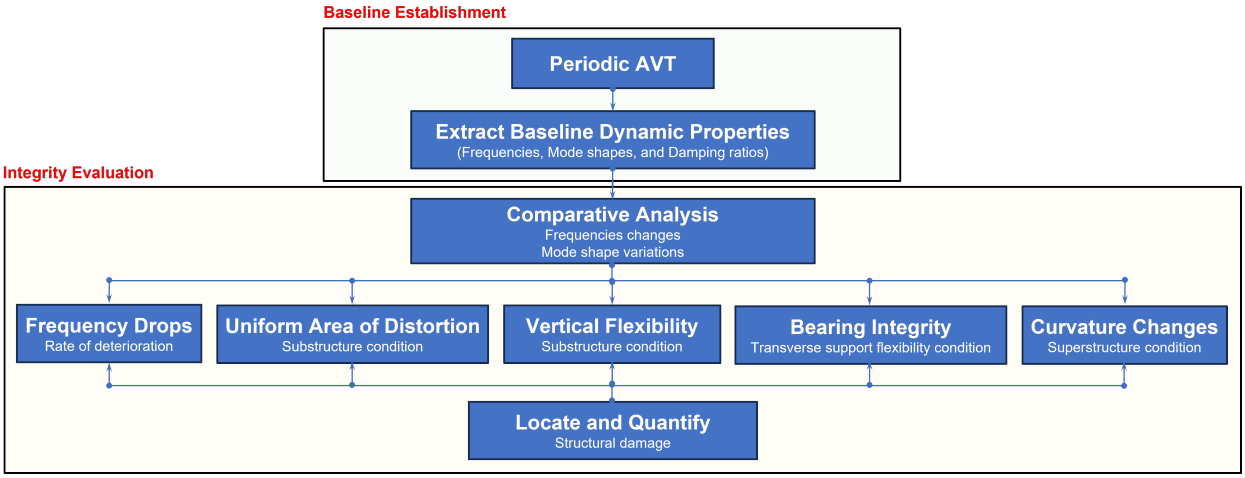
Methodology

Overview

The SHM methodology applied to the Selkirk Bridge is organized into two sequential phases, baseline establishment and integrity evaluation, as illustrated in **Figure 3**. Every AVT campaign contributes a unique

stiffness baseline for the period in which it was conducted. The scope of the integrity evaluation expands with each successive test: from Test 1 onward, mode shapes are assessed against Sensequake's proprietary database of healthy and unhealthy bridges; from Test 2 onward, comparative analysis against previously recorded baselines is added.

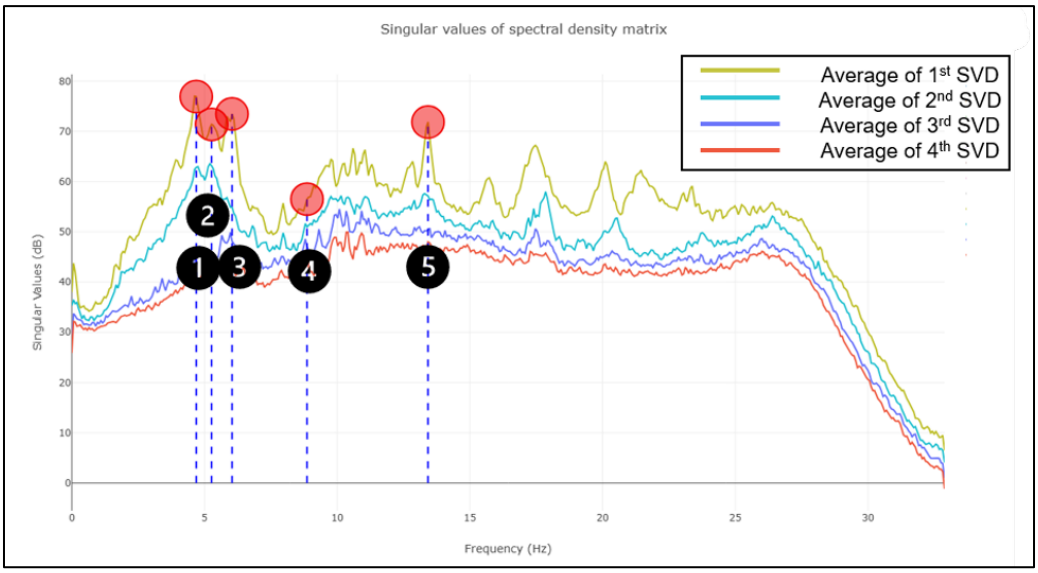
Figure 3. Periodic AVT-based baseline stiffness establishment and integrity evaluation



Baseline Establishment

Each AVT campaign established a dynamic-stiffness baseline for the Selkirk Bridge under the prevailing environmental conditions. The extracted modal properties (including natural frequencies, 3D mode shapes, and modal damping ratios) provide a dynamic signature of the bridge's global structural behaviour at the time of testing. Four baselines were established during the monitoring program: two summer baselines (Tests 1 and 3) and two winter baselines (Tests 2 and 4). These season-specific reference datasets were used to track subsequent changes in modal frequencies and mode shapes while accounting for the substantial effects of seasonal temperature variation.

Figure 4. Example SVD spectrum showing identified modal peaks for Span 2.



During each campaign, Sensequake wireless Larzé sensors were deployed at 132 locations along the outside shoulders of the bridge deck. Each sensor unit simultaneously recorded six channels, comprising translational acceleration and velocity responses along the three orthogonal axes. Data were acquired for 16 min per setup at a sampling frequency of 400 Hz, producing more than 304 million vibration data points per test. A simplified geometric 3D sensing-based model of each span was developed in Sensequake 3D-SAM™ software[22] to perform the analysis and support mode shape visualization.

Both frequency-domain Singular Value Decomposition (SVD) of cross-spectral matrices[23] and time-domain Stochastic Subspace Identification (SSI) [24] were used to identify the natural frequencies, 3D mode shapes, and damping ratios of each of the seven spans. Only modes independently identified by both methods were retained for further analysis. The accepted modes were additionally screened using modal assurance criterion (MAC), damping-range, mode-shape-quality, and real-portion criteria to ensure consistency and reliability of the extracted dynamic properties. **Figure 4** illustrates the identified modes (Span 2, Test 4) using a combination of frequency-domain SVD and time-domain SSI.

