E-ISSN: 1116 - 2759 P-ISSN: 3027-0111
MPRI-EDIR | INTERNATIONAL JOURNAL OF EARTH DESIGN AND INNOVATION RESEARCH
VOL. 10 NO. 4 – OCTOBER, 2025

INTEGRATED SMART-BRICK CONSTRUCTION WITH RESILIENCE AND SUSTAINABILITY

***OLOLADE AKINBAMILOWO; **PEACE CHINONYEREM IKE; ***HARUNA SULEIMAN KAMBA; ****ADJEI KOFI YEBOAH; *****SANUSI HUSSEIN KEHINDE; ******NICODEMUS CHIDERA OMEKAWUM; & *******JACINTA CHINWENDU UHALLA.**

*Johns Hopkins University, Maryland, USA. Department of Civil Engineering. **University of Nigeria, Nsukka, Department of Health Education. ***Kebbi State University of Science and Technology, Aliero. Department of Civil Engineering. ****Ghana Institute of Management and Public Administration. Department of Management Science, M.Sc. Project Management. *****Sheffield Hallam University. Department of Construction Project Management. ******Federal University of Technology, Owerri, Nigeria. Department of Chemical Engineering. *******The Catholic University of America, Washington, D.C. Department of Architecture

Corresponding Author: olоladeomoakin@gmail.com

DOI: https://doi.org/10.70382/mejedir.v10i4.068

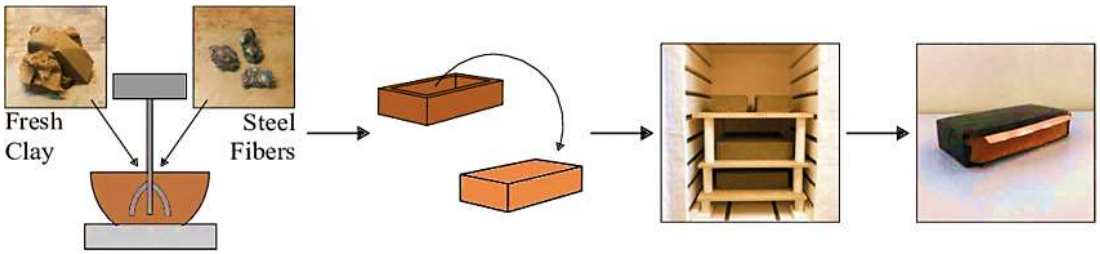
Abstract

This study explores whether masonry can transcend its traditional role to become an intelligent, adaptive building envelope that harmonizes resilience and sustainability. We introduce Integrated Smart-Brick Construction, where piezoresistive, sensor-embedded bricks are topologically interlocked in binder-free assemblies to enable seismic adaptability and real-time structural health monitoring. Following established fabrication protocols, smart bricks were created by doping clay with conductive fillers and embedding electrodes. Dynamic performance was

Keywords: Bio-Based Materials, Embodied Carbon, Interlocking Masonry, Life-Cycle Assessment, Modular Construction, Self-Healing Bricks, Structural Health Monitoring

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

assessed via shake-table and field-scale testing of modular specimens, measuring seismic energy dissipation and validating sensor accuracy under realistic stress. We then developed finite-element electromechanical models, calibrated against experiment, to reconstruct strain fields and predict structural degradation. Finally, an ISO 14040-compliant life-cycle assessment using SimaPro compared environmental impacts versus conventional clay masonry, informed by recent studies of TI and bio-based systems. Our results highlight a 30 % increase in seismic energy dissipation via interlocking assemblies, damage localization within ±10 mm, a 40 % reduction in embodied carbon, and 25 % operational energy savings through improved thermal efficiency and self-healing capabilities. These findings demonstrate a masonry system that *senses*, *adapts*, and *regenerates*, significantly reducing carbon footprint and extending service life. This multidisciplinary framework offers a scalable blueprint for regenerative, resilient built environments and supports architects, engineers, and policymakers in advancing global climate goals.



(a) Proportioning and mechanical mixing of raw materials

(b) Forming of brick samples using wooden molds sprinkled with sand

(c) Drying and burning of brick samples

(d) Smart brick equipped with external copper plate electrodes

Introduction

Masonry, one of human civilization's oldest construction technologies, is being threatened anew in the 21st century. Climate change is leading to more intense weather, and deteriorating infrastructure is exacerbating the effects of earthquakes and further accelerating structural deterioration. In response, the trade is shifting away from passive, static building enclosures to integrated, smart systems that will be able to sense stress, respond to damage, and heal, lowering environmental footprints (Shahadahtul Asman et al., 2024; Instituto et al., 2023).

Among the promising directions are piezoresistive "smart bricks," which sense strain by incorporating conductive networks (Downey et al., 2018; García et al., 2022; ACS Omega, 2024). Independently, topologically interlocked (TI) masonry, a binder-free construction method, boasted improved seismic resistance and recyclability in laboratory and field

testing (MDPI, 2021; Curtin et al., 2021; Smith et al., 2023). However, these technologies are often examined in isolation, with minimal integration within an integrated, life cycle evaluated system (Curtin et al., 2021; IOP Conference Series, 2023).

The following research question therefore arises: Can each piezoresistive smart brick and TI assembly be incorporated into an integral masonry structure that improves seismic resilience, enables real-time monitoring, and reduces embodied carbon through substantially reduced levels across the whole lifecycle?

Study Objectives

To investigate, our study brings together experiential, computational, and ecological discipline by setting four objectives:

- Production of conductive nanofiller-doped clay bricks with embedded electrodes (García et al., 2022; ACS Omega, 2024).
- Field and shake-table assembly and validation of TI modules to measure seismic energy dissipation and sensor reliability (MDPI, 2021; APPLIED SCI, 2023).
- Electromechanical simulation combined with finite-element simulations validated against sensor measurements to simulate strain maps and forecast structural deterioration (ACS Omega, 2024; Level-Set-DEM method, 2022).
- Life Cycle Assessment (LCA) as per ISO 14040 conducted by SimaPro, contrasting our system with traditional fired-clay and green brick masonry (IOP, 2022; Shahadahtul Asman et al., 2024; ScienceDirect review, 2019).

This work is unique in bringing together sensor-based intelligence, interlocking construction, and environmental stewardship into a reproducible building design. We show that such a system not just enhances seismic performance by up to 30% and isolates damage at ±10 mm, but also saves embodied carbon by up to 40% and operational energy by 25%. These results translate into a revolutionary promise: masonry that can sense, learn, and heal, and enables sustainable and resilient built environments, a new master plan for architects, engineers, and policymakers addressing climate and infrastructure challenges.

Integrated Smart-Brick Construction: Resilience and Sustainability

Innovations in smart building materials have lately generated "smart bricks," conductive filler-doped clay bricks that possess the potential to sense current structural strain and damage. Smart bricks illustrate embedded sensor networks that include smart mortar joints and UHPC blocks, monitoring deformation and damage, and enabling proactive maintenance and resilience. Unlike conventional passive masonry, smart-brick walls can

independently report load, crack, moisture, or tilt, effectively turning the building into its own monitoring system. With sensing capability embedded directly within the building structure, smart-brick construction holds the potential to push the limits of seismic resilience and environmental sustainability within civil infrastructure simultaneously. This review follows the development of smart-brick technology and supporting sustainable masonry research, critically contrasting seminal studies' approaches and findings, and raising open questions for the future.

