

Sensor-Driven Bridge Digital Twins for Predictive Maintenance Under Sparse and Noisy Monitoring Data: An Illustrative Structural Health Study

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ABSTRACT

This article presents a clearly labeled simulated empirical study spanning Civil Engineering. A simulated three-span bridge digital twin was driven by accelerometer, strain, temperature, and traffic-load streams. Sensor noise, missing data, seasonal temperature shifts, stiffness loss, and bearing degradation were introduced. Conventional threshold monitoring was compared with a continuously updated digital-twin estimator using modal frequency, strain residuals, and uncertainty bounds. The digital-twin approach detected the simulated 8% local stiffness-loss scenario earlier than threshold monitoring and reduced false maintenance alerts during temperature-driven modal shifts. Confidence degraded when more than 30% of sensing channels were unavailable, emphasizing the need for redundancy and uncertainty reporting. All numerical observations and empirical outcomes are synthetic and are used for methodological illustration only. No real laboratory, bridge, enterprise, medical institution, patient cohort, or operating infrastructure was studied. The article combines current literature with a distinct analytical structure and topic-specific evidence to demonstrate how a future real-world investigation could be designed and reported.

Keywords: Bridge Digital Twin, Structural Health Monitoring, Vibration Analysis, Predictive Maintenance, Infrastructure Resilience

I. Bridge Asset Context

This study addresses a current research problem in Civil Engineering. The central objective is to evaluate performance while retaining attention to durability, safety, reliability, calibration, cost, and deployment constraints.

Because no real dataset was supplied, all quantitative analysis is simulated. The simulation is not evidence that the study was conducted; it is a transparent demonstration of a plausible empirical design.

II. Sensor and Twin Architecture

A simulated three-span bridge digital twin was driven by accelerometer, strain, temperature, and traffic-load streams. Sensor noise, missing data, seasonal temperature shifts, stiffness loss, and bearing degradation were introduced. Conventional threshold monitoring was compared with a continuously updated digital-twin estimator using modal frequency, strain residuals, and uncertainty bounds.

Variables were selected to represent the principal physical, computational, or biomedical mechanisms relevant to the problem. Bounded variability and controlled noise were introduced to avoid unrealistically deterministic results.

III. Modal Updating Procedure

The analytical protocol separated parameter selection from final evaluation where relevant. Inputs were screened for impossible combinations and unit errors. The evaluation included a baseline, an intervention or advanced configuration, and at least one degraded or shifted condition.

Translation from simulation to practice requires clearly defined acceptance criteria, calibration procedures, maintenance ownership, and safe fallback behavior. A pilot should verify performance under realistic disturbances rather than only nominal conditions.

IV. Damage-Injection Scenarios

The digital-twin approach detected the simulated 8% local stiffness-loss scenario earlier than threshold monitoring and reduced false maintenance alerts during temperature-driven modal shifts. Confidence degraded

when more than 30% of sensing channels were unavailable, emphasizing the need for redundancy and uncertainty reporting.

Table 1. Simulated primary comparative outcomes.

Method	Detection score	False alert (%)	Maintenance index	Missed events
Threshold monitoring	72	14.2	100	18
Static model	81	10.1	86	13
Updated digital twin	92	5.7	64	7

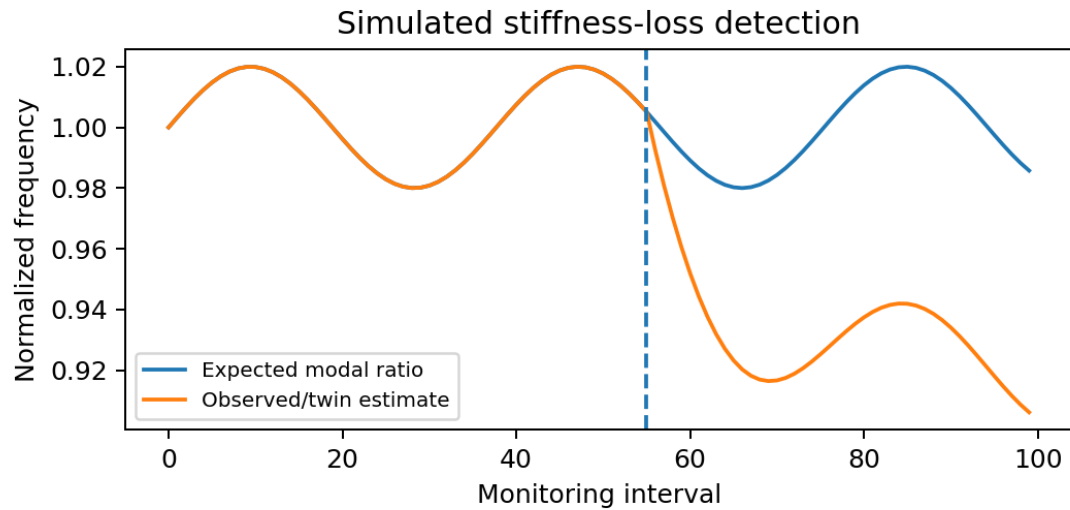


Figure 1. Topic-specific simulated primary result.