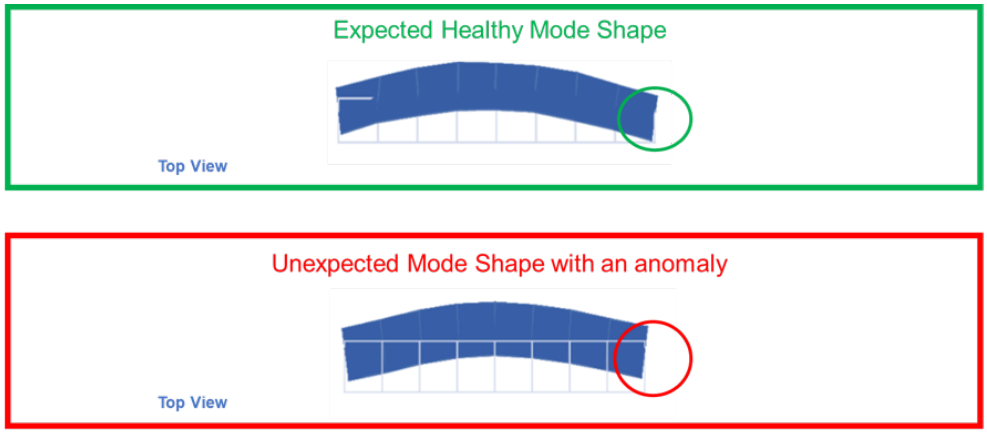
Integrity Evaluation

Database Comparison

From the first test onward, an integrity evaluation is performed by comparing the extracted mode shapes against Sensequake's database of healthy and unhealthy bridge baselines. This database, developed from a comprehensive collection of bridges encompassing a wide range of structural systems, span lengths, support configurations, construction materials, ages, and documented condition states, establishes the expected dynamic behavior and mode-shape geometries for common bridge typologies. Three categories of mode shape anomaly are evaluated:

- Fixed bearing anomalies (**Figure 5**): identified by excessive transversal displacement at the nominally fixed end of a span in the first transversal mode. In a well-functioning fixed bearing, transversal movement at that support should be minimal.

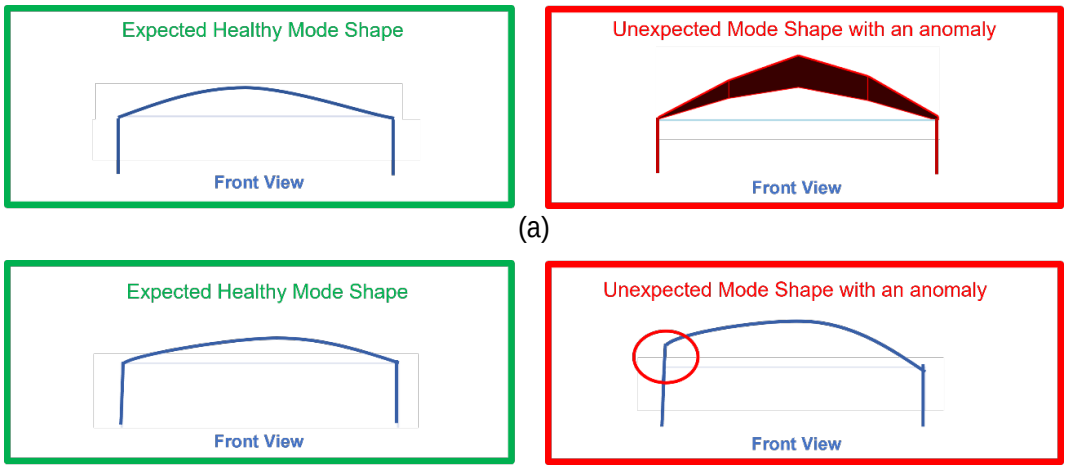
Figure 5. Healthy and unhealthy mode shape examples: bearing conditions



- Substructure anomalies (**Figure 6**): identified from vertical mode shapes through (i) localized vertical flexibility at pier-to-deck interfaces: deviations from the smooth, continuous curvature expected in a healthy support system and (ii) uniform distortion, expressed as non-symmetric bow-like deflection. These indicators can reflect reduced support stiffness associated with

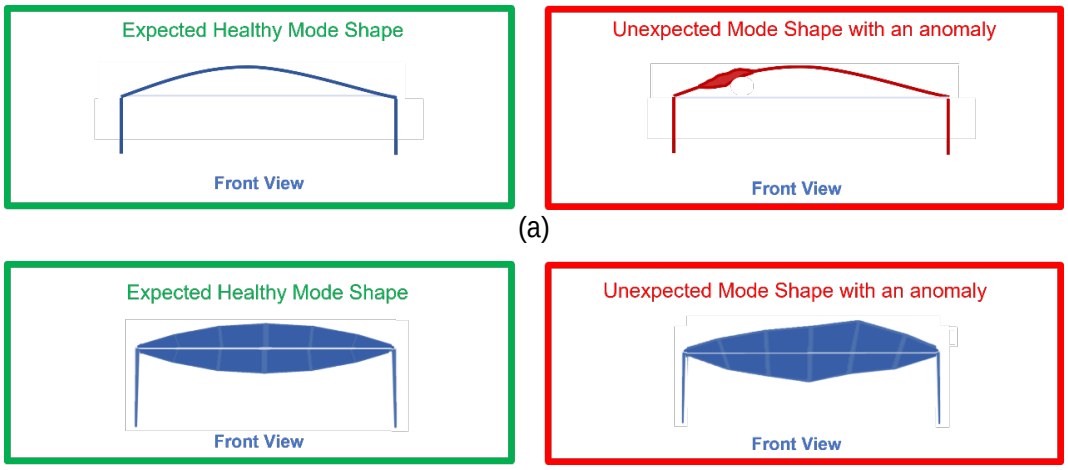
foundation degradation, pier deterioration, or unstable soil conditions; the distorted region may be quantified using its normalized area and evaluated against baseline-database thresholds.

Figure 6. Healthy and unhealthy mode shape examples, substructure conditions: (a) vertical flexibility and (b) uniform area of distortion



- Superstructure anomalies (**Figure 7**): identified by changes in curvature (asymmetric wave-like deformation) within torsional and vertical modes, associated with local stiffness loss in truss members, bracing, or connections.

Figure 7. Healthy and unhealthy mode shape examples — superstructure conditions in: (a) vertical mode and (b) torsional mode.



Anomalies are classified by type, mapped to their physical location on the bridge, and interpreted in terms of the likely structural cause. This comparisons with the data were conducted from Test 1 without requiring any prior test on the same bridge.

Periodic Comparative Analysis

Beginning with Test 2, comparative analysis against previously recorded baselines is added to the integrity evaluation. This introduces two parallel streams of evidence, frequency changes and mode shape variations, as shown in the lower portion of the methodology flowchart (**Figure 3**).

Frequency Comparison

Natural frequencies are sensitive to ambient temperature: structural bearing interfaces and soil-structure contact zones stiffen under freezing conditions, producing elevated winter frequencies relative to summer values. This thermal sensitivity means that direct frequency comparisons are only valid between tests conducted in the same season:

- Summer-to-summer comparisons: Test 1 (+20°C) vs. Test 3 (+23°C).
- Winter-to-winter comparisons: Test 2 (−7°C) vs. Test 4 (−23°C).

