ACS OMEGA

http://pubs.acs.org/journal/acsodf

Review

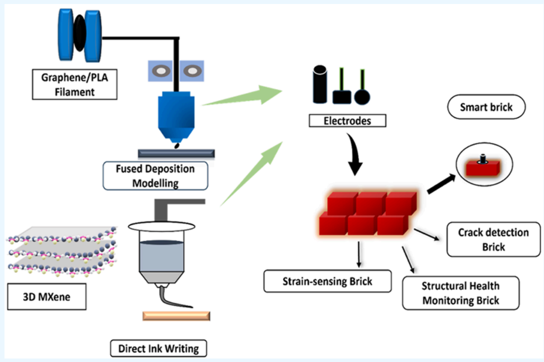
Adaptive Smart Materials in Architecture: Enhancing Durability and Sustainability in Modern Construction

Aiswarya Kallayil, Jigar Patadiya, Balasubramanian Kandasubramanian,* Aleksey Adamtsevich, Mohamed Kchaou,* and Faisal Khaled Aldawood

Cite This: *ACS Omega* 2025, 10, 22305–22322

Read Online

ABSTRACT: Adaptive materials in civil construction offer superior performance and high potential for 4D printing integration. Smart materials exhibit rapid response times, precise sensor applications, and real-time durability monitoring, with phase-changing materials improving thermal efficiency by 30% and self-sensing concrete detecting microstrains as low as 10 $\mu\varepsilon$. These materials enhance fracture toughness (50% increase), corrosion resistance (40% improvement), and fire stability (up to 1200 °C). Smart bricks incorporate phase-change materials, glazing systems, and recyclable composites, with some embedding electrodes achieving conductivity of 10^{-3} S/m for strain sensing. Additive manufacturing (AM) reduces material waste by 50%, enhances design flexibility (90%), and lowers the carbon footprint (40–60%). This review examines communication protocols such as Zigbee, LoRaWAN, and 5G, which enable real-time data transfer and processing. However, embedded systems in smart bricks may be vulnerable to cyber-attacks and data breaches. Ensuring security involves encryption methods, blockchain technology, intrusion detection systems to protect data integrity and network reliability, 3D-printed smart bricks, categorizing materials, and fabrication mechanisms. Integrating AM with smart materials fosters resilient, energy-efficient construction, essential for sustainable urbanization.

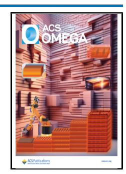


1. INTRODUCTION

One of the newest technological developments to enter the construction industry is Additive Manufacturing (AM), also called 3D printing. This invention dramatically aids the continuous digitalization of the sector.[1] 3D printing and increased interest in construction automation are transforming conventional building techniques. This trend toward automation is driven by several important considerations, including lowering manufacturing costs, increasing design possibilities, strengthening safety by eliminating the need for labor-intensive jobs and reducing the time that building takes on-site. Because of this, 3D printing is being utilized increasingly in the construction sector to enhance efficiency, accuracy, and design flexibility.[2] Different techniques are used for additive manufacturing, as mentioned in Table 1. The two main methods used in Additive Manufacturing for Construction (AMC) are extruded material and powder-based systems. Several different techniques are used in powder-based systems, such as binder jetting, selective paste intrusion, and selective binder (cement) activation (SBA). These techniques, which frequently employ the D-shape method to create solid structures, involve carefully placing and solidifying binding agents between layers of powdered materials.

In contrast, extruded material systems utilize a concrete mix pumped via a nozzle. This technique makes it possible to develop structures layer by layer by continuously depositing material in a regulated manner. Both methods contribute to improving and digitizing building processes by offering various advantages regarding adaptability, accuracy, and efficiency. Material extrusion is the basis for the most popular 3D printing. This typically involves heating, extruding, and selectively depositing a plastic filament that fused with the existing structure and hardened as it cooled. Similar procedures are applied in the building sector, where cement is the extruded material. Concrete printing (CP) and contour crafting (CC) are construction's central extrusion material systems. To construct the printed item, a mix, typically mortar is injected through a nozzle in contour crafting and concrete printing. The process is similar to fused deposition modeling (FDM) techniques, with one difference: heating is unnecessary

Received: May 25, 2024
Revised: March 24, 2025
Accepted: March 27, 2025
Published: April 8, 2025



https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305–22322

Table 1. Different Types of AM Methodologies in the Construction Industry

AM Techniques	Process	Materials	System	Reference
Contour Crafting	Material extrusion	Concrete	Gantry	36
3D Concrete Printing (3DCP)	Material extrusion	Concrete	Gantry	37
Concrete Printing	Material extrusion	Concrete	Gantry	38
Winsun	Material extrusion	Concrete	Gantry	39
Vulcan II	Material extrusion	Concrete	Gantry	40
Apis Cor	Material extrusion	Concrete	Arm	41
Minibuilders	Material extrusion	Polymer	Group of small robots	42
Hadrian X	Material assembly	Brick	Arm	43
In-situ Fabricator	Material assembly	Brick	Arm	44, 45
FreeFAB	Material extrusion	Wax	Gantry	46
Shotcrete Printing	Material Sprayed	Concrete	Gantry	47
D shape	Binder jetting	Microconcrete	Gantry	48

