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Using Structural Health Monitoring Data for Predictive Maintenance of Reinforced Concrete Bridges: A Case Study of Edion and Orle Bridges

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ABSTRACT

Structural Health Monitoring (SHM) has emerged as a critical tool for assessing the condition of reinforced concrete bridges and guiding predictive maintenance strategies. This study presents an investigation of two bridges along the Auchi–Benin Expressway, Edion and Orle, based on vibration analysis, crack assessment, deflection measurement, environmental monitoring, and traffic evaluation. The Edion Bridge demonstrated a 14% reduction in modal frequency, an increase in damping ratio from 1.81% to 2.62%, and an RMS velocity increase from 0.45 mm/s to 0.59 mm/s, along with crack widths of 0.28–0.35 mm. Conversely, the Orle Bridge maintained relatively stable vibration characteristics, minimal crack development (<0.06 mm), and satisfactory elastic recovery under service loads. These results indicate early-stage deterioration at Edion Bridge and satisfactory structural performance at Orle Bridge. The findings underscore the importance of continuous SHM and data-driven predictive maintenance for reinforced concrete bridges to optimize safety, serviceability, and lifecycle cost.

1. INTRODUCTION

Reinforced concrete (RC) bridges form essential components of modern transportation networks and remain continuously exposed to traffic loads, temperature variations, and environmental deterioration. As these structures age, stiffness loss, microcracking, reinforcement corrosion, and progressive fatigue can compromise safety and long-term serviceability. Traditional inspection techniques, though widely used, often fail to detect subsurface or early-stage deterioration, leading to delayed intervention and costly repairs. The transition from reactive inspection to proactive structural health monitoring (SHM) has therefore emerged as a preferred strategy for maintaining RC bridge decks (Li *et al.,* 2023; Hasani & Freddi, 2023).

SHM systems combine vibration analysis, crack assessment, deflection monitoring, environmental tracking, and traffic characterization to evaluate structural behavior under operational conditions. These data-driven approaches align with international guidelines such as FHWA (2020), ACI 224R (2001), ISO 13374 (2020), and Eurocode EN 1992-1-1 (2004), which emphasize predictive maintenance and continuous performance assessment. Two bridges (Edion and Orle) along the Benin-Auchi expressway Aviele axis of Etsako West local government area of Edo State, were selected for SHM deployment due to visible surface distress and dynamic anomalies consistent with early deterioration.

2. LITERATURE REVIEW

Recent research emphasizes vibration-based monitoring, crack propagation detection, and environmental coupling in early deterioration assessment of RC bridges. Zhang *et al.,* (2021) demonstrated that modal frequency reduction serves as a reliable indicator of stiffness degradation under operational loads. Wang *et al.,* (2022) further linked damping ratio increases to internal cracking and material discontinuities in RC bridges. More recent work highlights the integration of SHM with predictive maintenance tools. Mudahemuka, *et al.,* (2024) investigated the use of continuous vibration and thermal data to optimize maintenance cycles, reporting improved accuracy in identifying early deterioration. Similarly, Morozov *et al.,* (2023) explored real-time crack detection through digital micrometry and found that microcrack evolution correlates strongly with temperature fluctuations and vehicle-induced vibration. Collectively, prior studies affirm that multi-parameter SHM provides superior insight into RC bridge behavior compared to visual inspection alone, particularly for early-stage deterioration.

3. MATERIALS AND METHODS

The methodology adopted in this study integrates a multi-parameter Structural Health Monitoring (SHM) approach designed to capture the mechanical, physical, and environmental response of the bridge decks under real operational conditions. The process involves collecting dynamic, structural, and environmental data to evaluate the condition of the bridges, identify early deterioration, and compare observed responses with established code-based performance limits. The approach combines vibration-based assessment, surface crack evaluation, deflection monitoring, environmental tracking, traffic characterization, and analytical load estimation to produce a comprehensive assessment of structural behavior. After establishing this methodological framework, specific instruments and procedures were used to implement each component of the SHM program. The analysis carried out and the equipment's used include;

Vibration Monitoring: A Laser Doppler Vibrometer (LDV) served as the primary instrument for capturing vibration responses at mid-span and quarter-span locations. The LDV recorded velocity-time histories continuously over seven days, from which modal frequency, damping ratio, and RMS velocity were extracted. These parameters were used to evaluate changes in dynamic stiffness and to identify early signs of deterioration such as crack initiation or loss of material rigidity.