Cross-season comparisons are used only qualitatively, to identify departures from expected seasonal behaviour. An acceptable inter-test frequency variation is defined as ±2%; drops exceeding this threshold in same-season comparisons are flagged as indicators of structural deterioration and, starting from Test 3, can be used to quantify the rate of stiffness loss over time.

Mode Shape Comparison

Mode shapes are relatively insensitive to temperature variations and can therefore be compared across all seasons and between any pair of tests, starting from Test 2 onward. Mode shape comparisons enable three classes of structural anomaly to be identified, localized, and quantified: fixed bearing anomalies, substructure anomalies (vertical flexibility and uniform area of distortion), and curvature changes.

Together, these four indicators enable structural damage to be located and quantified throughout the bridge, as shown at the base of the methodology flowchart (**Figure 3**).

Structural Health Triage

At the conclusion of each test's integrity evaluation, a structural health triage is compiled for the bridge's three component systems (substructure, superstructure, and bearings) using a five-level colour scale: Dark Red (severe deterioration; immediate rehabilitation required), Red (high deterioration; short-term action required), Orange (moderate deterioration; monitor and include in next rehabilitation cycle), Yellow (early deterioration trend; monitor in upcoming tests), and Green (no significant anomaly detected). The triage maps deterioration findings onto the bridge's physical components, providing an integrated condition overview that evolves with each successive test.

Results and Discussion

The results are presented following the proposed periodic AVT framework. First, the baseline establishment process is discussed from the four measurement campaigns. The general integrity evaluation is then presented through comparisons of seasonal modal properties, together with frequency- and mode-shape-based indicators used to identify and localize potential anomalies in the bridge bearing, substructure, and superstructure systems. Finally, particular emphasis is placed on Span 4, where the dynamic properties measured before and after the June 2025 south bottom-chord rehabilitation are compared to evaluate the influence of the repair on the span’s torsional and transverse behaviour.

Baseline Establishment

The baseline dynamic properties of the bridge were identified using complementary frequency-domain and time-domain modal-identification techniques. Three to five vibration modes were successfully extracted for each span in each test, including vertical, transverse, and torsional modes.

Natural Frequencies

The identified natural frequencies for all four AVT campaigns are summarized in **Table 1**. For most spans and modes, winter frequencies were higher than their summer counterparts, consistent with the expected increase in apparent stiffness under freezing conditions. Therefore, structural integrity of the bridge was conducted primarily through same-season comparisons, Summer 1 (Test 1) versus Summer 2 (Test 3) and Winter 1 (Test 2) versus Winter 2 (Test 4), to minimize the influence of temperature.

Table 1. Identified natural frequencies (Hz)

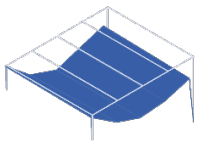
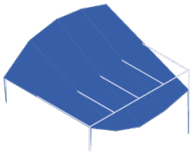
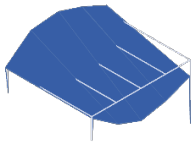
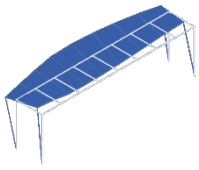
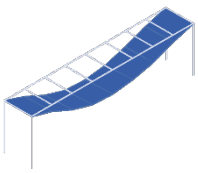
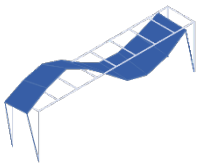
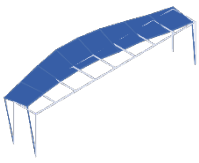
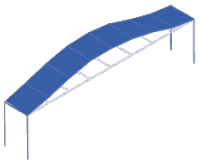
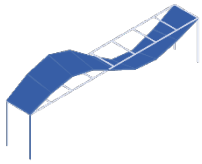
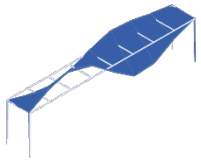
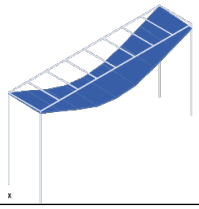
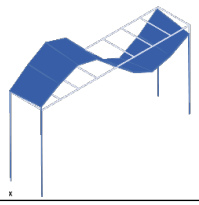
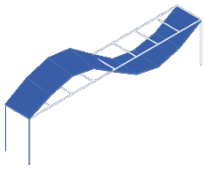
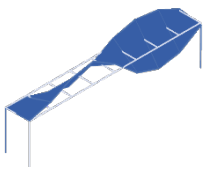
Span	Mode type	Test 1 (+20°C)	Test 2 (–7°C)	Test 3 (+23°C)	Test 4 (–23°C)
1	1st Vertical	10.24	12.11	10.13	12.75
	1st Torsional	11.26	15.22	11.37	15.28
	1st Torsional	14.20	17.36	14.27	17.92
2	1st Transversal	3.93	4.78	3.96	5.29
	1st Vertical	4.36	4.65	4.42	4.66
	1st Torsional	5.77	5.93	5.82	6.03
	2nd Vertical	8.52	8.77	8.66	8.87
	2nd Torsional	12.96	13.29	13.03	13.41
3	1st Transversal	3.67	4.27	3.65	4.73
	1st Vertical	4.06	4.18	4.09	4.23
	1st Torsional	5.16	5.54	5.48	5.88
	2nd Vertical	8.81	8.68	8.77	8.86
	2nd Torsional	12.37	12.43	12.34	12.58
4	1st Vertical	3.86	4.21	3.90	4.33
	Coupled Torsional	5.95	5.56	5.92	5.77
	2nd Vertical	8.99	10.60	8.81	11.03
5	1st Transversal	3.55	4.06	3.45	4.53
	1st Vertical	3.79	4.00	3.82	4.13
	1st Torsional	5.11	5.25	5.13	5.80
	2nd Vertical	8.59	8.75	8.57	8.85
	2nd Torsional	11.51	11.66	11.56	12.49
6	1st Transversal	3.98	4.80	3.99	5.13
	1st Vertical	4.23	4.51	4.27	4.61
	1st Torsional	5.78	5.90	5.81	6.01
	2nd Vertical	9.71	10.91	9.79	11.16