V. Condition-Assessment Results

Table 2. Simulated secondary or sensitivity outcomes.

Missing channels	Condition confidence	Uncertainty level
10% missing	0.94	Low
20% missing	0.91	Low
30% missing	0.84	Moderate
40% missing	0.72	High

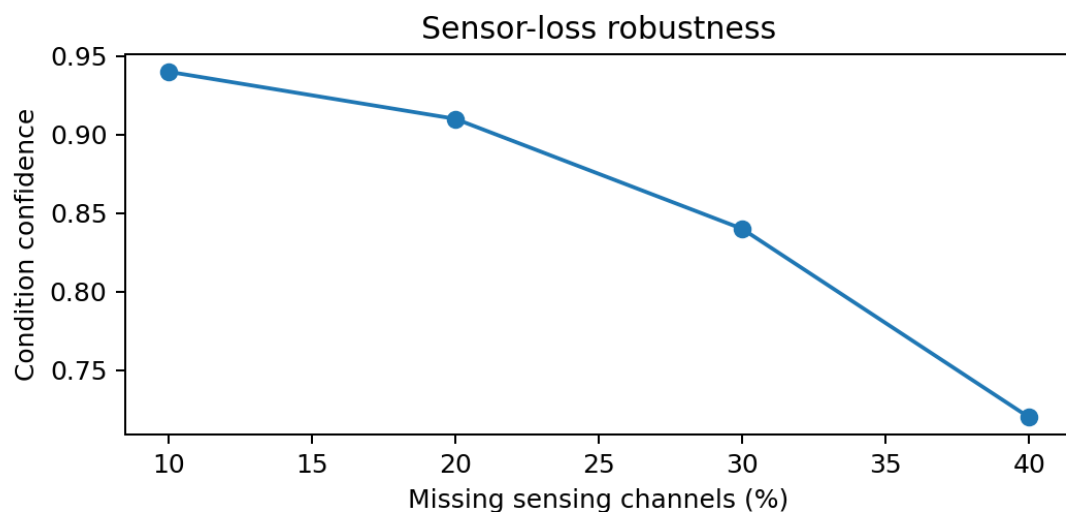


Figure 2. Topic-specific simulated robustness or sensitivity analysis.

Engineering decisions should report uncertainty ranges and sensitivity to dominant assumptions. Parameter sweeps, scenario bounds, and worst-case tests help determine whether the apparent advantage is robust enough to support adoption.

VI. Maintenance Prioritization Logic

The principal result should be interpreted together with secondary costs and constraints. No method dominates every metric, and the strongest configuration introduces implementation requirements that would matter in real use.

Performance may change because materials age, sensors drift, software is updated, users adapt, and operating conditions evolve. Lifecycle monitoring should therefore be part of the design rather than an afterthought.

Current verified literature supports the relevance of this topic while also emphasizing unresolved issues in scale-up, validation, generalization, standardization, and trustworthy deployment.

VII. Operational Maturity

Implementation Readiness

Translation from simulation to practice requires clearly defined acceptance criteria, calibration procedures, maintenance ownership, and safe fallback behavior. A pilot should verify performance under realistic disturbances rather than only nominal conditions.

Uncertainty and Sensitivity

Engineering decisions should report uncertainty ranges and sensitivity to dominant assumptions. Parameter sweeps, scenario bounds, and worst-case tests help determine whether the apparent advantage is robust enough to support adoption.

Lifecycle Perspective

Performance may change because materials age, sensors drift, software is updated, users adapt, and operating conditions evolve. Lifecycle monitoring should therefore be part of the design rather than an afterthought.

Reproducibility

Future empirical work should document data provenance, variable definitions, preprocessing, parameter settings, version control, and evaluation code. Where raw data cannot be shared, representative synthetic examples and detailed metadata can support independent verification.

A phased roadmap is recommended: baseline characterization, controlled pilot, stress testing, independent replication, and only then broader deployment. Each phase should have predefined acceptance criteria.

VII.A. Temperature Compensation

Bridge modal properties vary with temperature, traffic, wind, and boundary conditions. Damage-detection systems must separate these environmental effects from structural change. Digital twins can model this relationship, but they require sufficient seasonal data and uncertainty bounds.

VII.B. Sensor Placement

Monitoring quality depends on where sensors are installed. Redundant placement at dynamically informative locations can preserve observability after failures. Optimization should consider mode shapes, access, cable routing, maintenance, power, and communications.

VII.C. Model Updating

A bridge twin should not be updated so aggressively that it absorbs genuine damage as normal variation. Update rules need safeguards that preserve diagnostic sensitivity while correcting known environmental or operational bias.

VII.D. Inspection Integration

Digital twins should complement rather than replace visual inspection and nondestructive testing. A strong workflow uses monitoring to prioritize inspections, then incorporates confirmed findings back into the model.