Crack Assessment: Cracks were documented using visual inspection supported by a micrometer screw gauge with 0.01-mm resolution. The instrument enabled precise measurement of crack widths, while field notes captured their location and propagation pattern. The collected crack dimensions were compared with allowable limits to assess whether the observed cracking could influence serviceability or signal progressive deck degradation.

Deflection and Angular Displacement: Inclinometers were deployed to record vertical deflection and angular rotation of the deck under traffic movement. The instrument produced a continuous displacement-time record, which was evaluated against code-based deflection limits. These data were used to determine whether the deck exhibited unusual movement patterns associated with stiffness reduction or load-induced distress.

Environmental and Traffic Characterization: Environmental conditions were monitored using automated sensors that logged temperature, humidity, and wind variations. This data were collected from the hydrological centre of the department of civil engineering, Auchi polytechnic, Auchi. Traffic loading was documented through manual vehicle counts combined with a handheld speed gun used to record vehicle speeds. These datasets were used to relate structural responses to actual operating conditions, ensuring that variations in vibration, deflection, or cracking were interpreted in the context of real environmental and traffic loads.

Load Calculations: Load estimation involved computing dead loads from deck geometry and material unit weights, and live loads using recorded traffic categories in conjunction with standard loading models. These calculated loads established the baseline structural demand, allowing comparison between expected responses and the measured vibration, deflection, and crack behaviour. The Load calculations were carried out using;

Uniform load on deck: $w = DL + LL$ (1)
Line load per girder: $wg = w \times s$ (where s = spacing of girders) (2)
Total span load: $W = wg \times L$ (where L = span length) (3)

These calculations apply to both Edion and Orle Bridges since they share identical geometry and loading conditions.

4. RESULTS AND DISCUSSION

4.1. Vibration Performance

The seven-day monitoring period revealed distinct trends in the dynamic behaviour of both bridges (Table 1). At Edion Bridge, the modal frequency declined from 3.54 Hz to 3.06 Hz, representing a 14% reduction. Such a drop is significant for short-span RC decks and suggests measurable stiffness degradation, consistent with early cracking or progressive material weakening. This behaviour aligns with the observations of Wang *et al.,* (2022), who identified frequency decreases above 10% as reliable indicators of early stiffness loss.

Table 1: Vibration Parameters of Edion and Orle Bridges

Bridge	Modal Frequency (Hz)	Damping Ratio (%)	RMS Velocity (mm/s)
Edion	3.54-3.06	1.81-2.62	0.45-0.59
Orle	3.50-3.37	1.54-1.85	0.44-0.48

The results for the modal frequency, damping ratio and RMS velocity for both bridges were graphically represented (Figure 1, 2, and 3). Figure 1 shows that the modal frequency of Edion Bridge dropped significantly from 3.55 Hz to 3.06 Hz, while Orle Bridge reduced slightly from 3.50 Hz to 3.37 Hz over the monitoring period. The larger reduction in Edion Bridge indicates a greater loss of structural stiffness and a higher level of deterioration compared to Orle Bridge.