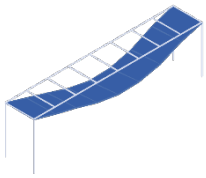
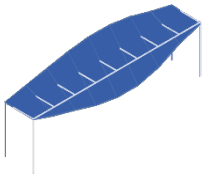
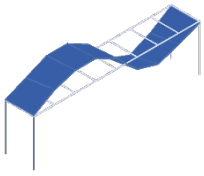
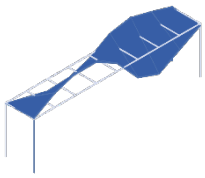
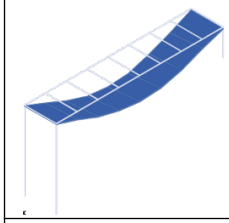
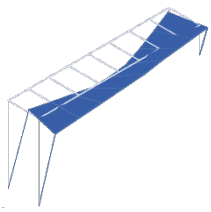
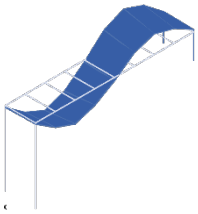
	2nd Torsional	12.93	13.24	12.81	13.37
7	1st Vertical	4.87	5.87	4.89	5.99
	1st Transversal	4.55	4.63	4.56	4.74
	1st Torsional	6.08	6.14	6.04	6.17
	2nd Vertical	11.05	11.34	11.13	11.41
	2nd Torsional	13.68	13.77	13.59	13.66

Mode Shapes

The mode-shapes associated with the identified frequencies are summarized in **Table 2**. Three modes were identified for Spans 1 and 4, while five were extracted for the remaining spans across all tests.

Table 2. Extracted mode shapes of Selkirk Bridge

Spans	Modes				
	1	**2**	**3**	**4**	**5**
1				–	–
	1st Vertical	1st Torsional	1st Torsional		
2					
	1st Transversal	1st Vertical	1st Torsional	2nd Vertical	2nd Torsional
3					
	1st Transversal	1st Vertical	1st Torsional	2nd Vertical	2nd Torsional
4				–	–
	1st Transversal	1st Vertical	1st Torsional		
5					
	1st Transversal	1st Vertical	1st Torsional	2nd Vertical	2nd Torsional

6					
	1st Transversal	1st Vertical	1st Torsional	2nd Vertical	2nd Torsional
7					
	1st Vertical	1st Transversal	1st Torsional	2nd Vertical	2nd Torsional

Structural Integrity Evaluation

Frequency Variations

In general, Winter frequencies were generally higher than summer frequencies as freezing conditions can increase apparent structural stiffness, particularly at supports and soil–structure interfaces. Accordingly, same-season comparisons (Test 1 versus Test 3 and Test 2 versus Test 4) were used to assess potential structural changes, with variations greater than approximately ±2% considered for further evaluation using the corresponding 3D mode shapes.

As demonstrated in **Table 1**, Span 1 exhibited the greatest seasonal variation: its first vertical frequency increased from approximately 10.2 Hz in summer to 12.8 Hz in winter. This response is attributed to winter stiffening at the West Abutment and Pier SU2, likely associated with freezing at the soil–structure interface. Nevertheless, summer frequencies remained within ±2% between Test 1 and Test 3, indicating no substantial global stiffness change during that period. Spans 2 and 6, which have comparable geometry and structural configurations, showed closely matched frequencies throughout the monitoring program and similarly stable summer responses. In contrast, Span 5 consistently exhibited lower frequencies than the geometrically comparable Span 3. Its first transversal mode decreased from 3.55 Hz in Test 1 to 3.45 Hz in Test 3, exceeding the ±2% criterion and indicating a potential progressive reduction in stiffness.

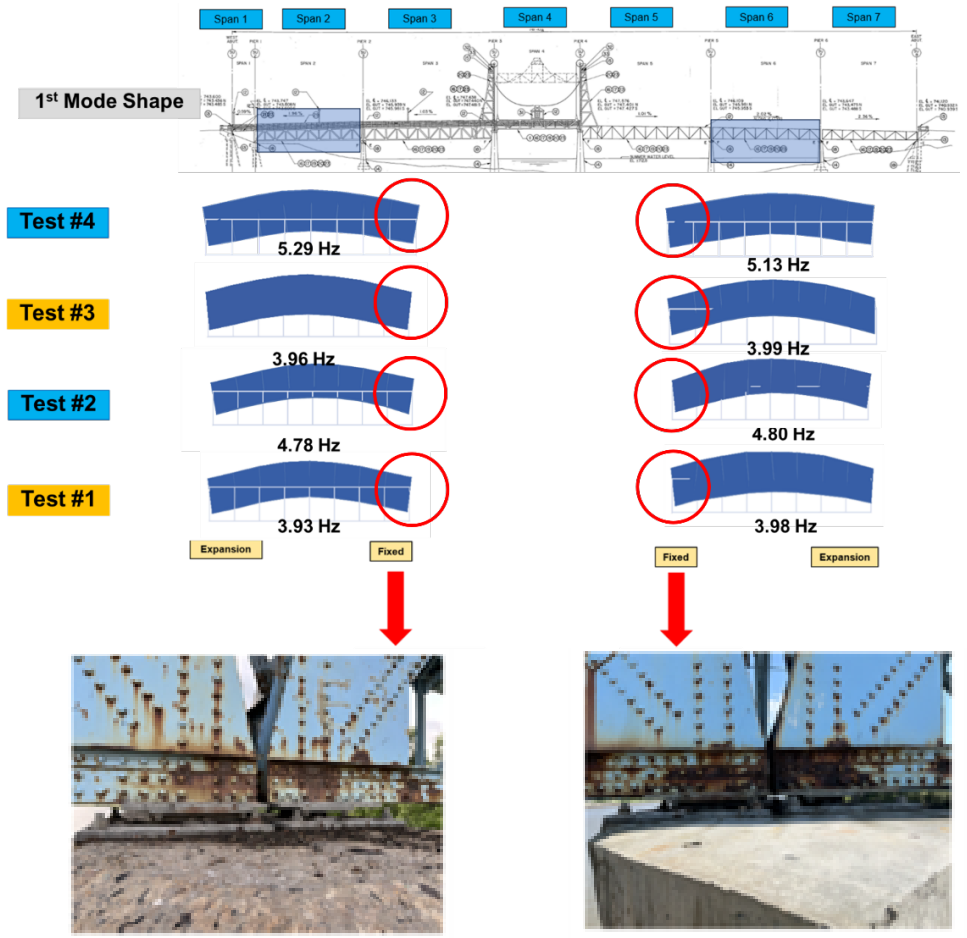
Span 4 produced the most notable frequency anomaly. Its coupled torsional mode decreased from 5.95 Hz in Test 1 to 5.56 Hz in Test 2, contrary to the generally higher winter frequencies observed elsewhere on the bridge. Following the June 2025 repair, the mode increased to 5.92 Hz in Test 3; however, its winter value in Test 4 remained relatively low at 5.77 Hz. Together with the mode-shape results, this behaviour indicates that the repair improved the response of Span 4 but did not fully restore its torsional and transverse stiffness. Detailed analysis and observations of these results are provided in the subsequent sections of this paper.