because the material is already fluid.[3] These methods increase the flexibility of complex structures by making their construction accurate and efficient. The materials used in 3D printing must meet specific requirements to be compatible with the technology.[4] Cementitious, polymer, and metallic materials are the most frequently used materials in 3D printing.[5] Melting polymers and printing products are the main objectives of fused filament fabrication, also known as fused deposition modeling, or FDM.[6] Polymer materials, often used for aesthetic purposes due to their lack of structural properties, provide a low-risk option for implementing additive manufacturing technology in construction. PLA (poly(lactic acid)) and ABS (acrylonitrile butadiene styrene) are both of the most commonly utilized polymer-based printing materials.[7] Since both are thermoplastic polymers, they melt and solidify when heated to a high temperature. Because PLA degrades naturally, it is considered a more sustainable material than ABS.[8]

The word "smart bricks" is extensively utilized in many different technological areas, and "smart" implies the capacity to gather in situ data on environmental conditions like force, stress, Temperature, tilt, moisture, and so on in creating intelligent building materials. The term "smart bricks" is composed of a unique burned clay brick stuffed with electrically conductive fillers and electrodes acting as a piezoresistive strain detecting unit fabricated by a sensor. Bright Brick is an incredible concept with sensors, data capabilities, and adaptability in the developing world. The resulting bricks can fundamentally change building methods by overcoming difficulties with resource scarcity, urbanization, and energy efficiency.[9,10] The beginning of Green building, also referred to as Sustainable building, has become the concept behind developing and creating buildings while using methods that provide importance to resource efficiency and environmental consciousness at each stage of a building lifecycle, spanning from inception through construction, use restoration, maintenance, and demolition.[11] The overarching aim of green buildings is to reduce their influence on the environment and the wellness of people by ensuring the utilization of water, energy, and other natural resource.[12] Incorporating green building methods and materials that place a priority on reducing the consumption of energy, reducing waste, and utilizing sustainable resources not only minimizes the environmental impact of a building but also develops spaces that are more affordable to operate and upkeep over time.[13] The requirement for sustainable and ecologically conscious techniques in construction and design contributes to the rising importance of green building methods in modern society. The necessity arises from various factors, such as environmental percussion of traditional building techniques, heightened understanding of climate change, and the aspiration to encourage safer and more efficient living conditions for residents.[14] Innovative materials have become crucial to green building movements to create green and sustainable cities since they provide creative solutions to sustainable construction methods; these materials are produced to reduce waste, optimize energy use, and respond to changes in the environmental conditions throughout a building.[15] Conventional building construction has an enormous adverse effect on the global environment, mainly due to the substantial emission of greenhouse gases into the atmosphere, excessive use of water, and wastewater production. Additionally, they utilize nonsustainable materials for construction, which raises CO_2 emissions, and they add an accumulation of building debris, which consists of plastic, concrete, glass, wood, metals, and more.[16]

Smart bricks represent a transformative approach to reducing embodied carbon and improving energy efficiency in modern construction. By integrating advanced materials and technologies, they address critical sustainability challenges while enhancing building performance. One key innovation lies in high-performance insulation materials that significantly improve thermal regulation. These materials help maintain stable indoor temperatures, reducing dependence on energy-intensive heating and cooling systems and lowering overall energy consumption. Similarly, phase change materials (PCMs) offer dynamic thermal management by absorbing and releasing heat as temperatures fluctuate, contributing to passive energy savings and enhanced occupant comfort. Using sustainable and recycled materials further highlights the potential of smart bricks in reducing the environmental impact of construction. Recycled materials minimize waste and reduce the carbon footprint associated with extracting and processing virgin resources. Innovations in eco-friendly concrete, such as incorporating supplementary cementitious materials (SCMs), exemplify strategies to lower emissions during production while maintaining structural integrity. Beyond material innovations, smart bricks incorporate adaptive and intelligent technologies that elevate energy efficiency. Advanced glazing systems, for instance, reduce heat loss in winter and heat gain in summer, optimizing the energy balance within buildings. IoT-enabled devices integrated with smart bricks allow real-time monitoring of environmental conditions, dynamically adjusting heating, cooling, and lighting systems to optimize energy usage. These systems demonstrate a powerful synergy between material advancements and intelligent building management, as evidenced by case studies showcasing significant energy savings and enhanced indoor comfort. Moreover, smart materials embedded within these bricks