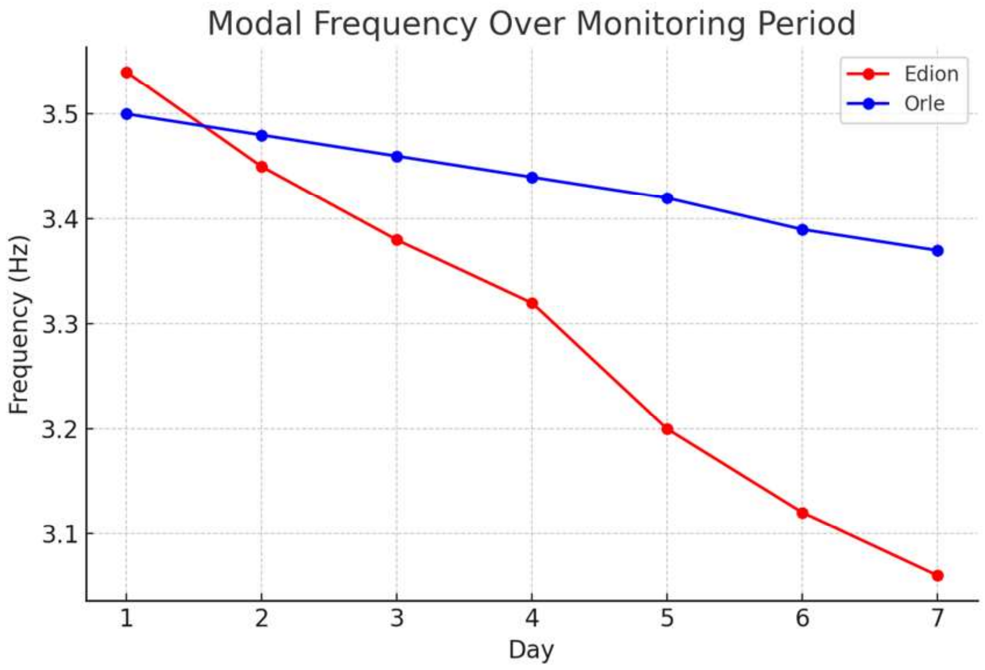

Figure 1. Modal Frequency of Edion and Orle Bridges

This result suggests that Edion Bridge requires urgent inspection and maintenance, whereas Orle Bridge remains relatively stable under standard monitoring limits. Figure 2 shows that the damping ratio of **Edion Bridge** increased steadily from about **1.81% to 2.62%,** indicating rising internal energy dissipation associated with possible structural distress such as microcracking and friction within the system.

In contrast, Figure 2 shows that **Orle Bridge** experienced only a small increase from about **1.54% to 1.85%,** suggesting relatively stable structural behaviour with minimal internal damage development. Overall, Figure 2 confirms that Edion Bridge is more dynamically affected and is undergoing higher deterioration compared to Orle Bridge. Figure 3 indicates a continuous increase in RMS velocity at **Edion Bridge** from about **0.45 mm/s to 0.59 mm/s,** reflecting increasing vibration levels and possible progressive structural deterioration.