Bearing Condition Assessment

In all four tests, excessive transversal flexibility was identified at the fixed bearing end of Spans 2, 6, and 7. **Figure 8** shows the bearing anomality observed in Spans 2 and 6; the same was observed for Span 7. This indicates that the fixed bearings are not restraining lateral movement as intended. Visual inspection

confirmed missing anchor bolts at Spans 2 and 6, consistent with dynamic observations. For Span 7, no visual anomaly was recorded, but the bearing anomaly was consistently flagged across all four AVT campaigns, demonstrating the diagnostic value of vibration testing beyond visual inspection.

Figure 8. Fixed bearing anomalies: transversal flexibility at fixed support end, Mode 1 for Spans 2 and 6



Typical SU3 bearing

Typical SU6 bearing

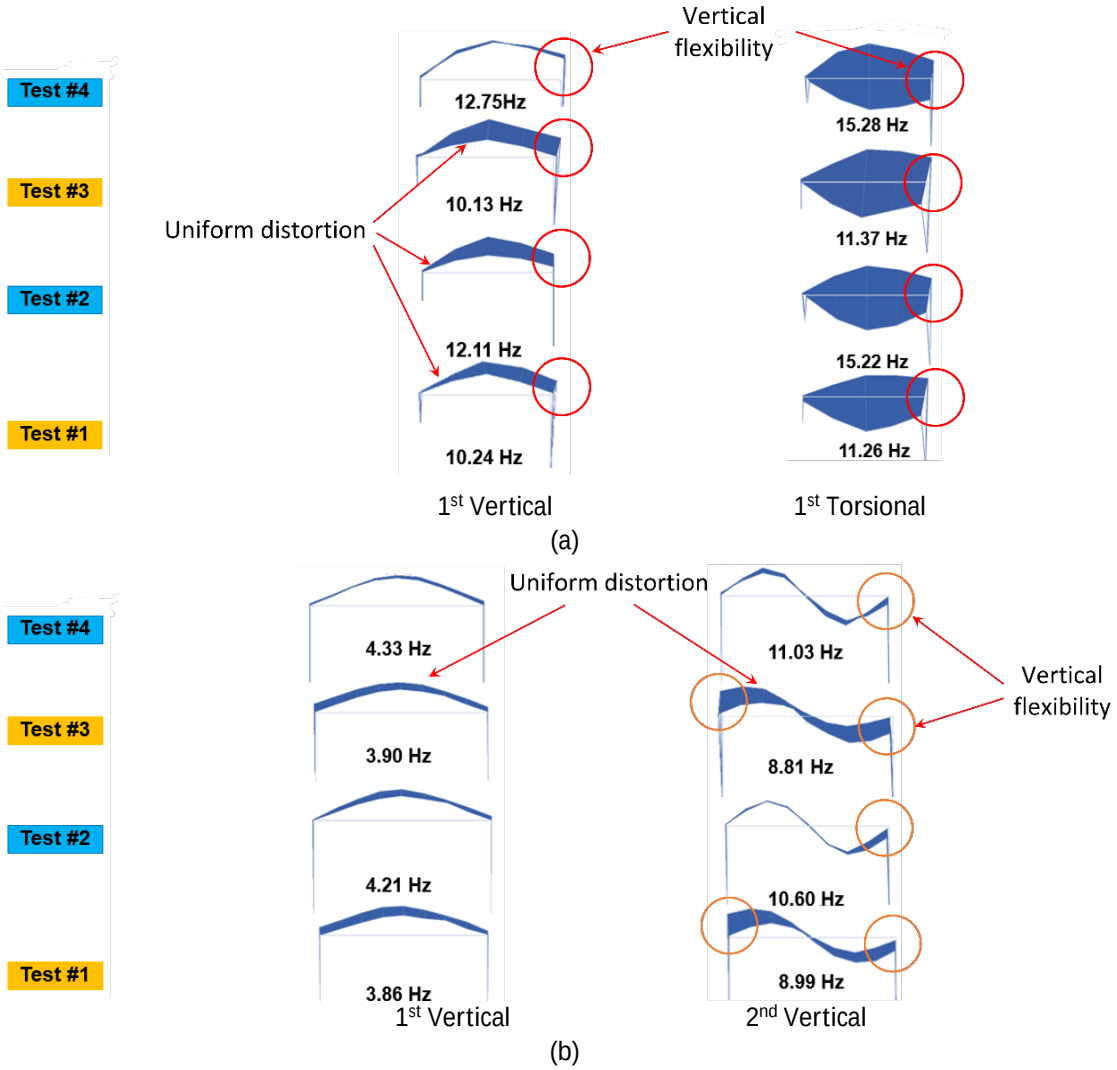
Substructure Condition Assessment

Uniform distortion was observed in the vertical mode shapes of several spans, indicating potential deterioration of their supporting systems. In Span 1, the distortion pattern was associated with deterioration at the West Abutment and Pier SU2. Similar distortion was consistently observed in the second vertical modes of Spans 2, 3, 5, and 6 throughout the four tests, suggesting deterioration at intermediate pier supports. Span 4 exhibited uniform distortion in both its first and second vertical modes, indicating potential deterioration associated with Pier SU5.

The utility of these mode-shape indicators is demonstrated in **Figure 9**, where Spans 1 and 4 serve as representative cases of substructure-related anomalies. In both spans, the vertical and torsional modes exhibit a vertical flexibility at the supports and a non-symmetric "bow-like" deflection, visually confirming the localized stiffness loss identified. These visualizations highlight how the high-resolution 3D mode

shapes effectively localize supporting-system deterioration that might otherwise be obscured in global frequency-only analysis.

Figure 9. Substructure anomalies: (a) vertical flexibility and uniform distortion in Span 1 and (b) vertical flexibility and uniform distortion in Span 4, across Tests 1, 2, 3, and 4