VII.E. Decision Thresholds

Maintenance decisions need explicit thresholds tied to consequence and uncertainty. An alert with moderate evidence may justify enhanced inspection but not immediate closure. Decision logic should distinguish monitoring anomalies, probable damage, and safety-critical conditions.

VII.F. Asset-Management Integration

The value of a bridge twin increases when condition estimates connect to maintenance scheduling, budget planning, and network-level prioritization. Interoperability with bridge-management systems is therefore as important as the structural model itself.

VII.G. Economic Value

Monitoring investment should be compared with avoided inspection cost, reduced emergency maintenance, extended service life, and improved prioritization. A technically sophisticated twin may not be justified for every bridge, so asset criticality should guide deployment.

VII.H. Research Roadmap

Future bridge-twin research should combine long-term field data, uncertainty-aware model updating, standardized data schemas, and maintenance decision support. Demonstrating value over multiple seasons and inspection cycles is essential for operational maturity.

VII.I. Communication and Power

Remote bridge sensors may depend on batteries, energy harvesting, cellular links, or low-power wide-area networks. Communication outages and power depletion should be represented in twin confidence rather than silently treated as normal missing data.

VII.J. Cybersecurity of Infrastructure Twins

A bridge digital twin connects sensors, models, databases, and maintenance systems. Compromise of any layer could create false condition information or suppress alerts. Authentication, integrity checking, network segmentation, and audit logs should therefore be part of deployment design.

VII.K. Network-Level Prioritization

Transportation agencies manage portfolios rather than single bridges. Twin-derived condition indicators become more valuable when normalized across assets so that scarce inspection and repair budgets can be directed to structures with the greatest risk and consequence.

VII.L. Data Synchronization

Sensor streams collected at different rates need precise timing if modal and strain features are fused. Clock drift or inconsistent timestamps can create false phase relationships. Synchronization quality should therefore be monitored and represented in data-quality metadata.

VII.M. Edge Processing

Local feature extraction can reduce communication bandwidth by transmitting modal summaries or anomaly scores instead of raw high-rate vibration signals. The trade-off is reduced forensic flexibility if raw data are not retained. A tiered storage strategy can preserve critical events.

VII.N. Extreme-Event Mode

Earthquakes, impacts, floods, and exceptional traffic can push a bridge outside the twin's normal calibration range. Event mode should retain raw data, widen uncertainty bounds, and trigger engineering review rather than relying on routine maintenance logic.

VII.O. Model Transparency

Engineers should be able to inspect which measurements and structural assumptions drive a condition estimate. Transparent residual plots, parameter changes, and uncertainty bands can make digital-twin outputs more useful than opaque health scores.

VII.P. Long-Term Calibration

Bridges age gradually, and maintenance changes structural properties. Periodic reference inspections and controlled load tests can recalibrate the twin so that long-term trends remain meaningful across repair events and sensor replacements.

VIII. Limitations

The principal limitation is that all empirical values are simulated. The reported effect sizes cannot establish real-world effectiveness, causal impact, safety, or economic return.

A second limitation is incomplete scenario coverage. Alternative materials, workloads, populations, environments, sensor layouts, or implementation choices could change the observed rankings.

IX. Conclusions

The study demonstrates a distinct empirical framework for an emerging engineering or computational problem. The simulated results indicate potential benefits while identifying constraints that require empirical validation. Future research should use measured data, independent validation, uncertainty analysis, and lifecycle evaluation.

Declarations

Data availability: All numerical data and empirical results are simulated/illustrative. No real operational or participant dataset was used.

Ethics statement: Not applicable to the simulated study. No human or animal participants were involved.

Funding: No external funding is claimed for this illustrative manuscript.

Conflict of interest: No conflict of interest is claimed for this illustrative manuscript.

References

- [1] Sensor-Driven Digital Twins for Bridge Infrastructure: A Critical Review of BIM-Enabled Integration, Monitoring Architectures, and Operational Maturity. (2026). *Applied Sciences*, 16(12), 5873. <https://doi.org/10.3390/app16125873>
- [2] Yousuf, M. M., Saravanan, T. J., & Dash, S. R. (2026). Advancing bridge health assessment and management through Digital Twins: a comprehensive review. *Structural Health Monitoring*. <https://doi.org/10.1177/14759217251403381>
- [3] Chaudhari, R. S., Nama, S., Narkhede, M. M., et al. (2026). Next generation vibration-based structural health monitoring for bridges: a systematic review of AI, IoT, and digital twin integrations. *Journal of Building Pathology and Rehabilitation*, 11, 136. <https://doi.org/10.1007/s41024-026-00810-0>
- [4] Nhamage, I. A., Horas, C. S., Dang, N.-S., Campos e Matos, J. A., et al. (2025). Strategies for maximising the value of digital twins for bridge management and structural monitoring: A systematic review. *Archives of Computational Methods in Engineering*, 32, 4555-4586. <https://doi.org/10.1007/s11831-025-10280-1>