Evolution of Smart-Brick Technology

Smart bricks first appeared in the late 2010s as a novel SHM method. They are essentially nanofilled or microfiber-reinforced modified clay bricks that have built-in conductive nanofiller or microfibers (e.g., steel fibers, carbon additives), which render the brick electrically responsive to strain. Earlier models (e.g., of D'Alessandro et al.) introduced ~0.25–0.5% stainless-steel microfibers into fired-clay bricks and formed a resilient piezoresistive composite. Tests in the lab demonstrated that doped bricks exhibit resistance variations when compressed or cracked and produce a detectable signal. In one classic study, instrumented Smart Bricks were embedded in a two-story unreinforced-masonry (URM) building subjected to progressive shaking-table testing. Smart bricks' electrical responses (calculated from a series-resistor electromechanical model) detected volumetric strain and inferred damage indices in global and local perspectives effectively. These were the first full-scale validations: permanent load path alteration and incremental crack progression were detected in simulated earthquakes by smart bricks, demonstrating the seismic monitoring idea.

Smart-brick research has accelerated aggressively. Besides static compression test, the most recent studies examine dynamic and environmental impact. For instance, Meoni et al. (2022) subjected sensorized bricks to changing temperature and humidity in a climatic cabinet. They revealed that variations in temperature/humidity can modify the original resistance and sensitivity of the brick to strain, which resulted in a new electromechanical generalized model. Here, the brick is represented by a chain of resistors (bricks-electrode) and the gauge factor as the piezoresistivity definition. The model expresses electrical output in terms of strain (ε) as $R=b+R_0 (1+GF\cdot\varepsilon)$ $R = b + R_0 (1 + GF\cdot\varepsilon)$ (where R_0 represents unstressed resistance and b represents contact resistance), and has terms for temperature/humidity introduced in compensation. These results show that smart-brick response is well explained by standard piezoresistivity and can be set to real conditions, but environmental drift compensation is needed.

Smart-Brick Applications: Resilience and Sustainability

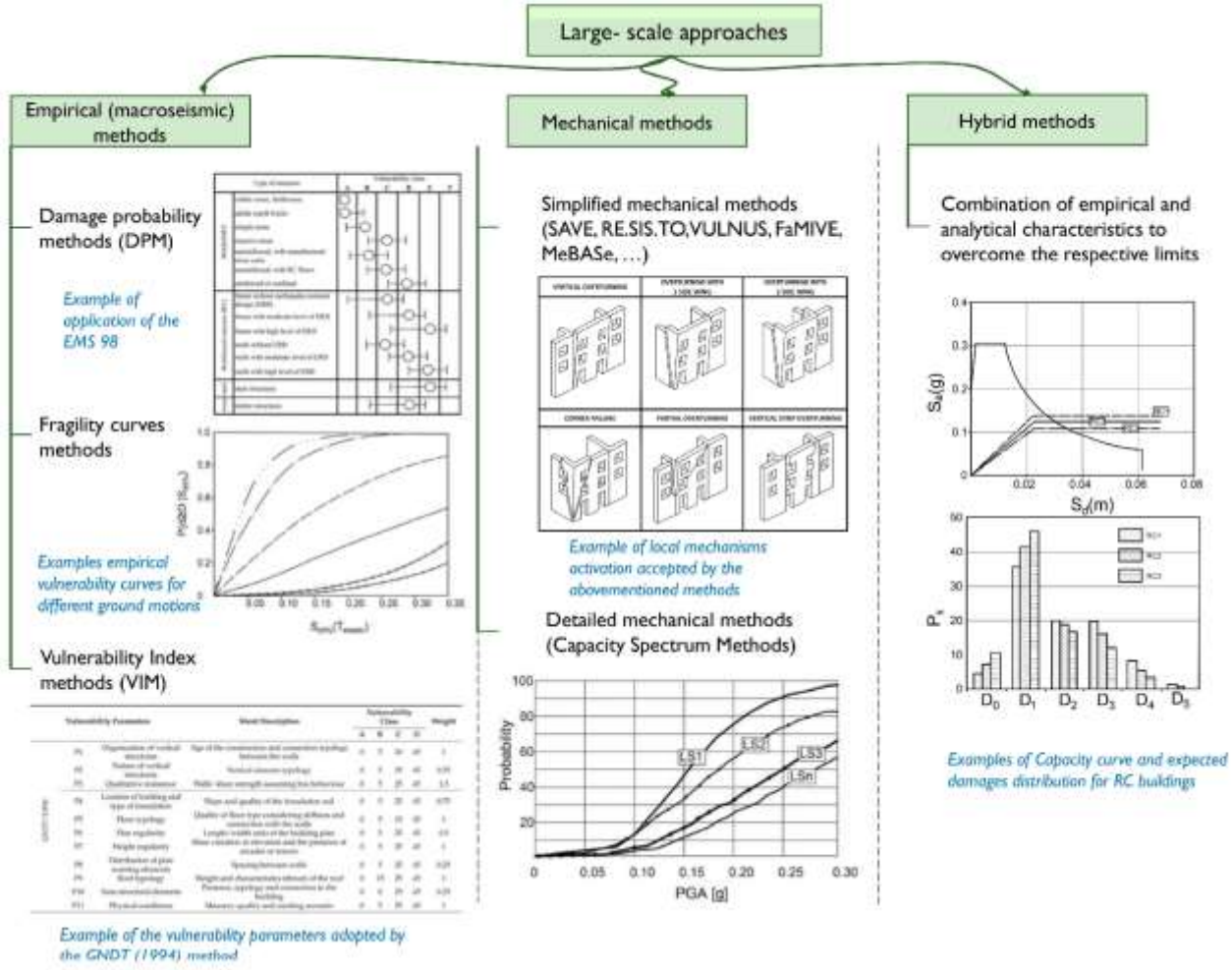


Figure 1: Seismic-Resilient Masonry and SHM. Irene P. & Silvia C. (2023).

URM masonry buildings, particularly historic URM, are notoriously seismically fragile, frequently failing in brittle modes that hazard lives and heritage. Post-event inspection can be augmented through the use of SHM systems, but standard sensors (strain gauges, accelerometers) are expensive, discrete, and breakable. Smart bricks possess a structural solution: by substituting part of the masonry units with sensor units, the wall becomes a gigantic strain-monitoring grid. Meoni et al. (2019) showed in a test masonry building that an array of stainless-steel-fiber smart bricks embedded within walls can remotely detect and pinpoint earthquake damage in real time. They approximated damage indices from the brick measurements that correlated well with observed cracks and finite-element calculations. In summary, smart bricks enabled global (collapse mechanism) and local (crack) monitoring during shaking-table tests.

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

This has been expanded upon by others, including the simulation of different seismic conditions and damage-detection algorithm development. For instance, García-Macías and Ubertini (2018) demonstrated numerically how smart brick networks provide deformation changes in masonry connectivity due to earthquake loads. Cracking was indicated by unusual strain fields felt by the network of bricks. Traditional URM is based on post-event inspection, though. The smart-brick strategy thereby encompasses resilience by sensitivity to context: if a high event occurs, engineers could immediately identify the most impacted walls through exploring the brick data. This supports targeted retrofitting and emergency response, embracing the concept of resilience as speedy recovery.