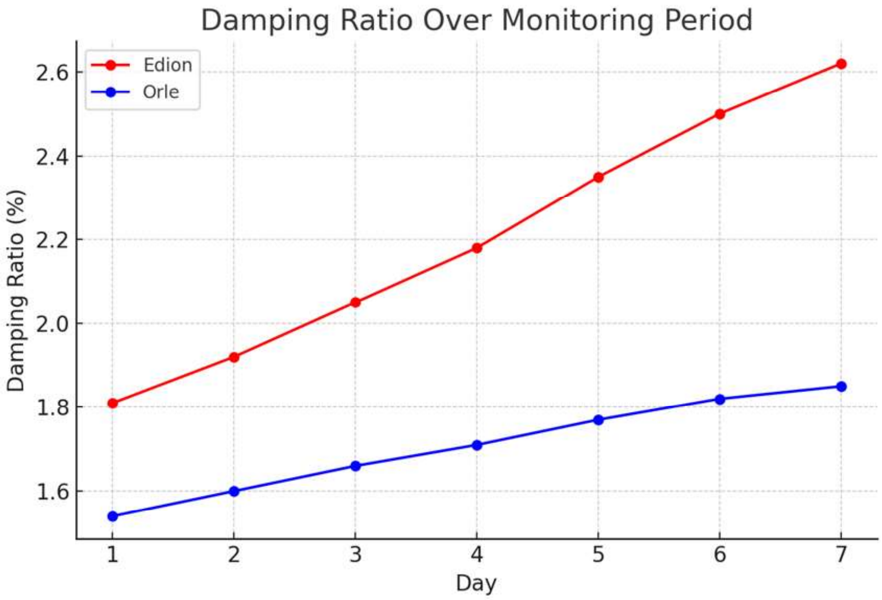

Figure 2: Damping Ration of Edion and Orle Bridges

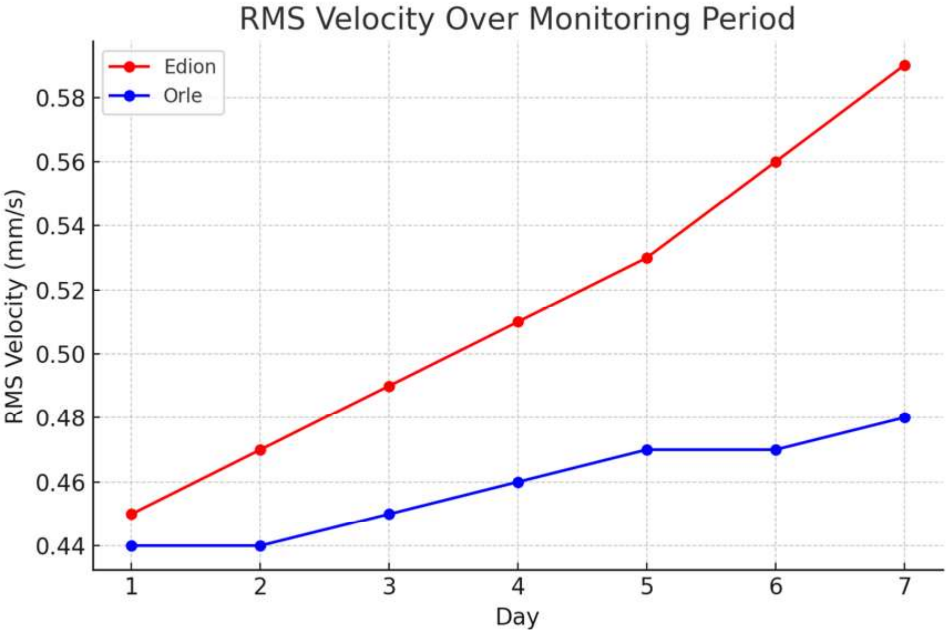

Figure 3. RMS Velocity for Edion and Orle Bridges

In contrast, Figure 3 shows only a slight rise in RMS velocity at **Orle Bridge** from about **0.44 mm/s to 0.48 mm/s,** remaining within normal limits for traffic-induced vibration. Overall, Figure 3 confirms that Edion Bridge is experiencing greater dynamic impact and should be given higher priority for structural evaluation. Analysis of both bridges shows trends of frequency reduction, damping increase, and elevated RMS response demonstrate that Edion Bridge is exhibiting more pronounced dynamic deterioration than Orle Bridge. The graphical trends presented in Figures 1, 2 and 3 reinforce these observations, showing clearer downward shifts in stiffness-related parameters at Edion compared with the relatively stable response of Orle

4.2. Crack Behavior

According to standard design codes, allowable crack width for reinforced concrete under serviceability conditions typically ranges from **0.3–0.4 mm** based on ACI 224R and EN 1992-1-1, beyond which durability and long-term performance may be compromised due to increased risk of moisture ingress and reinforcement corrosion. Crack widths of Edion bridge as shown in Table 2 (**0.20–0.35 mm)** fall largely within the generally acceptable serviceability range of **0.30–0.50 mm;** however, the occurrence of values close to and slightly above 0.30 mm indicates the onset of distress rather than a critical failure condition. As shown in **Table 2,** the measured crack depths of **10–15 mm** suggest penetration toward the reinforcement zone, increasing the risk of moisture ingress and corrosion. Although still within permissible limits, these observations point to **early-stage deterioration** consistent with the detected reduction in stiffness and progressive material degradation at Edion Bridge

Table 2. Crack Width and Depth Measurements

Bridge	Crack Width (mm)	Crack Depth (mm)	Standard Limit (mm)
Edion	0.28-0.35	10-15	0.3-0.4
Orle	0.04-0.06	1-3	0.3-0.4

These observations are consistent with Morozov *et al.,* (2023), who associated microcracks > 0.25 mm with early reinforcement corrosion risk.

