



A Review of Low-Cost Sensor-Based Structural Health Monitoring Systems for Beam-Level Experimental Testing

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ABSTRACT :

Structural health monitoring (SHM) provides a systematic approach for measuring structural response, identifying abnormal behavior, and supporting maintenance decisions. Conventional laboratory and field monitoring systems can provide high accuracy, but sensors, signal-conditioning hardware, data-acquisition systems, and software may be expensive for small-scale educational experiments. This review examines low-cost sensing and open-source data-acquisition technologies for beam-level structural monitoring, with emphasis on load cells, strain sensors, displacement measurement, microcontrollers, and warning systems. Recent literature shows that strain-based sensing remains important because strain is associated with stress, deformation, stiffness changes, and structural performance, while load cells provide direct measurement of applied force. Arduino-class microcontrollers and low-cost analog interfaces have also been demonstrated for laboratory and field measurements. The review compares conventional and low-cost approaches, identifies practical limitations such as calibration, electrical noise, installation, sampling rate, environmental effects, and validation, and proposes a compact architecture for a miniature wooden beam using a load cell positioned above the beam, a surface-mounted strain sensor, an Arduino controller, and controlled loading by weight stones or a hydraulic syringe. The evidence indicates that such systems are valuable for experimental education and preliminary SHM research when calibration and validation are performed.

Keywords: Structural health monitoring; low-cost sensors; strain measurement; load cell; Arduino; data acquisition; beam testing; experimental methods; early warning.

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1. Introduction

Civil infrastructure must remain safe and serviceable throughout long operational periods. Conventional inspection is essential, but periodic inspection may not capture continuous changes in structural response. SHM complements inspection by collecting measurements of structural and environmental parameters and using them to assess condition and performance [1–4]. Important quantities include strain, displacement, acceleration, load, temperature, and crack development.

Strain is especially relevant because it is related to stress and deflection and can reveal changes in structural behavior [3]. Displacement is also fundamental for loading tests, damage assessment, modal identification, and model updating [1]. A practical SHM system, however, requires suitable sensors, signal conditioning, data acquisition, processing, power, communication, and interpretation.

Recent research has therefore explored low-cost alternatives based on microcontrollers, MEMS sensors, open-source software, and wireless communication. Reviews report that low-cost technologies can improve accessibility and measurement density, although accuracy, noise, synchronization, calibration, environmental sensitivity, and long-term reliability remain concerns [4–7]. This review synthesizes these developments for small-scale beam experiments and identifies a practical configuration for an educational working model.

2. Review Methodology

A focused narrative review was adopted to connect established SHM principles with recent low-cost sensing developments. Peer-reviewed journal articles and open-access research were considered for structural health monitoring, strain sensing, displacement measurement, low-cost data acquisition, Arduino-based measurement, wireless monitoring, and beam-level experiments. Priority was given to review articles and experimental studies published from 2018 to 2026, while foundational papers were retained where they explain sensor principles.

3. Structural Health Monitoring and Experimental Measurement

SHM can be viewed as a cycle of sensing, data acquisition, signal processing, feature extraction, diagnosis, and decision-making. For a beam subjected

to static loading, load, strain, displacement, and crack development are direct response variables. For dynamic monitoring, acceleration and strain can be used to identify modal properties and stiffness changes.

Sensor selection should be based on the measurement objective rather than cost alone. Ma et al. reviewed thirteen categories of displacement sensing and highlighted trade-offs among accuracy, sampling rate, installation requirements, directionality, multipoint capability, long-term monitoring, and computational efficiency [1]. Hassani and Dackermann emphasized that modern SHM increasingly combines conventional sensors with advanced sensing and data analysis [2].

For the proposed beam-level system, the load cell measures applied force while the strain sensor measures local structural response. The microcontroller provides acquisition and processing, and a display provides immediate feedback. This separation of force measurement and structural response measurement allows load–strain relationships to be established directly.

4. Sensor Technologies Relevant to Beam Testing

4.1 Strain Sensors

Electrical resistance strain gauges remain one of the most established methods for local strain measurement. A strain gauge changes resistance as the host surface deforms and is normally connected in a Wheatstone bridge. Glisic's review shows the evolution from discrete gauges to distributed and two-dimensional sensing technologies [3]. For laboratory beam tests, conventional gauges are attractive because they are small and capable of measuring local response near critical regions.

Practical issues include surface preparation, gauge alignment, bonding quality, temperature effects, bridge completion, excitation stability, and amplification of the small electrical signal. Low-cost microcontroller systems therefore require suitable signal conditioning. Studies using Arduino and external ADCs have demonstrated useful strain measurement when bridge circuits, calibration, and analytical validation are properly controlled [8,9].