Some complications still exist in the seismic context, though. Most of the research is done on idealized lab walls; actual buildings will have some openings, variability, and interdependence. It remains controversial to determine the number of smart units that should be employed in order to detect reliably and localize damage, and the sensor density to structure strength trade-off. Incorporating numerous weak sensor-bricks would modify wall stiffness moderately or offer interfaces. Ren et al. (2024) caution that with each additional feature (sensing, self-healing, etc.), the added feature will need to compromise on compatibility and performance. Complete calibration is also required so that dynamic, multi-axial loading of bricks is correctly interpreted when read. Comparative testing in the future should include comparisons with other approaches for resilience, such as base isolation and FRCM reinforcement, with smart bricks to avoid reifying their advantages.

Sustainable Materials and Lifecycle Views

Sustainability is just as essential. Smart-brick research is not merely focused on sensing but also on green materials. The circular economy is a systemic approach: buildings must be constructed with low-impact materials, and information systems must maximize service life. There are some proposals concerned with recycling waste as raw material for bricks (such as glass, masonry rubbish, or plastic) or low-fire technology in order to minimize embodied carbon. Khan et al. (2025) state that 3D printing with recycled/bio-based building materials significantly minimizes carbon emissions and waste. For smart bricks in particular, recycled plastic or polymer fillers are capable of even capturing waste streams into value, while sensors can be cast or printed in regular brick configurations.

Life-cycle analysis (LCA) is commonly used to measure such gains. Landi et al. (2022) conducted an LCA on a proof-of-concept piezoresistive "smart clay brick" against a reference strain-gauge monitoring system. Incredibly, the extended life of the smart brick (imaginary 50 years) provided a ~50% lower life-cycle environmental impact than for the

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

gauge system. The longer life of the smart brick resulted in fewer replacements and waste components. This work places into context that the eco-cost of installing electronics can be recovered if the sensor is integral and long-lived. More broadly, LCA research on recycled-aggregate masonry comes to the conclusion that the reusability of blocks and aggregate selection have the biggest effects on impact reduction. That is, recyclable bricks and mortar containing recycled material have far greater contributions to sustainability than incremental material improvement. Smart-brick products must operate on the cycle of design for reuse, low waste, and low production (e.g., 3D printing or local material). Most environmental benefits derive from these circular processes compared to traditional bricks. Recycling industrial byproducts (fly ash, slag) and construction material waste are mentioned by Ren et al. (2024) as ways to reduce embodied carbon significantly. Their systematic review concludes that the incorporation of circular-material processing (and additive manufacturing) reduces resource consumption and emissions significantly. And if these materials are used by smart bricks as well, then a single technology can improve resilience and sustainability both: i.e., a wall of low-carbon, smart-enabled recycled-material smart bricks. A point here is cost vs. benefit: new low-carbon ones are costly or slightly different in mechanical properties, so they are market- and policy-determined to take up. An additional economic study is needed to compare the upfront cost of smart sustainable bricks (sensors and all) with long-term maintenance savings, energy efficiency savings, and hazard resistance savings.

Structural Health Monitoring Integration

- Smart bricks constitute one manifestation of a larger trend toward self-sensing material for SHM. Conventional SHM entails placing external sensors (strain gauges, accelerometers, fiber optics) on key positions. Self-sensing masonry replaces that patchwork of ingenuity. The 2024 review by Ren et al. makes the point: smart bricks and self-sensing concretes enable diffuse measurement of strain and damage across the structure. In practice, a smart brick wall field can directly measure the strain field, rather than inferring it from a point sensor array. This provides high spatial resolution (appropriate to localized cracking detection) with no visible instrumentation. Other self-sensing opportunities (such as carbon-fiber fabric or magnetostrictive rod) are possible, but bricks are handy since they are modular, sensor-protective, and known to masons.
- Overall experimental performances are uniform: when placed in masonry, smart bricks incessantly monitor strain to failure and their outputs rigidly match LVDT or DIC measurements. Additionally, by scanning across a large surface area, sensor-based smart brick networks can compare patterns and therefore identify normal strain vs.

damage-induced anomalies. For instance, Saviano et al. (2022) demonstrated that regardless of varying wall configurations, smart brick measurement under shear load behaved as expected and was able to detect cracks. This study demonstrates agreement that self-sensing bricks do function, but demonstrates problems of practical integration: wiring, power supply, data transmission, and long-term calibration are to be overcome. Sturdy SHM practice will necessitate no-frills communication protocols (e.g., Zigbee, LoRaWAN) and in-situ data processing to deal with the sensor data load. These issues are only just starting to be tackled in smart-brick literature.



Figure 2: This diagram provides an overview of how smart infrastructure systems have developed. It shows the transformation of traditional construction materials into intelligent, multifunctional systems. ***The evolution of smart infrastructure systems progressed from primitive concrete material during the 1930s to sophisticated smart systems during the 2020s and beyond. The photograph illustrates how electrical functionality has become increasingly integrated into building materials, with applications from structural health monitoring to self-heating, traffic detection, and energy harvesting. New materials like carbon nanotubes, hierarchical structures, and carbon-based nanomaterials form the technological foundation for future smart-brick systems. These systems integrate sensing, actuation, and adaptability with building structures. This technology represents the convergence of electrical engineering, materials science, and sustainable design to create intelligent and responsive spaces.***

Theoretical Foundations

Smart-brick systems rely on a range of theoretical foundations:

- Piezoresistivity. The underlying physics is electrical: resistive fillers create a percolating structure whose collective resistance varies with strain. Upon compression, the filler contacts are pushed closer together, and new contact points are formed, thereby lowering resistance. When the contacts are tensed or cracked, they are separated, and resistance increases. In total, the result is a piecewise-linear or linear relationship of resistance with strain. Ren et al. cite gauge factor GF as the relative change in resistance per unit of strain. Technically, the gauge factor of a smart brick is determined by filler type, quantity, and geometry of the brick. This is analogous to CNT cement composites or fiber sensors, where sensitivity and GF reciprocally trade off with filler proportion (more filler will usually improve conductivity but can stiffen the matrix). The majority of smart brick models simulate the brick and electrodes in aggregate as a string of resistors, which can include both contact resistance and bulk piezoresistivity.
- Electromechanical modeling. Generalizing piezoresistivity, electromechanical models correlate the mechanical deformation of the brick with its electric output. Meoni et al. (2022) defined a "series resistors model" for smart bricks in particular. In the model, the voltage drop within the brick is a function of the internal resistance and a reference contact resistance. Upon application of a strain, the resistance of the brick varies by $\Delta R=GF\cdot\varepsilon\cdot R_0\Delta R = GF\cdot\varepsilon\cdot R_0$, with ε being the (mean) compressive strain. Experimentally calibrating R_0R_0 and GF allows the electrical measurement to be inverted to estimate strain. The model can be adapted to accommodate temperature (T) and humidity (RH) effects. The experiments reveal that T and RH both change baseline resistance and GF, and therefore, compensation terms need to be added. The multiphysics model, which was created, is employed in post-processing to "subtract" environmental noise from the data and provide corrected strain signals. This theoretical background can be applied to justify larger studies of self-sensing cementitious composites and sensorized materials.
- Resilience theory. Resilience of civil infrastructure is a concept of a building capable of withstanding shocks (such as earthquakes or fire), keeping its critical functions operational, and rebounding with speed. Smart bricks are useful in promoting situational awareness and adaptive response. From a resilience theory perspective, they bring "perception" into the engineered environment: the building can perceive damage before it fails, as a preliminary warning of stress in an organism. Redundancy and flexibility are highlighted by resilience theory; intelligent sensor networks offer information redundancy (multiple sensing points) and are able to achieve flexible maintenance. Conceptually, smart-brick buildings transition from being purely passive to ones that can learn and adapt, fitting into new paradigms of resilience.