Superstructure Condition Assessment

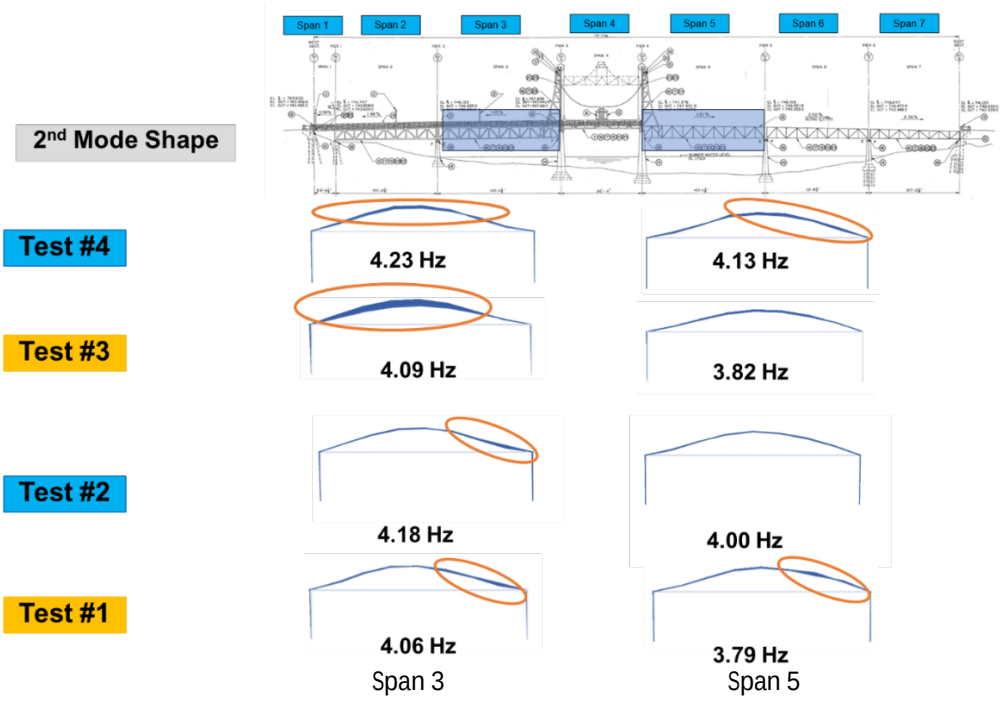
Minor changes in curvature were identified in the first vertical and second torsional modes of Spans 2, 3, 5, 6, and 7 in all four tests. These curvature changes indicate local stiffness reductions in truss members, bracing, and connections. The utility of these mode-shape indicators is demonstrated in **Figure 10**, where Spans 3 and 5 showed curvature changes in their 1st vertical mode and 2nd torsional modes.

Effect of Bottom-Chord Rehabilitation on the Dynamic Behaviour of Span 4

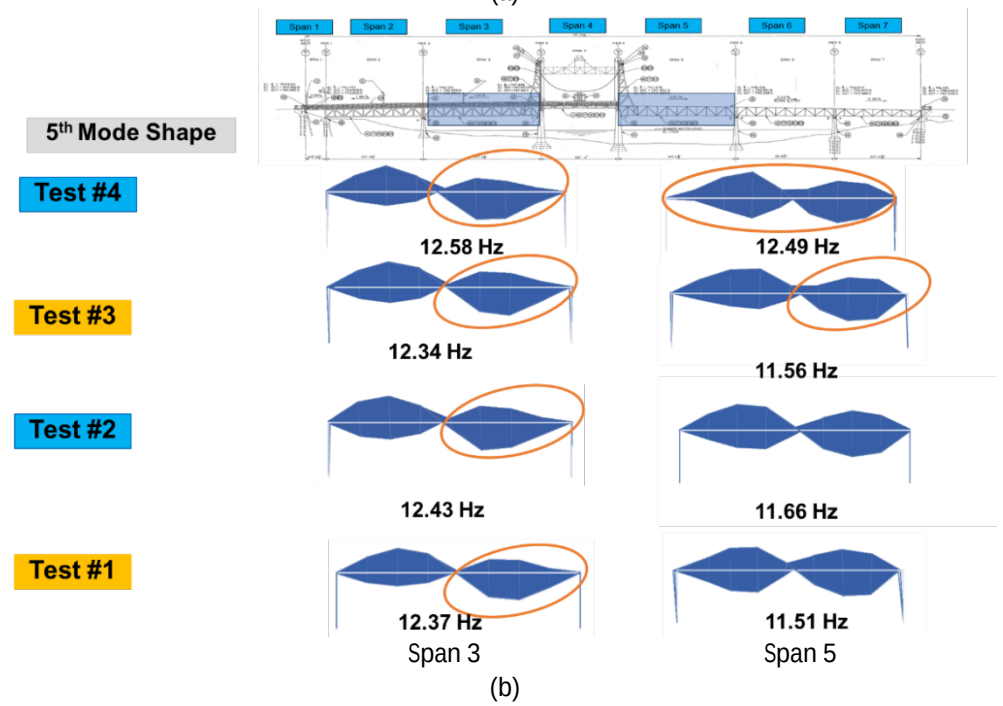
The effect of the rehabilitation completed on the south bottom chord of Span 4 was evaluated using the coupled torsional mode, which was identified as particularly sensitive to the transverse and torsional

response of the span. The repair, completed on June 4, 2025, consisted of bolted steel plate splices installed at the deteriorated bottom-chord region (**Figure 11**). Its effectiveness was assessed by comparing the dynamic properties obtained before the repair (Tests 1 and 2) with those obtained after the repair (Tests 3 and 4), while maintaining separate summer-to-summer and winter-to-winter comparisons to account for seasonal effects.

Figure 10. Superstructure anomalies, local curvature in Spans 3 and 5 in: (a) 1st vertical mode and (b) 2nd torsional mode across Tests 1, 2, 3, and 4



(a)



(b)

Figure 11. Bolted steel plate splices added to the south bottom chord, Span 4



Frequency Response Before and After Repair

Table 3 summarizes the modal frequencies identified for Span 4 during the four AVT campaigns. The first and second vertical modes exhibited the expected increase in frequency during winter testing, reflecting the influence of colder temperatures and altered boundary conditions. For the first vertical mode, the summer frequency changed slightly from 3.86 Hz in Test 1 to 3.90 Hz in Test 3, while the winter frequency increased from 4.21 Hz in Test 2 to 4.33 Hz in Test 4, corresponding to a 2.8% winter-to-winter variation. Similarly, the second vertical mode changed from 8.99 Hz to 8.81 Hz between the two summer tests and increased from 10.60 Hz to 11.03 Hz between the winter tests. The respective summer and winter variations were −2.0% and 4.0%. These changes indicate that the vertical response of Span 4 remained sensitive to seasonal environmental and boundary-condition effects.

Table 3. Natural frequency of Span 4 before and after bottom-chord rehabilitation

Mode	Type	Test 1 (20°C)	Test 2 (−7°C)	Test 3 (23°C)	Test 4 (−23°C)	Summer Diff. (%)	Winter Diff. (%)
1	1st Vertical	3.86	4.21	3.90	4.33	1.0%	2.8%
2	Coupled Torsional	5.95	**5.56**	5.92	**5.77**	-0.5%	3.7%
3	2nd Vertical	8.99	10.60	8.81	11.03	-2.0%	4.0%