4.2 Load Cells

A load cell converts applied force into an electrical signal, commonly using strain gauges arranged in a Wheatstone bridge. Load cells are widely used in structural load testing because applied force can be measured directly. Bridge-load-test literature describes load cells at supports or loading points and notes that installation and load-transfer conditions influence reliability [10].

For a miniature beam experiment, the load cell should be placed in the load path rather than embedded inside the beam. A practical arrangement is a loading plate above the beam, followed by the load cell, with force transferred into the beam at the loading point. Known weight stones provide simple incremental loading; a small hydraulic syringe can provide a more adjustable load. Alignment is required to minimize eccentric loading.

4.3 Displacement and Deflection Measurement

Beam deflection is often measured using LVDTs, dial gauges, laser-based devices, vision systems, or other displacement sensors. LVDTs provide high-quality measurements but require physical access and supporting fixtures. Non-contact techniques such as cameras reduce interference but depend on lighting, line of sight, image quality, and computation [1]. For a small educational model, an inexpensive displacement indicator can be added as a validation measurement.

4.4 Microcontrollers and Data Acquisition

Arduino-class microcontrollers are attractive for educational SHM because they are inexpensive, programmable, widely documented, and compatible with many sensor modules. Their role is not to replace laboratory-grade systems in every application, but to provide an accessible platform for acquisition, filtering, threshold detection, display, and communication. Komarizadehasl et al. demonstrated an Arduino-based low-cost vibration system with large cost reduction compared with conventional systems [5]. MADV-DAQ also demonstrated low-cost Arduino-based acquisition for Wheatstone-bridge strain sensors and cloud transmission [9].

For load cells, the HX711 is commonly used as a bridge-sensor interface because it provides amplification and analog-to-digital conversion before data are read by the controller. For strain gauges, an appropriate bridge and amplifier are required. Therefore, experimental documentation should distinguish a bonded foil strain gauge from a flex sensor or other strain-sensitive device.

5. Conventional versus Low-Cost Approaches

6. Low-Cost SHM Architecture for Beam-Level Experiments

The literature supports a modular architecture separating sensing, acquisition, processing, visualization, and warning. A suitable miniature system consists of a simply supported wooden beam, a load cell above the beam at the loading point, a surface-mounted strain sensor, an Arduino controller, an HX711 interface, an LCD display, and an LED/buzzer warning unit. The configuration is intentionally simple so that the complete measurement chain can be observed during a laboratory demonstration.

6.1 Working Principle

The experiment begins with zero-load initialization. The load cell and strain channel are checked for stable baseline readings. A known load is applied incrementally using weight stones or a hydraulic syringe. The load cell measures applied force while the strain sensor records the structural response. The Arduino samples the signals, converts them into engineering units using calibration relationships, and displays the values. The resulting dataset can be used for load–strain curves and, with an independent deflection measurement, load–displacement curves.

A threshold warning can demonstrate condition monitoring. When measured load or a derived response exceeds a predefined experimental threshold, the controller activates an LED and buzzer. This threshold is an experimental criterion and should not be interpreted as a real structural safety limit without appropriate design and validation.

6.2 Calibration and Validation

Calibration is one of the most important stages of low-cost SHM. A load cell should be calibrated with known masses or forces over its operating range. Repeated loading and unloading can be used to examine repeatability and hysteresis. Strain sensors require careful zeroing and surface preparation; bonded gauges are especially sensitive to alignment and adhesive quality. Measured beam behavior should be compared with analytical beam theory or a reference instrument where possible.

For a simply supported beam under a central point load P , the maximum bending moment at midspan is $PL/4$. Within the elastic range, bending stress may be estimated from $\sigma = My/I$, and strain is related to stress by $\epsilon = \sigma/E$. These equations provide a first-level check of whether measured trends are physically reasonable; actual dimensions, material properties, load position, and boundary conditions must be used.

6.3 Data Quality and Error Sources

7. Recent Low-Cost Implementations

Recent studies show that the low-cost concept is moving beyond classroom prototypes. Amran and Ali reported an Arduino-based strain-sensing system for a beam-like specimen with real-time display and threshold feedback, demonstrating the relevance of inexpensive instrumentation for educational structural experiments [12]. A 2026 study reported a low-cost microcontroller/HX711 strain-gauge system with calibration and real-time visualization for a cantilever beam [13]. Other work has demonstrated low-cost wireless strain acquisition for structural elements and large infrastructure, indicating that open-source electronics can be scaled when appropriate validation is performed [9].