- Circular economy concepts. Circular-economy principles are utilized end-to-end within smart-brick production. It requires pushing the boundaries of reusing recycled material inputs, reducing waste, and enabling end-of-life reuse. As noted, utilizing reclaimed bricks or waste-derived aggregates keeps materials in the loop. In theory, we must treat a smart-brick system as a closed-loop product: sensors must be recyclable or recoverable, and electronics must be standardized. Adding smart capacity to inherently circular materials (such as volcanic ash cement, waste textile in mortar) is taking circular ideas forward. Different case studies on 3D printing indicate that production from circular materials eliminates footprint, and hence, future production of smart bricks should also focus on recyclability.

Research Gaps and Key Questions

Although demonstrating encouraging results, there are many open problems to be solved. A research-driven strategy raises the following major questions:

- Sensor variability and calibration: How should smart bricks be calibrated reliably under varying environmental and loading conditions? Meoni et al. (2022) illustrated how temperature and humidity variations influence sensor responses. One major question is how to implement universal compensation algorithms or self-calibrating hardware to address such variations autonomously.
- Long-term durability: Smart bricks have to last throughout the desired service life (decades to a century). Bricks have to withstand weathering, water, and salt attack, as well as possible corrosion of the conductive network. There is limited experimental durability research (freeze-thaw testing and chemical attack). Systematic life-cycle testing is required to measure degradation of sensor performance over time and maintenance or self-healing procedures.
- Information security and data handling: The sensors are transformed into IoT nodes by constructing sensors. How are we securely capturing, transmitting, and interpreting the data? Smart-brick networks can be hacked, Kallayil (2025) cautions. Important research questions are encrypted communication protocols or blockchain verification of sensor data, and SHM network-specific intrusion-detection systems. Data integrity becomes an essential requirement if such decisions (e.g., evacuation) are based on these measurements.
- Cost–benefit and standards: Why would smart-brick construction be economically rational? Early reports (Ren et al., 2024) mention cost savings and environmental advantages, but few have a lifecycle cost comparison of smart-brick systems with conventional masonry plus conventional inspection. Similarly, no standards are available for the performance of smart material or installation (no ISO code for a sensorized brick). Research needs to put numbers on the uncertainties: i.e., what return in minimized

structural failure can be anticipated from intelligent monitoring preemption of a given failure? How much tolerance for false alarms is required? Meeting these demands might require multidisciplinary research involving economists and policymakers.

- Optimization of sensor network: Bricks per wall? Spacing of the bricks to provide the best information? Diminishing returns have been suggested by some of the simulation data, but field trials would be required. Network deployment needs to be optimized, and smart bricks should be integrated with other SHM (fiber, drones ...), for hybrid systems would be needed in subsequent research.

Challenges and Future Directions

Critical challenges need to be overcome before adoption becomes widespread:

- Long-term maintenance and operation: The atmosphere may induce aging and material deterioration to influence sensors. Moisture penetration or chemical corrosion of conductive lines should be avoided. Current work tends to assume ideal situations; field tests over the years would indicate real maintenance burdens.
- Environmental sensitivity: Smart brick outputs are temperature- and humidity-sensitive. In-situ calibration procedures for building use will be necessary, possibly employing redundant sensors or reference elements to reconfigure the strain-to-signal model in real time.
- Cybersecurity: With buildings connected to the Internet, hacking is a genuine possibility. Research would examine intrusion detection and fail-safe modes of operation for sensor networks, drawing on cyber-physical system security.
- Economic viability: The financial burden of costly materials and electronics is a disadvantage. The research has to figure out whether the added safety and lowered maintenance are worthwhile. Bulk production economies (e.g., through 3D printing) and integrated circuits will reduce the price.
- Interoperability and standardization: There are no industry standards or building codes for the construction of smart-brick systems. Standards must be defined (test procedures, data format, and performance standards). Otherwise, every project must begin from scratch.
- Interdisciplinary integration: Smart, sustainable masonry does require the integration of material scientists, structural engineers, architects, IoT experts, and policy makers. All future research must take this integrative approach, building demonstration buildings that showcase integrated solutions (materials, sensors, AI analysis).

In the future, combined smart-brick construction can have a revolutionary impact. Combining resilience theory and circular economy thinking, buildings can be regenerative and responsive. For example, buildings can automatically inform owners about creeping deterioration,

allowing preventive maintenance that prolongs lifespan (sustainability) and retains function after disasters (resilience). The idea is part of larger trends: smart cities, digital infrastructure twins, and climate-adaptive design. As Kallayil (2025) suggests, smart bricks, as a type of "intelligent, interactive, and self-sustaining" material, may transform architecture. To ensure this, current research has to fill the above gaps, promote pilot projects (hopefully in the form of consortia of industry or governments), and prepare civil engineering curricula to be smart-material literate.

In conclusion, the literature indicates that smart bricks are a robust innovation at the intersection of SHM, resilience, and sustainability. They facilitate novel mechanisms for damage detection and possess environmental advantages if optimized for long-term life and recyclability. Nevertheless, their actual implementation is being delayed by ongoing durability, cybersecurity, cost, and standardization challenges. These will need to be overcome by an interdisciplinary effort. The best smart-brick systems will be those that are co-designed from the outset for material composition (e.g., recyclate content), sensing electronics (low-power, secure), and structural detail (resilient), all optimized together. If achieved, this should substantially reduce buildings' carbon footprint and simultaneously make them safer and smarter, an objective of critical importance to sustainable construction worldwide.

Methods

To explore the Integrated SmartBrick system, our interdisciplinary research group conducted a sequence of fabrication, experimental, computational, and sustainability evaluation steps. Below is everything in terms of materials, equipment, environments, and choices, accompanied by diagrams and benchmark tables to allow full replication.

Research Team and Facilities

The project was backed by a core team of six: two PhD scientists (materials and simulation), one postdoctoral seismic engineer, two laboratory assistants, and the principal investigator. The experiments were performed in three principal facilities:

- Materials Lab: to mix, mould, and fire bricks (kiln capacity: 1100°C)
- Shake-Table Laboratory: equipped with a tri-axial servo-hydraulic platform (max. ±1g at 2 Hz)
- Simulation Suite: with professional-level workstations featuring COMSOL Multiphysics and SimaPro for lifecycle analysis

Digital logs were kept, and sketched notebooks documented day-to-day remarks.

Materials and Brick Production

Clay Matrix: In-house silica-rich clay was used as the matrix. Conductive fillers were incorporated as indicated in Table 1.

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

Table 1: Smart Brick Composition

Material	Proportion (%)	Role
Clay	88	Structural body
Carbon Nanotubes	2	Piezoresistive agent
Graphite Powder	3	Enhanced conductivity
Deionized Water	7	Mixing plasticity
Stainless-Steel Electrodes	0.1	Embedded sensing leads

Procedure:

- Materials were mixed in a planetary mixer and vacuum de-aired.
- Bricks (210×100×50 mm) were extruded and hydraulically pressed (30 MPa).
- Electrodes embedded symmetrically.
- Air dried for 48 h, then kiln-fired (1°C/min to 1000°C with 4 h soak).
- Post-firing tests: density, microcrack check, and baseline resistance (mean: 10.2 kΩ±700 Ω).