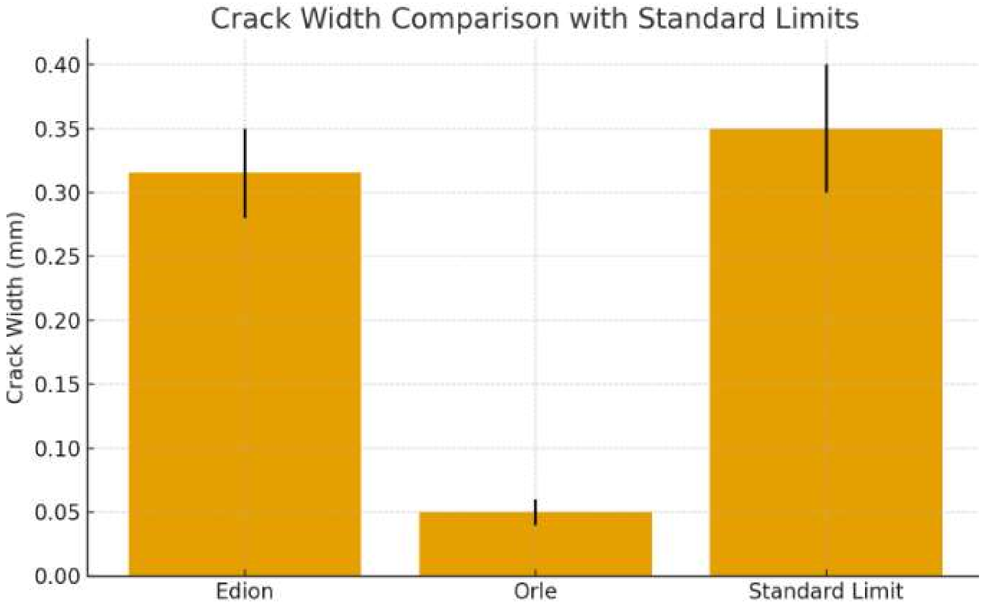

Figure 4. Crack with of Edion and Orle Bridges

Conversely, (Figure 4), Orle Bridge shows only minor surface cracking, with widths of 0.04–0.06 mm and depths of 1–3 mm, far below international limits. These cracks are superficial and pose no threat to durability or structural performance. Overall, the data confirm that Edion Bridge requires closer monitoring and early maintenance action, while Orle Bridge remains in good condition.

4.3. Deflection and Elastic Recovery

The measured vertical deflections (Table 3 and Figure 5) indicate that Edion Bridge experienced a maximum deflection of 21.6 mm with 88% elastic recovery. According to AASHTO LRFD Bridge Design Specifications (2022) and Eurocode 2 (EN 1992-1-1), serviceability limits for deflection are generally defined to prevent excessive deformation affecting ride quality or structural integrity.

Table 3. Deflection and Elastic Recovery

Bridge	Angular Disp. (^{0})	Vertical Deflection (mm)	Residual Deflection (mm)	Elastic Recovery
Edion	0.16	21.6	2.6	88.0
Orle	0.05	13.5	0.6	95.6

The residual deflection of 2.6 mm suggests some permanent deformation, reflecting a modest stiffness degradation under service loads. In contrast, Orle Bridge demonstrated a lower deflection of 13.5 mm and higher elastic recovery of 95.6%, remaining comfortably within permissible limits and indicating minimal stiffness loss.

Figure 5 visually confirms these trends, showing a greater residual displacement for Edion Bridge compared to Orle Bridge, consistent with the observed reduction in elastic response. The results highlight that while both bridges remain structurally sound, Edion Bridge may require closer monitoring for progressive stiffness reduction under repeated loading.

4.4. Environmental Conditions

The recorded environmental conditions for the two bridges (Table 4) show that **Edion Bridge** experienced slightly higher average temperature (33 °C) and relative humidity (78%) compared to **Orle Bridge** (32 °C, 74%). Wind speeds were moderate, with Orle Bridge slightly higher (14 km/h vs. 12 km/h for Edion).

According to **ACI 224R-01** and **EN 1992-1-1,** elevated temperature and humidity can accelerate concrete microcracking and reinforcement corrosion, especially in reinforced concrete bridge decks. The recorded 33 °C and 78% RH at Edion Bridge fall within ranges where moisture-related deterioration is more likely. Higher humidity facilitates moisture ingress and promotes corrosion of steel reinforcement, while higher temperatures can increase concrete shrinkage rates and exacerbate thermal stresses.

Table 4. Environmental Conditions for Edion and Orle Bridges

Bridge	Average Temperature (°C)	Relative Humidity (%)	Wind Speed (km/h)
Edion	33	78	12
Orle	32	74	14