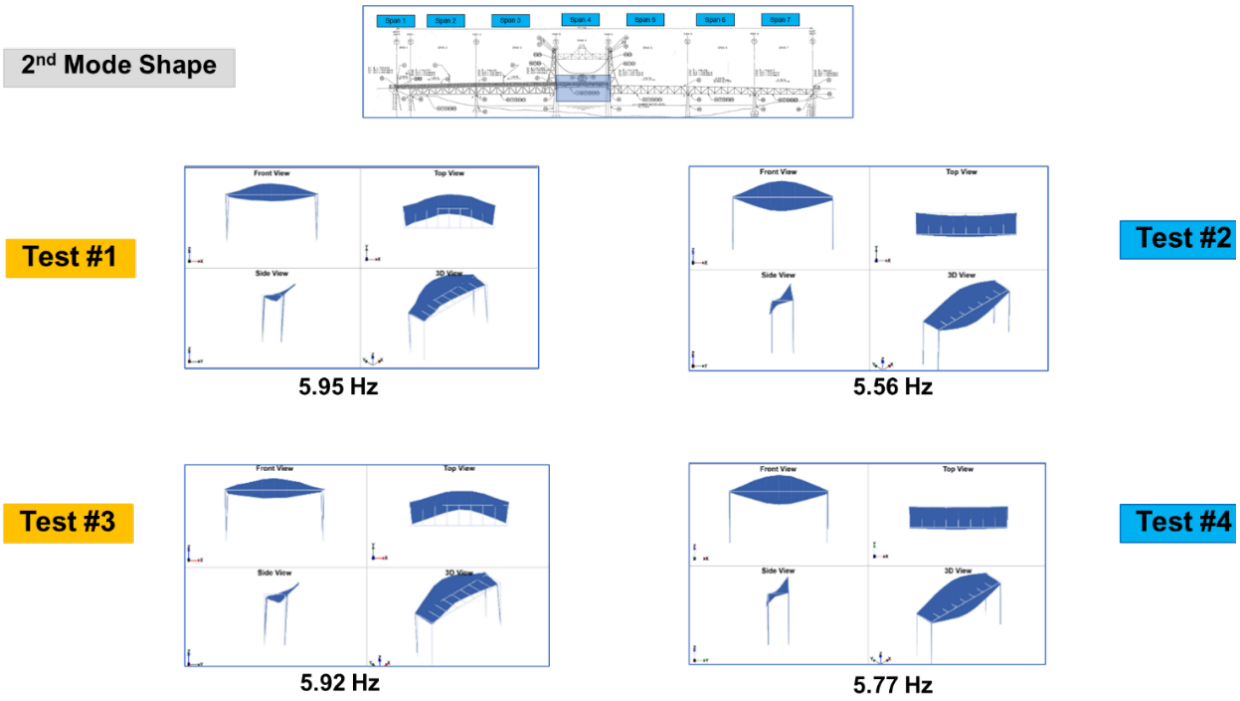
In contrast, the coupled torsional mode (Mode 2) exhibited a different and more critical response. Before rehabilitation, its frequency decreased from 5.95 Hz in Summer 2024 (Test 1) to 5.56 Hz in Winter 2025 (Test 2), contrary to the frequency increase generally expected under colder conditions. Together with the associated mode-shape anomaly, this response indicated reduced torsional and transverse stiffness and was consistent with the severe deterioration subsequently observed in the south bottom chord. Following the June 2025 rehabilitation, the summer frequency increased to 5.92 Hz in Test 3, closely matching the pre-repair summer value and indicating that the bolted steel plate splices improved the dynamic response of the span. However, the Mode 2 frequency in Winter 2026 was measured at 5.77 Hz, remaining below the summer values: unlike the two other modes, whose frequencies increased. These

results indicate that, although the repair has partially improved the span, its torsional and transverse stiffness behaviour was not fully stabilized under cold-weather conditions.

Mode-Shape-Based Evaluation of Repair Effectiveness

Figure 12 compares the coupled torsional mode shape of Span 4 for the four AVT campaigns. Before rehabilitation, the mode shape exhibited an asymmetric transverse response, with substantially lower transverse flexibility during the first winter test. Following the repair, the Mode 2 shape obtained in Test 3 became more symmetric and was accompanied by recovery of the corresponding summer frequency. Together, these changes provide evidence that the repair positively influenced the stiffness distribution and torsional response of the span.

Figure 11. Span 4 Mode 2 (Coupled torsional) comparison across Tests 1, 2, 3, and 4



Nevertheless, Test 4 showed that the winter mode shape continued to exhibit reduced transverse flexibility relative to the summer tests. This persistent seasonal asymmetry, combined with the lower Mode 2 frequency in winter, indicates that the repair did not fully restore the expected torsional and transverse stiffness behaviour of Span 4. This interpretation is also consistent with the visual inspection findings (**Figure 13**), which documented severe corrosion, deformation, and perforations in other bottom-chord regions beyond the repaired location. These observations indicate that despite the localized repair, structural deterioration remained. Together, the persistent anomalous frequency response, mode shape change, and the sparse visual evidence confirm that while the bolted plate splices addressed a critical section, they were insufficient to fully restore the global torsional and transverse stiffness of the span.

Integrity-Evaluation Implications

The results from Span 4 demonstrate the critical value of seasonal periodic AVT for the evaluation of structural repairs. While the recovery of summer frequencies and improved modal symmetry in Test 3 confirmed a measurable improvement in the span's dynamic response, the subsequent winter test (Test 4) identified persistent anomalous behavior that would have been entirely overlooked by a single post-repair campaign. This highlights that seasonal periodic AVT serves as an essential diagnostic tool to distinguish between temporary improvements and full structural restoration, providing bridge owners with the actionable evidence needed to justify continued monitoring or targeted intervention.

Figure 13. Anomalies of the bottom chord of Span 4 during visual inspection



Span 4, Bottom chord. Note: typical very severe corrosion on bottom angles.



Span 4, Bay 4, South truss. Note: perforations in bottom angles.



Span 4, vertical gusset plate at bottom chord. Note: typical severe corrosion.