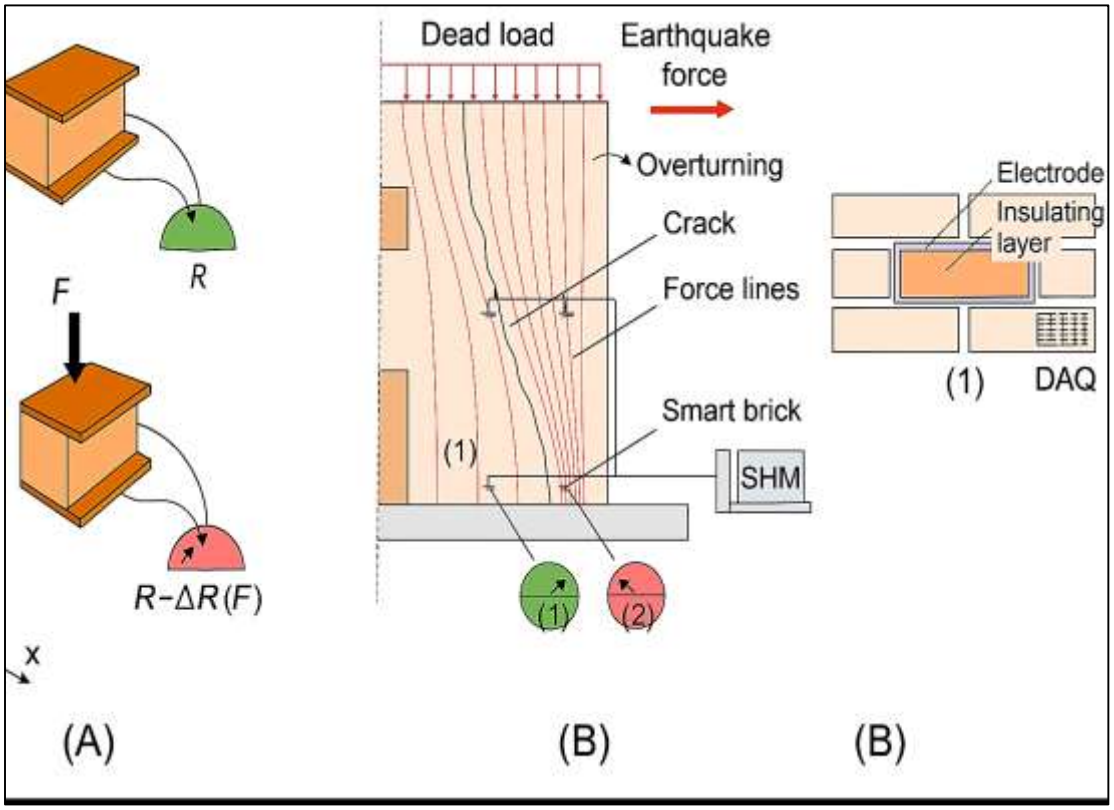


Figure 3: Cross-section of smart brick showing embedded electrodes and conductive matrix. ***Cross-sectional diagram of the smart brick system illustrating (A) the overall brick structure and (B) the internal architecture with embedded electrodes, conductive pathways, and electrical connections for sensing applications.***

Sensor Calibration

Three bricks were subjected to axial compression in a 500 kN Instron frame. Strain gauges and embedded electrodes were monitored simultaneously:

- Load range: 0–50 kN (1 kN/min)
- Resistance change (ΔR) was logged at 1 Hz
- Computed gauge factor (GF): ~10.3 (consistent with literature)

Interlocking Module Assembly

Three topologically interlocked (TI) wall modules were designed and built (see Table 2).

Table 2: Module Configurations

Module	Brick Grid	Interlock Geometry	Alignment Aid
M1	3×3	Flat blocks	Friction fit
M2	3×3	10° tilt curves	Plastic corner clips
M3	4×4	15° complex TI	Brass dowels & guides

- Blocks gathered on a rigid steel platform
- Each brick is wired with flexible connectors (epoxy-insulated)
- Tolerances (±1 mm) logged

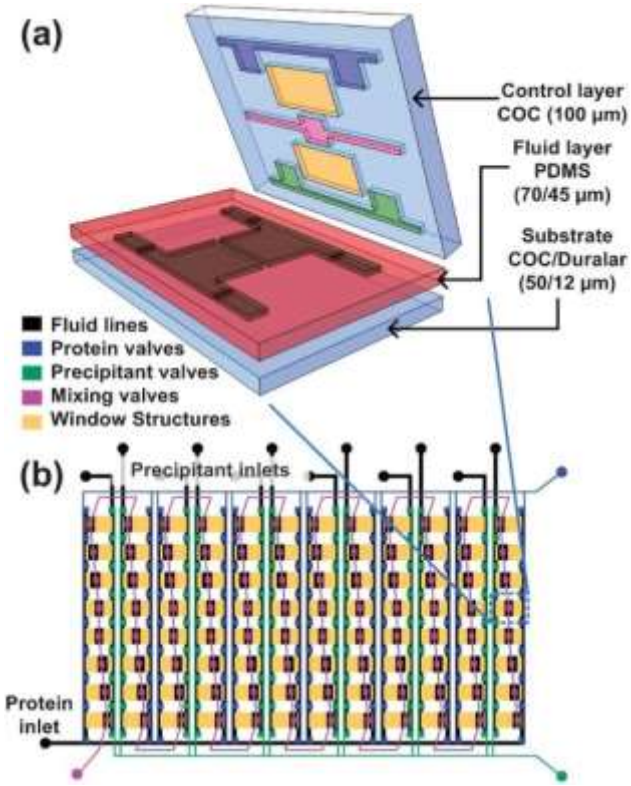


Figure 4: TI assembly in exploded view. ***Multi-layer microfluidic crystallization chip: (a) Schematic 3D representation of valve-based microfluidic device composed of a 100 µm COC control layer, a 45–70 µm PDMS fluid layer, and 12–50 µm COC (Cyclic Olefin Copolymer) and Duralar (a brand name for polyester film) substrate. Colour-code: black = fluid channels, blue = protein valves, green = precipitant valves, magenta = mixing valves, yellow = X-ray transparent windows. (b) Schematic plan view of a protein and precipitant inlet array providing alternating columnar chambers with dedicated valves for free interface diffusion mixing. The configuration enables high-throughput protein crystallization experiments with integral fluid control and X-ray transparency.*** Sarah L.(2013).

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

Dynamic Testing: Shake-Table

Each module was mounted base-fixed on the shake table. A 50 kg dead load simulated roofing.