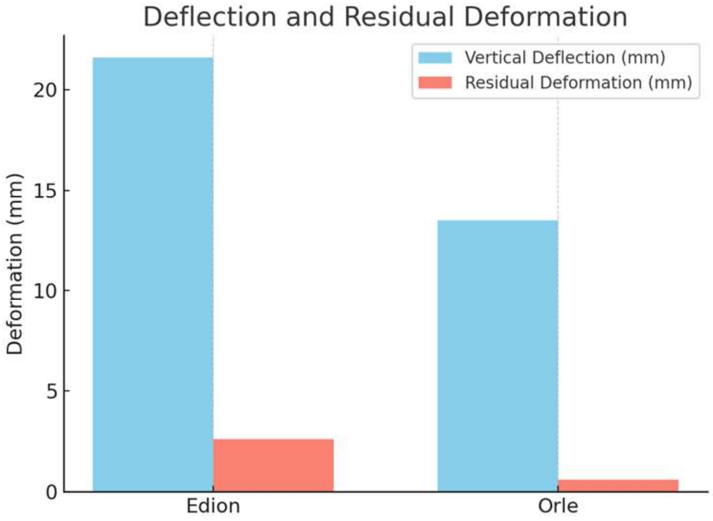

Figure 5. Deflection and Residual Deformation of Edion and Orle Bridges

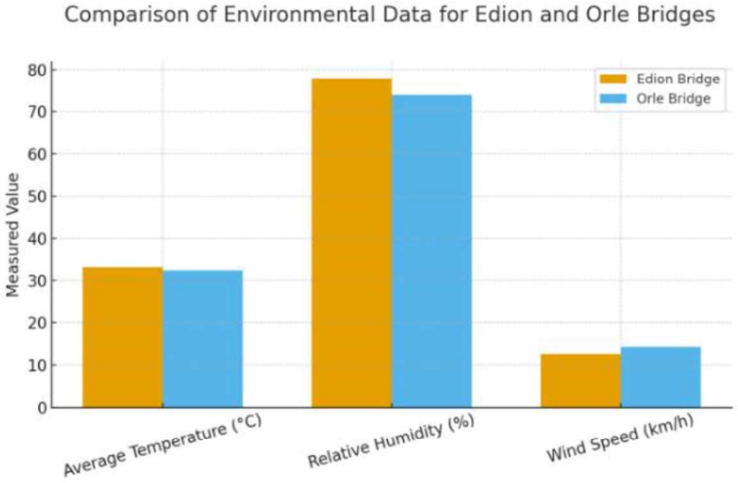

Figure 6. Environmental Data for Edion and Orle Bridges

Wind speeds (Figure 6) of 12–14 km/h are below thresholds for structural vibration concerns per AASHTO LRFD Bridge Design Specifications, but can influence evaporation rates, which indirectly affects concrete curing and surface cracking. Overall, Edion Bridge's environmental conditions suggest a slightly higher risk for early-age microcracking and long-term durability concerns compared to Orle Bridge, warranting more frequent monitoring per serviceability criteria outlined in ACI 224R-01 and EN 1992-1-1.

4.5. Load Estimations

Using **Equations (1), (2), and (3)** to determine the uniform deck load, line load per girder, and total span load respectively, the results in **Table 5** show that both Edion and Orle Bridges carry identical dead loads of **7.94 kN/m²** and live loads of **11.6 kN/m².** The calculated line load per girder is **29 kN/m,** which gives a total span load of **580 kN** for each bridge. These values are consistent with the **AASHTO LRFD Bridge Design Specifications,** confirming structural adequacy under both service and ultimate loading conditions.

Table 5. Load Estimates

Bridge	Dead Load (kN/m^2)	Live Load (kN/m^2)	Line load per Girder (kN/m)	Span Load (kN)
Edion	7.94	11.6	29	580
Orle	7.94	11.6	29	580

As shown in Table 5, the load distribution along the spans of both bridges, highlighting uniformity in load transfer to the girders. The identical loading conditions suggest similar structural responses under service conditions, indicating that both bridges meet the required load-carrying standards and do not exhibit unusual stress concentrations.

5. CONCLUSION

Structural health monitoring enabled early detection of deterioration in RC bridge decks. Edion Bridge displayed measurable stiffness reduction, crack widths exceeding serviceability limits, reduced elastic recovery, and elevated environmental stressors. Orle Bridge remained structurally sound with stable vibration response, minimal cracking, and high recovery. The study confirms the importance of multi-parameter SHM vibration, cracking, deflection, environment, and traffic in establishing data-driven maintenance strategies. The results are consistent with recent studies advocating continuous sensor-based monitoring for early deterioration detection (Hasani & Freddi, 2023; Li *et al.,* 2023).

6. RECOMMENDATIONS

The assessment shows that Edion Bridge needs urgent repairs due to ongoing deterioration, while Orle Bridge remains stable but requires continued observation. A predictive, data-driven maintenance approach will help improve long-term performance of both bridges. The following recommendations were made:

1. **Immediate Repair of Edion Bridge:** Apply epoxy injection for cracks, repair spalled concrete, and improve drainage to limit moisture infiltration.
2. **Continuous SHM for Edion Bridge:** Maintain monitoring to track crack progression, moisture effects, and structural response after repairs.
3. **Routine Monitoring for Orle Bridge:** Continue regular inspections, focusing on traffic changes and environmental conditions.
4. **Predictive Maintenance for Both Bridges:** Use SHM data with Bayesian reliability assessment and lifecycle cost analysis in line with FHWA (2020) guidelines.

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials,
RMS	Root mean square
LDV	Laser Doppler Vibrometer
FHWA	***Federal Highway Administration***
RC	Reinforced concrete
SHM	Structural Health Monitoring

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