Structural Health Triage

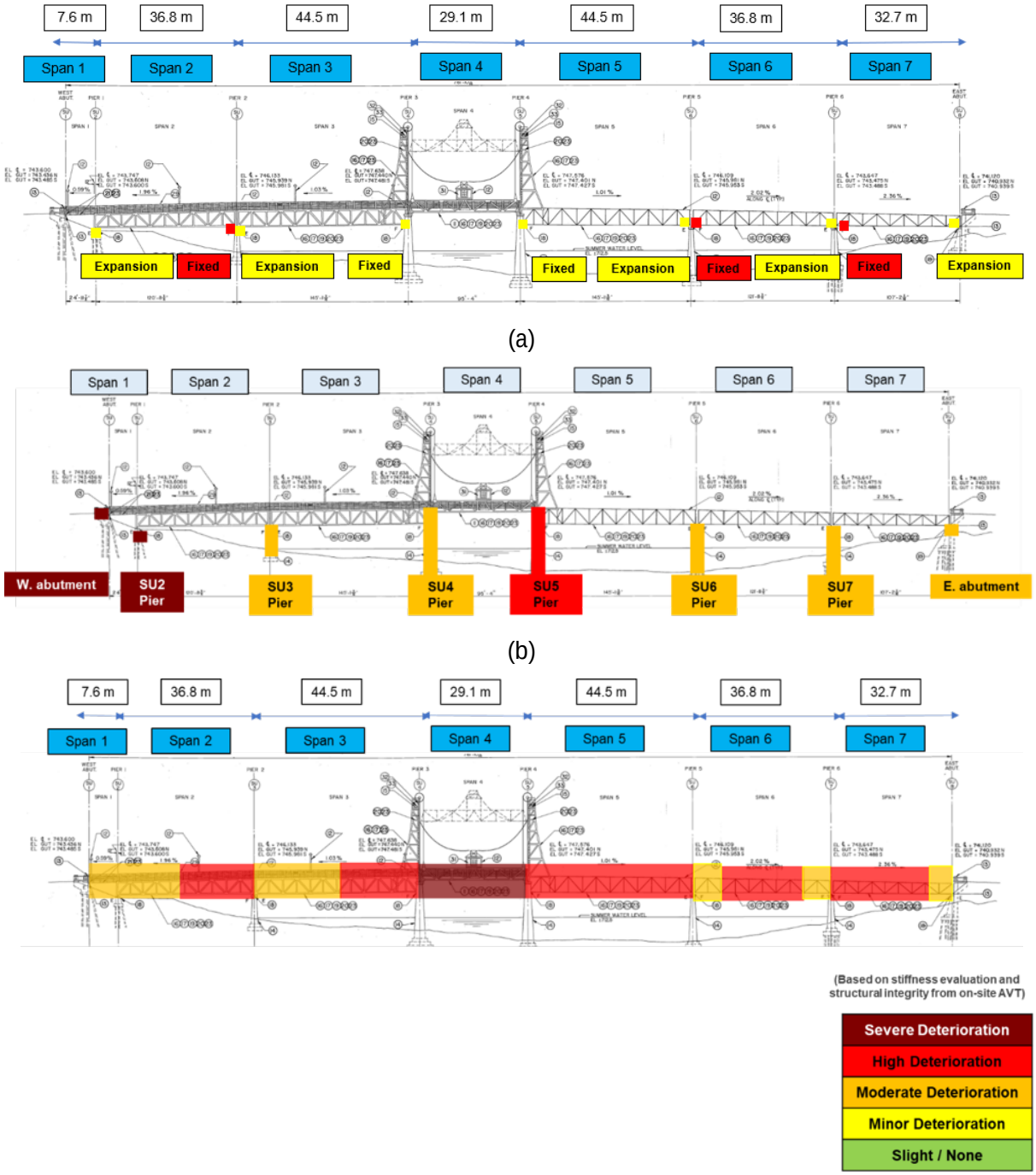
Following the periodic AVT campaign, a structural-health triage was compiled for the substructure, superstructure, and bearing systems based on the measured dynamic response, including frequency trends, 3D mode-shape distortions, and normalized mode-shape areas.

For the bearing system, the nominally fixed bearings at Spans 2, 6, and 7 were classified as Red (**Figure 14a**). Their 3D mode shapes repeatedly exhibited excessive transverse flexibility, indicating insufficient lateral restraint. The interpretation for Spans 2 and 6 is supported by visual-inspection observations of missing anchor bolts, while the result for Span 7 identifies a bearing-related concern requiring further detailed assessment.

For the substructure, the West Abutment was classified as Dark Red, reflecting the critical condition indicated by the normalized modal area below 0.70 (**Figure 14b**). Pier SU2 was also classified as Dark Red because of persistent excessive vertical flexibility in Span 1 and evidence of worsening support behaviour. Pier SU5 was classified as Red, based on consistent stiffness-related indicators in the adjacent spans, particularly Spans 4 and 5. The intermediate piers and East Abutment were classified as Orange, indicating moderate deterioration requiring continued observation and targeted inspection.

From the superstructure, Span 4 was classified as Dark Red because its coupled torsional mode continued to show an abnormal winter response following the bottom-chord repair, indicating that its torsional and transverse stiffness had not been fully restored (**Figure 14c**). Span 5 was classified as Red due to its lower frequencies relative to the comparable Span 3 and persistent curvature changes in its mode shapes. Spans 2, 3, 6, and 7 were classified as Red because of recurring localized mode-shape curvature changes consistent with stiffness reductions in truss members, bracing, or connections.

Figure 14. Structural health triage: (a) bearings, (b) substructure, and (c) superstructure



Conclusions

This study presented a novel dynamic SHM framework, based on a periodic AVT, for evaluating the integrity of aging bridges using dense, synchronized wireless sensing and operational modal analysis. The methodology was demonstrated through four test campaigns on the seven-span PR204 Red River Selkirk

Bridge, conducted under summer and winter conditions between August 2024 and January 2026. During each one-day campaign, 132 high-resolution sensors, each recording six channels, were deployed to capture the bridge's full 3D dynamic behavior, utilizing complementary frequency- and time-domain modal identification methods.

A principal advantage of the framework is its use of periodic, high-resolution measurements to establish season-specific dynamic-stiffness baselines. This is particularly important in cold-climate regions, where modal frequencies and support behaviour can vary substantially because of temperature, frozen bearing interfaces, and ice-induced changes. Accordingly, structural changes should be evaluated primarily through same-season comparisons, while 3D mode shapes provide spatial information for locating anomalies and assessing their structural significance. Applied to the PR204 Red River Selkirk Bridge, the framework evaluated the structure in its actual in-service condition without requiring permanent instrumentation or complete structural drawings, enabling the identification of bearing-related flexibility, substructure distortion, localized superstructure anomalies, and changes in dynamic properties associated with rehabilitation.

A key application of this general integrity-evaluation approach was the assessment of the June 2025 rehabilitation of the south bottom chord in Span 4. The coupled torsional mode provided a sensitive indicator of the span’s torsional and transverse stiffness: the post-repair summer test showed recovery of the Mode 2 frequency and improved modal symmetry following installation of the bolted steel plate splices. However, the subsequent winter test identified a persistent anomalous response, as the coupled torsional-mode frequency remained below its summer values, unlike the vertical modes. Together with the persistent mode-shape anomaly and the severe corrosion, deformation, and perforations observed elsewhere in the bottom chord, these results indicate that the repair improved the dynamic response of Span 4 but did not fully restore its torsional and transverse stiffness behaviour.

Unlike traditional inspections or alarm-based SHM systems, the proposed one-day periodic AVT framework provides detailed, actionable diagnostics through rapid wireless deployment, dense 3D modal measurements, season-specific baselines, and repeatable operational modal analysis. This approach is particularly valuable in cold-climate regions, where same-season comparisons help distinguish structural changes from temperature-, freezing-, and ice-related variability. It enables infrastructure owners to target inspections, track deterioration, evaluate rehabilitation effectiveness, and prioritize maintenance actions, thereby supporting proactive, data-driven life-cycle management of aging bridge networks.

Declaration of Conflicting Interests

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