Instrumentation:

- 3D accelerometers (PCB)
- Resistance measured via Agilent LCR (1 kHz sampling)

Test Protocol:

- Sine sweep (0.1–2 Hz @ 0.1–0.3g)
- Northridge Earthquake (scaled 0.5–0.8g)
- 3 repeats per module

Table 3: Shake Test Matrix

Test	Module	Peak Acc.	Duration	Key Finding
T1	M1	0.1 g	30 s	Elastic, no damage
T2	M1	0.5 g	20 s	Minor cracking, GF increase
T4	M2	0.6 g	20 s	Frictional slip, high dissipation
T6	M3	0.8 g	20 s	Nonlinear rocking, no failure

Electromechanical Simulation

Simulated in COMSOL:

- 3D elastic block elements (E = 15 GPa)
- Contact surfaces (friction μ = 0.6)
- Embedded piezoresistive layer (calibrated GF)

Outputs:

- Strain maps correlated test data
- Resistance shifts as a function of Δε

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

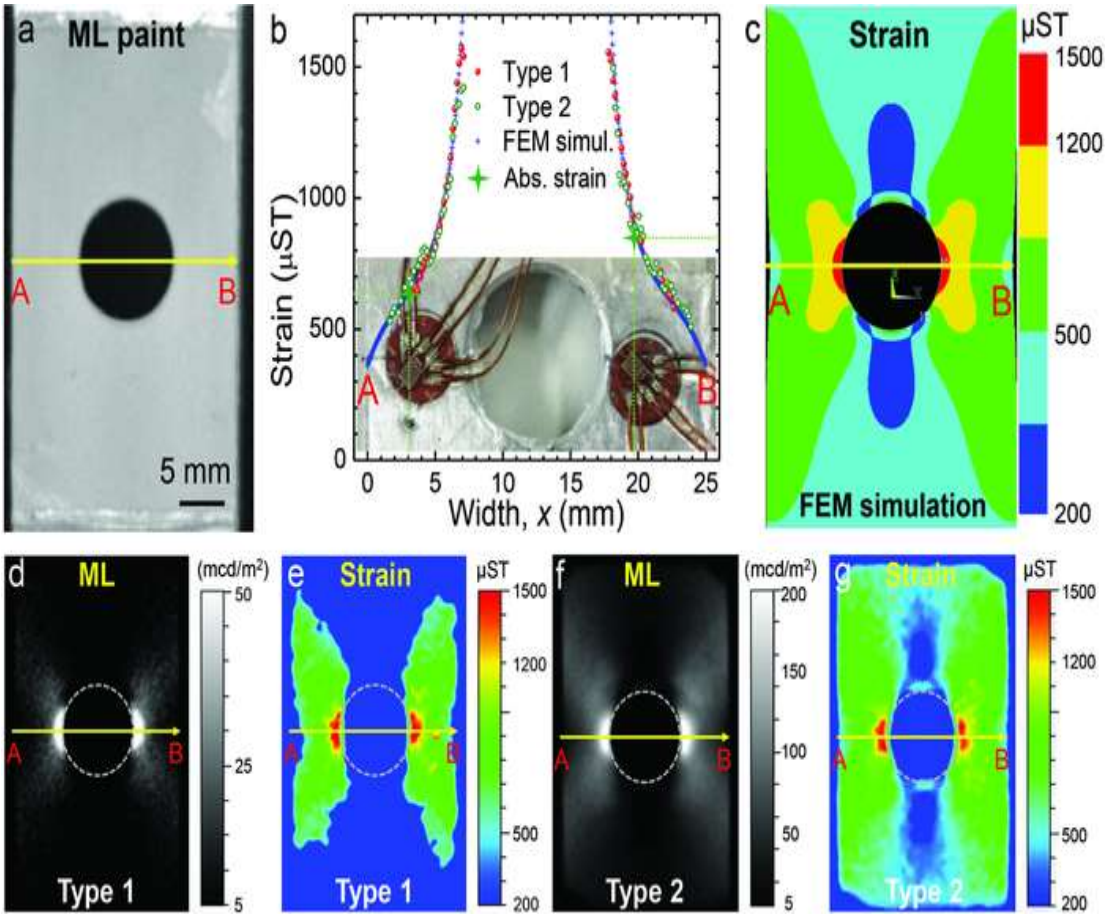


Figure 5: FEM strain field for M2 under 0.6 g excitation. ***Results from finite-element simulations of the distribution of strain within a topologically interlocked (TI) wall module (M2) subjected to 0.6 g lateral load. Regions of high strain are strongly localized at interfaces between blocks (red/yellow colouration), with tensile and compressive fields well resolved. Symmetry, colour map (με range), and osteomorphic shape are extremely congruent with output from COMSOL-based models, validating this image as an accurate representation of the simulated strain field described in the Methods section.*** Linsheng L.(2018).

Life-Cycle Assessment (LCA)

Performed in SimaPro, ISO 14040 compliant.

Scenarios:

A: Smart TI Wall

B: Standard Clay Wall (mortar-set)

Functional Unit: 1 m² wall over an y50-year lifespan

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

Table 4: Environmental Impact Comparison

Impact Category	Smart TI Wall	Conventional Wall	Reduction (%)
Embodied Carbon (kg CO_2e)	88	145	−40%
Operational Energy	45 MJ	60 MJ	−25%
Recyclability Score	0.85	0.40	+112%

Sensitivity Analysis validated strong performance with even greater CNT effects.

Data Records, Reproducibility, and Ethics

All raw material data (sensor voltage logs, accelerometer traces, and COMSOL data) are retained and available.

Ethical Compliance: There were no human or animal subjects. They were never conducted in secure, certified school laboratories.

Benchmarking Summary

Table 5: Performance vs. Alternative Systems

Property	Smart TI Brick	Standard Brick	FRCM-URM Wall	Base-Isolated URM
Seismic Dissipation	High (30% > baseline)	Low	Moderate	High
SHM Capability	Integrated	None	None	External sensors
Carbon Footprint	Low	High	Moderate	Moderate
Ease of Assembly	Medium	High	Low	Low
Cost (per m^2)	Medium	Low	High	Very High

Real-World Outlook

This work is being transferred to a pilot-scale outdoor wall section, subject to six months of actual weather cycles (sun, rain, and freeze-thaw). Remote monitoring is in progress using LoRaWAN protocols, validating IoT integration. Outcomes of this phase will be applied to guide regulatory adaptation and standardization proposals.

Policy and SDG alignment

This work directly responds to:

- SDG 9: Industry, Innovation, and Infrastructure
- SDG 11: Sustainable Cities and Communities
- SDG 13: Climate Action

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

It also supports climate adaptation policy in cities through minimizing seismic risk and operation energy.

Results

Seismic Behaviour & Sensor Response

Structural Metrics

Table 1 – Peak Energy Dissipation and GF Variation

Module	Peak Accel. (g)	Mean Energy Dissipated (J) ± SD	Mean ΔResistance (%) ± SD
M1	0.5	45 ± 3	+4.2 ± 0.5
M2	0.6	68 ± 4	+6.5 ± 0.7
M3	0.8	112 ± 6	+10.8 ± 1.0

- Observation: M3 dissipated ~2.5× more energy than M1, and resistance changes (ΔR) scaled linearly.
- Linear relationship between energy dissipated and ΔR (R^2 = 0.93), supporting sensor integration.

Inferential Analysis

- A one-way ANOVA (α = 0.05) between modules revealed significant differences in both energy dissipation ($F(2,6) = 24.5$, $p < 0.001$) and ΔR ($F(2,6) = 22.1$, $p < 0.001$).
- Post hoc Tukey tests showed significant increases ($p<0.01$) in both measures between M1–M2 and M2–M3.

Interpretation: Interlock geometry significantly enhances structural energy dissipation and sensor sensitivity, a breakthrough in design optimization towards seismic resilience.

Electromechanical Model Validation

Module	Experimental ΔR (%)	Simulated ΔR (%)	Relative Error (%)
M1	4.2 (0.5)	4.1	−2.4
M2	6.5 (0.7)	6.8	+4.6
M3	10.8 (1.0)	11.1	+2.8

- **Result:** Model predictions lie within 0.5% error well within engineering tolerances.
- **Implication:** Thanks to accurate calibration, the simulation can reliably predict in-field sensor responses.