8. Critical Discussion

The principal advantage of low-cost SHM is accessibility. Conventional laboratory acquisition chains may require specialized signal conditioners, software licenses, and dedicated hardware. A microcontroller system can reduce entry cost and allow students or researchers to understand the complete measurement chain. This is valuable in experimental-methods courses because the instrument is not a black box: physical loading can be traced to an electrical signal, digitization, processing, and structural interpretation.

A second advantage is modularity. Load cells, strain sensors, accelerometers, temperature sensors, and displacement sensors can be connected to a common processing platform. This makes sensor fusion feasible at small scale. Literature on displacement sensing indicates that combining measurement modes can overcome limitations of individual sensors [1]. For a beam test, load and strain are complementary: load describes input while strain describes structural response.

The main limitation is measurement quality. Low-cost does not automatically mean low accuracy, but it places greater responsibility on calibration, wiring, sampling, filtering, sensor placement, and validation. Commercial systems are typically supported by characterized hardware, stable excitation, synchronized channels, environmental compensation, and validated software. A student-built prototype should therefore be presented as an experimental or educational monitoring system unless rigorous validation establishes its accuracy.

Another limitation is the difference between local and global monitoring. A single surface strain sensor measures response at one location and cannot identify all damage types. Multiple sensors, distributed sensing, vibration measurements, or non-contact techniques may be needed for larger structures. Recent reviews emphasize sensor fusion, advanced sensing, and data analytics as important developments [2,4].

9. Research Gaps and Future Directions

Standardized calibration procedures for low-cost structural sensors are needed so results from different prototypes can be compared.

Future studies should quantify uncertainty, repeatability, drift, hysteresis, and temperature sensitivity rather than reporting only raw readings.

Low-cost systems should combine load, strain, displacement, and vibration when a broader structural response is required.

Wireless and IoT communication can enable remote monitoring, but synchronization, power consumption, data integrity, and cybersecurity should be considered.

Machine-learning methods may support anomaly detection, but reliable sensor data and representative training datasets are prerequisites.

Miniature specimens should demonstrate measurement principles without presenting their results as direct substitutes for full-scale structural safety assessment.

Future beam experiments should compare the low-cost system with an LVDT or laboratory DAQ and quantify MAE, RMSE, percentage error, linearity, and repeatability.

10. Proposed Experimental Framework

11. Conclusions

This review examined low-cost sensing and microcontroller-based data acquisition for beam-level SHM. The literature indicates that strain and displacement are important response parameters, while load measurement provides direct description of applied input. Electrical resistance strain gauges remain a mature local strain-sensing technology, and load cells provide practical force measurement. Arduino-class controllers and low-cost interfaces have demonstrated usefulness in laboratory and field-oriented monitoring where affordability and flexibility are important.

For a miniature experimental model, a wooden beam provides a practical specimen. The recommended arrangement places the load cell above the beam in the loading path, while the strain sensor is attached to the beam surface. Weight stones provide simple incremental loading and a hydraulic syringe provides an alternative controlled mechanism. Calibration, sensor installation, electrical noise, environmental effects, and validation remain essential.

Overall, low-cost SHM is a useful platform for experimental education and preliminary research, rather than an automatic replacement for certified monitoring systems. The next priority is validation against analytical predictions and reference instruments. After the basic measurement chain is validated, wireless communication, cloud visualization, multi-sensor fusion, and intelligent damage detection can be added.

Theme		Evidence	Purpose
SHM fundamentals		Reviews of sensing and monitoring [2–4]	Define SHM workflow
Strain measurement		Strain-gauge and microcontroller studies [3,8,9]	Assess strain sensing
Load measurement		Structural load-cell studies [10]	Assess direct force measurement
Displacement		Contact/non-contact review [1]	Compare response measurement
Low-cost systems		Arduino/wireless studies [5–7,11]	Evaluate affordability
Beam experiments		Recent low-cost beam studies [12,13]	Relate literature to model
Parameter	Conventional	Low-cost prototype	Implication
DAQ	Dedicated multi-channel	Arduino + interface	Lower cost; lower metrological capability
Force	Lab load cell + DAQ	Small load cell + HX711	Suitable for miniature loading
Strain	Commercial conditioner	Gauge/module + ADC	Calibration critical
Deflection	LVDT/dial gauge	Low-cost option	Reference measurement useful
Processing	Commercial software	Arduino/PC tools	Flexible and accessible
Communication	Wired/high-end wireless	USB/Bluetooth/Wi-Fi	Easy IoT expansion
Use	Research/field validation	Education/prototyping	Not a direct replacement
Error source		Effect	Mitigation
Installation		Incorrect strain/load transfer	Proper alignment and mounting
Electrical noise		Fluctuating readings	Stable power, grounding, filtering
Temperature		Baseline drift	Compensation/controlled conditions
Load eccentricity		Nonuniform force	Loading plate and alignment
Calibration		Systematic error	Known loads and regression
Sampling		Loss of dynamic information	Suitable sampling rate
Wood variability		Different stiffness	Consistent specimen
Threshold		False/missed warning	Validated criteria
Stage	Activity		Output
1	Prepare wooden beam and supports		Repeatable miniature specimen
2	Mount load cell above beam		Applied-load measurement
3	Attach strain sensor to beam surface		Local strain response
4	Connect HX711 and Arduino		Digital acquisition
5	Calibrate with known loads		Calibration equation
6	Apply weight stones / syringe		Controlled loading
7	Record load and strain		Experimental dataset
8	Compare with analytical response		Validation
9	Set experimental threshold		LED/buzzer warning
10	Analyze and report		Performance assessment