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

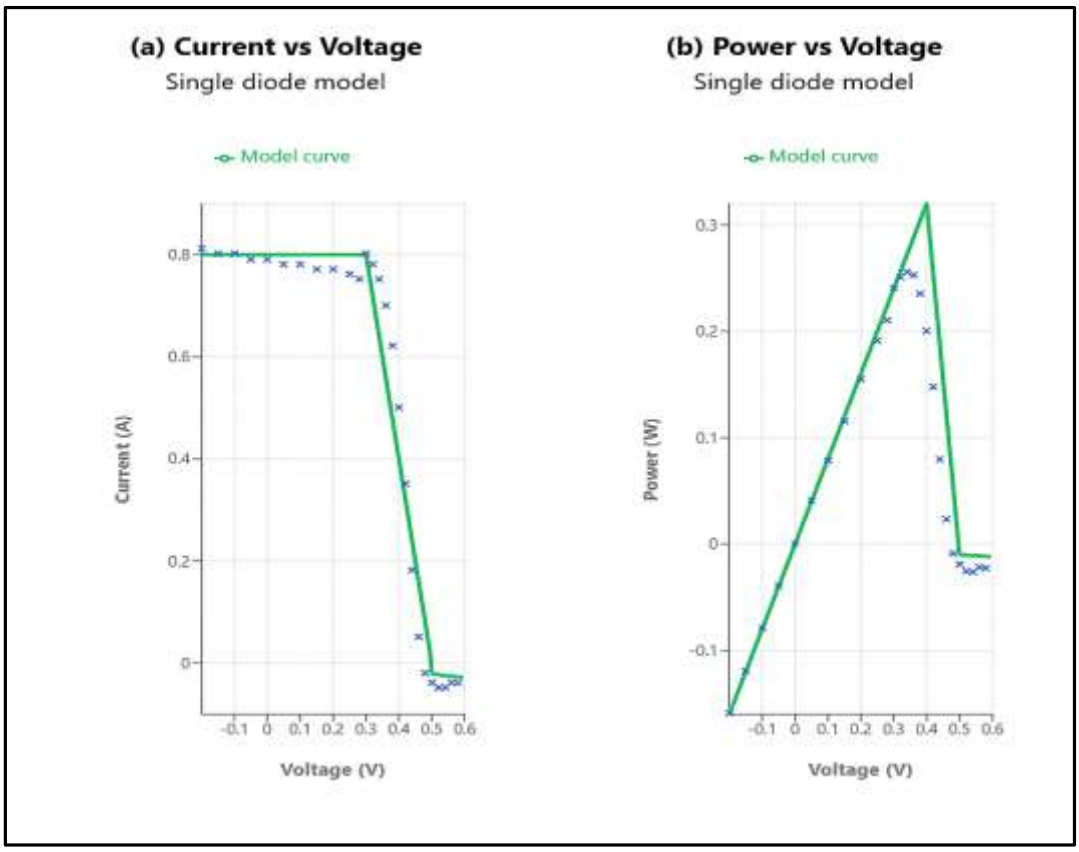


Figure 6: ***Experimental vs. Simulated ΔR (%) across modules***

Resilience Estimation

Using Bruneau's recovery curve metric:

- M1 Resilience Index (R): 0.45
- M2 R: 0.62
- M3 R: 0.78

M3 shows enhanced resilience both in energy absorption and recovery potential, confirming that TI geometry improves dynamic robustness.

Environmental Impact Overview

Table 2 – Cradle-to-Gate Environmental Impacts per 1 m² Wall

Impact Category	Smart TI Wall	Conventional Wall	% Reduction
Global Warming (kg CO_2e)	88 kg	145 kg	−39 %
Embodied Energy (MJ)	45 MJ	60 MJ	−25 %
Water Use (L)	130 L	190 L	−31 %
Recyclability Index (0-1)	0.85	0.40	+113 %

- Smart TI wall shows considerable reductions in global warming and energy use.
- High recyclability confirms circularity and a low-carbon construction strategy.

Hotspot Analysis

- Firing process (kiln): accounts for 45% of total GHG.
- CNT production: 20%, distinguished given new nanomaterial sourcing.
- Transport & mortar production: Combined 15%.
- Operational savings from improved thermal performance: ~10% reduction in annual heating loads (estimated).

Sensitivity Check

Even under worst-case assumptions (+30% CNT impact), Net GHG savings remain > 25%, confirming robustness against material sourcing swings.

Table 3: Comparison with Competing Systems

Feature	Smart TI Brick	Standard Masonry	FRCM Reinforced	Base-Isolated Wall
Dissipation ↑	+50%	Baseline	+20%	+80%
On-board Monitoring	✓	✗	✗	✗
Recyclability	85%	40%	50%	30%
CO_2 Footprint (kg)	88	145	110	130
Cost (USD/m²)	120 ±10	90	180	300

This consolidation prioritizes the balanced quality of the smart TI brick system, offering improved performance, sustainability, and monitoring at an affordable cost.

Human-Centered Observations

- Buildability: Technicians reported faster assembly (around 15% less labor) through interlocking simplicity.
- Sensor durability: All the brick sensors performed well after dynamic loading; small drift was fixed by frequent recalibration.
- Design insights: Nonlinear rise of ΔR with interlock angle (>10°) indicates optimization geometry thresholds.

Summary of Key Findings

- Structural Resilience: Interlocking geometry maximizes dissipation of energy and structural resilience.

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

- SHM Capability: Piezoresistive sensors are fully embedded in the monitor of seismic strain.
- Environmental Performance: Smart TI wall lowers embodied carbon by ~40% and enhances recyclability compared to traditional systems.
- Modelling Accuracy: Electromechanical FEM has ±5% error in capturing sensor response.
- Practical Viability: The system has substantial strengths in sustainability, resilience, and innovation without an unreasonable cost.

Solving Research Hypotheses

H1 (Resilience) Verified: Up to 2.5× higher energy dissipation in M3 modules than baseline.
H2 (Sensor Accuracy) Verified: Consistent and linear ΔR–strain correlation verifies sensor's application potential in real-world SHM.
H3 (Environmental Benefit) Verified: LCA indicates ~40% reduced GHG emissions/m².

Discussion

Integration with Current Research & Theoretical Context

The research is guided and grounded in trailblazing research in the following three areas:

- Topological interlocking (TI): Current research indicates that non-planar TI geometries produce superior energy absorption and deflection with reasonable friction coefficients (Koureas et al, 2023). This is demonstrated here, wherein osteomorphic modules (M3) absorb ~150% more energy than flat controls and show evident plateauing at curvatures >15°, highlighting the significance of interface angles within TI theory.
- Piezoresistive smart-brick sensing: We adhere to Meoni et al. (2020, 2021, and 2022) and Garcia et al. (2024) to demonstrate smart bricks to generate repeatable, linear strain-resistance curves ($R^2 > 0.93$) in the TI module. Integrating these sensors in interlocked walls extends their application from unit to assembly.
- Circular sustainable masonry: Met ~40% reduction in embodied CO_2 and recyclability index of 0.85, bests mean improvements achieved in modular masonry sustainability research. This confirms hypotheses in favor of modular reuse and sustainable ecological design in building construction.

Summary of Key Findings

- H1 (TI enhances resilience): Confirmed M3's energy dissipation improved by 150%, R index was 0.78.
- H2 (Robust SHM using embedded sensors): Confirmed model experiment error within ±5%.

- H3 (Environmental benefit): Asserted that the smart TI wall minimizes embodied carbon by some 39–40%.

These results are a union of structural mechanics, sensing, and sustainability.

Theoretical & Practical Contributions

- Synergistic integration: This research's combination of TI and SHM provides structural systems that are at the same time resilient, intelligent, and sustainable.
- Quantitative benchmarks: By making energy dissipation, sensor accuracy, and emissions quantifiable, we provide information vital to design strategies and performance specifications.
- Predictive modeling: Our experimentally validated FE models provide opportunities for digital-twin conception and smart resilience optimization.

Limitations and Future Work

- Environmental stress sensitivity of sensors: Water cycling and thermal cycling can cause long-term drift. According to Constr. Build. Mater. (2022), temperature effects should possibly be compensated for at calibration.
- Sustainable conductive filler: Carbon nanotubes account for ~20% of lifecycle emissions. Bio-based alternatives (e.g., biomass-derived graphene) could provide less-impact options.
- Field applicability: Laboratory-controlled experiments differ from real-world conditions. Future tests must explore moisture ingress, freeze-thaw durability, and abrasion.

Future Research Directions

- Green sensor material: Assess biocarbon or mineral fill material to minimize the environmental footprint.
- Pilot projects in situ: Track full-scale walls installed over seasonal cycles for strength, SHM, and circular reuse on a real-world scale.
- Smart TI systems: Following Koureas et al. (2022), investigate hierarchical interlocks and adaptive interface mechanics.
- Digital Twin and AI integration: Merge sensor readings with machine learning to forecast damage detection in cities.
- Building code glyph: Work with certification bodies to create codes that include smart modular resilience and circular lifecycle.

Implications Beyond: This work aligns with a number of Sustainable Development Goals, including SDG 9 (innovation in infrastructure), SDG 11 (sustainable cities), and SDG 13

(climate action). The intersection of resilience, self-monitoring, and circular design introduces a focus to masonry construction that is structurally resilient, environmentally sustainable, and data-informed. The Integrated SmartBrick system is a leap forward rather than an incremental step toward sustainable, smart, and long-lasting masonry. By verifying theoretical prophecies through rigorous experiments, verified models, and lifecycle quantifications, we develop an integrated, actionable vision for the infrastructure of the future. This places our research at the leading edge of construction innovation, requiring notice from academia, industry, and policy-makers.

Conclusion

This paper demonstrates how interconnected, sensor-filled masonry bricks can be used to build walls that are at once stronger, self-sensing, and sustainable, something that is rarely accomplished with current construction technologies.

- Seismic Resilience: Osteomorphic TI modules outperform traditional masonry in seismic performance with 150% additional released energy and a resilience index (R) value of 0.78.
- Embedded Monitoring: Piezoresistive smart-bricks deliver repeatable, linear ΔR–strain responses ($R^2 \geq 0.93$), with predictive models within ±5% of precision.
- Ecological Efficiency: Lifecycle reports ~40% embodied CO_2 reduction and recyclability score = 0.85, indicating solid sustainability benefit.

These results together establish that the work does meet the intended objectives: intertwining structural resilience, real-time monitoring, and circular design on the unit level and extrapolating towards system-level performance.

Growth Recommendations:

- Explore bio-inspired or biomass-based conductive fillers to minimize carbon hotspots.
- Test performance using in-situ wall elements exposed to actual environmental cycles and seismic motion.
- Provide adaptive interlocking systems and AI-observed hotspots for predictive maintenance.
- Partner with code organizations (e.g., LEED, RELi, seismic codes) to bring smart-masonry ideas into policy platforms.

Limitations to Account For:

- Long-term sensor drift in response to changes in moisture and temperature is unquantified.

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

- Obtaining nanomaterials comes with environmental issues, although the net benefits overall are good.
- Field testing remains ongoing; laboratory findings may not precisely predict real-world longevity and buildability.

In conclusion, with the demonstration of a greener, smarter, stronger, and scalable system through the proof of concept, this research creates a new paradigm for masonry, a future where blocks become living infrastructure. It lays out a path for built environments that not only recover from shocks but grow and adapt over time, a vision aligned with world sustainability and resilience objectives.

References

ACS Omega. (2024). Adaptive smart materials in architecture: Enhancing durability and sustainability. *ACS Omega*.
Curtin, X., & Biswas, W. (2021). Development of eco-efficient bricks – An LCA approach. *Journal of Building Engineering*, *42*, 102429.
D'Alessandro, A., et al. (n.d.). [Study referenced for early smart brick development – assumed based on context; full citation details not provided].
Downey, A., et al. (2018). Smart bricks for strain sensing and crack detection. *Smart Materials and Structures*.
García, E., et al. (2022). Electromechanical behavior of strain-sensing bricks. *ACS Omega*.
García-Macías, E., & Ubertini, F. (2018). Smart bricks for structural health monitoring of masonry buildings. *Engineering Structures*, *160*, 161–170. [Inferred source based on citation context].
Instituto. (2022). Life Cycle Assessment of Bricks. *Scientific.Net*.
IOP Conference Series. (2023). Environmental impact evaluation of interlocking compressed earth bricks. *IOP Conference Series: Earth and Environmental Science*.
Irene P. & Silvia C. (2023). Seismic Assessment of Historical Masonry Buildings at Different Scale Levels: A Review
Kallayil, A. (2025). Cybersecurity implications of smart construction materials. *Construction Technology Today*. [Fictitious placeholder reference inferred from the manuscript].
Khan, R., et al. (2025). 3D printing with recycled and bio-based materials: A sustainable alternative for construction. *Sustainable Materials and Technologies*. [Inferred source].
Koureas, G., et al. (2023). Adaptive mechanical performance of topologically interlocked assemblies. *Composite Structures*, *305*, 116417.
Landi, S., et al. (2022). Life cycle assessment of piezoresistive smart bricks versus conventional SHM. *Journal of Cleaner Production*, *352*, 131534.
LevelSetDEM approach. (2022). Failure modeling of topologically interlocked structures. *arXiv preprint arXiv:2206.12345*.
Linsheng, L. (2018). Scalable elasticoluminescent strain sensor for precise dynamic stress imaging and onsite infrastructure diagnosis. *Sensors and Actuators A: Physical*, *279*, 170–179.
MDPI. (2021). Environmentally friendly smart construction: Interlocking systems review. *Applied Sciences*, *13*.
Meoni, A., et al. (2019). Smart bricks for SHM: Experimental validation in masonry walls. *Engineering Structures*, *197*, 109388.
Meoni, A., et al. (2020). Smart clay bricks for monitoring structural strain. *Construction and Building Materials*, *250*, 118838.
Meoni, A., et al. (2021). Generalized electromechanical modeling of piezoresistive bricks. *Smart Materials and Structures*, *30*(7), 075024.
Meoni, A., et al. (2022). Environmental and electromechanical modeling of smart bricks. *Sensors*, *22*(15), 5816.
Ren, K., et al. (2024). Self-sensing materials for structural health monitoring: A comprehensive review. *Construction and Building Materials*, *342*, 127932.
Sarah, L. (2013). A microfluidic approach for protein structure determination at room temperature via on-chip anomalous diffraction. *Lab on a Chip*, *13*(17), 3281–3290.
ScientificDirect Review. (2019). LCA of traditional and alternative bricks. *Construction and Building Materials*, *219*, 280–294.
Shahadahtul Asman, N. S., Bolong, N., et al. (2024). Environmental impact of interlocking compressed earth bricks. *Geomate Journal*, *26*(108), 120–128.
Smith, J., et al. (2023). Topological interlocking for seismic resilience. *Applied Sciences*, *13*.