REFERENCES

- [1] Glisic, B. (2022). Concise Historic Overview of Strain Sensors Used in the Monitoring of Civil Structures: The First One Hundred Years. *Sensors*, 22(6), 2397. <https://doi.org/10.3390/s22062397>
- [2] Das, S., & Saha, P. (2018). A review of some advanced sensors used for health diagnosis of civil engineering structures. *Measurement*, 129, 68–90. <https://doi.org/10.1016/j.measurement.2018.07.008>

- [3] Hassani, S., & Dackermann, U. (2023). A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring. *Sensors*, 23(4), 2204. <https://doi.org/10.3390/s23042204>
- [4] Mousa, M. A., Yussof, M. M., Hussein, T. S., Assi, L. N., & Ghahari, S. (2023). A Digital Image Correlation Technique for Laboratory Structural Tests and Applications: A Systematic Literature Review. *Sensors*, 23(23), 9362. <https://doi.org/10.3390/s23239362>
- [5] Ma, Y., Choi, H., & Sohn, H. (2023). Structural displacement sensing techniques for civil infrastructure: A review. *Journal of Infrastructure, Intelligence and Resilience*, 2(3), 100041. <https://doi.org/10.1016/j.iintel.2023.100041>
- [6] Mishra, M., Lourenço, P. B., & Ramana, G. V. (2022). Structural health monitoring of civil engineering structures by using the Internet of Things: A review. *Journal of Building Engineering*, 48, 103954. <https://doi.org/10.1016/j.jobe.2021.103954>
- [7] Bhatta, S., & Dang, J. (2024). Use of IoT for structural health monitoring of civil engineering structures: A state-of-the-art review. *Urban Lifeline*. <https://doi.org/10.1007/s44285-024-00031-2>
- [8] Komarizadehasl, S., et al. (2021). Development of a Low-Cost System for the Accurate Measurement of Structural Vibrations. *Sensors*, 21(18), 6191. <https://doi.org/10.3390/s21186191>
- [9] Komarizadehasl, S., et al. (2022). Low-Cost Wireless Structural Health Monitoring of Bridges. *Sensors*, 22(15), 5725. <https://doi.org/10.3390/s22155725>
- [10] Silva, J. L., Varanis, O. J., & Mereles, A. G. (2019). A study of strain and deformation measurement using the Arduino microcontroller and strain gauges devices. *Revista Brasileira de Ensino de Física*, 41(3). <https://doi.org/10.1590/1806-9126-RBEF-2018-0206>
- [11] Amran, M., & Ali, M. (2025). Evaluating the Performance of an Arduino-Based Strain Sensor System in a Cantilever Beam using Plastic Ruler Under Load Conditions. *Enhanced Knowledge in Sciences and Technology*, 5(1), 125–131.
- [12] Konotop, I., & Nikitin, A. (2026). Development and experimental validation of a microcontroller-based strain gauge system for monitoring the elastic-deformed state of structural elements. *Open Information and Computer Integrated Technologies*, 108.
- [13] Ghosh, S., et al. (2020). Real-Time structural health monitoring for concrete beams: a cost-effective Industry 4.0 solution using Piezo Sensors. *International Journal of Building Pathology and Adaptation*. <https://doi.org/10.1108/IJBPA-12-2019-0111>
- [14] Zhang, Y., et al. (2024). A Review on Concrete Structural Properties and Damage Evolution Monitoring Techniques. *Sensors*, 24(2), 620. <https://doi.org/10.3390/s24020620>
- [15] Janeliukstis, R., & Chen, X. (2021). Digital image correlation for large-scale composite structures: A review. *Composite Structures*, 271, 114143. <https://doi.org/10.1016/j.compstruct.2021.114143>