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

Table 2. Types of Sensors with Properties along with Applications

SL. No	Types of Sensors	Properties	Applications	Reference
1	Temperature sensor	Measure temperature readings from outside	Checking building temperature for climate control, detecting fire, and energy conservation.	49
2	Humidity sensor	Detect the atmosphere's moisture content.	Promoting indoor air quality	50
3	Accelerometers	Calculate vibration and accelerators.	Identify the vibration caused by earthquakes and unauthorized incursion.	51
4	Pressure sensor	Determine the variations in atmospheric pressure.	Check the potential structural errors, forecasting the pressure.	52
5	Motion sensor	Capable of detecting movement.	Sensing system.	53
6	Light sensor	Measure Intensity of Light	It is utilized in automobiles	54
7	Electric sensor	They are used to measure and interpret electrical signals that occur when quantities or events change.	It is used in house appliances and industrial systems.	55
8	Water sensor	Calculate the volume of water used.	Employed to start and stop water pumps, water heaters	56

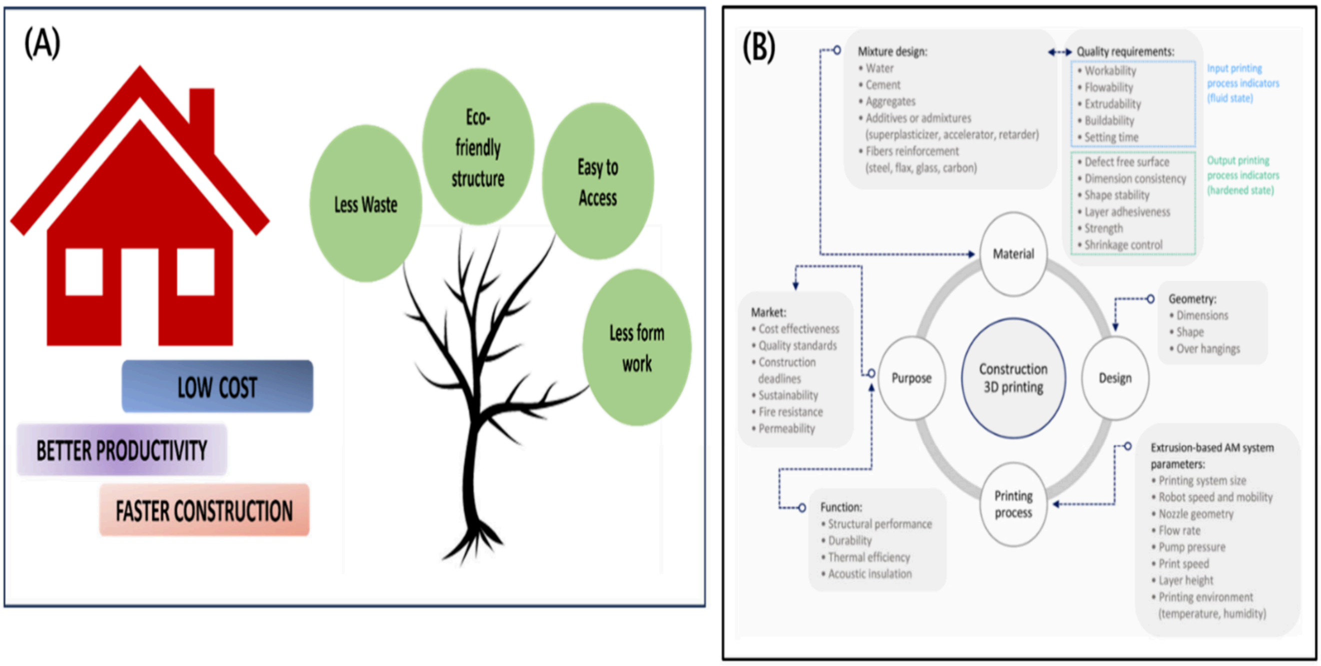


Figure 1. (A) Positive aspects of 3D printing, (B) Separation of material, process, design, and function in construction 3D printing. Reprinted with permission from ref 23. Copyright 2021, Elsevier.

adapt to environmental changes, such as temperature or humidity, providing a responsive and self-regulating approach to building design. This adaptability enhances durability and functionality, ensuring sustainable performance over the building's lifecycle. By integrating these advanced features, smart brick technologies reduce embodied carbon and contribute to a new energy-efficient and environmentally conscious construction paradigm, paving the way for a more sustainable built environment.[17,18]

Bright bricks provide innovative roots for ecologically conscious construction, seamlessly incorporating technology into green building operations to enhance sustainability and efficiency. The bright bricks are embedded with sensors, signal processors, and wireless communication links that act as vigilant guardians, inferring the underlying pressure or damage.[19] There are different types of sensors, including those for moisture, force, stress, chemicals, humidity, and sound; these bricks seamlessly integrate into walls and observe the Temperature, vibration, and motion monitors in buildings.[20] Table 2 illustrates the sensors' type, properties, and application. Suppose a sensor node positioned inside stairwell fire curtain walls carefully delivers crucial data about the safety of buildings in case of a fire. When temperature sensors are used to identify the region that is rapidly burning or deemed unsafe for an exit because of detective fire curtains, tilt and acceleration sensors produce important data on structural damage. The data, orchestrated using a scattered sensor network through an enormous structure or skyscraper, acts as a formidable ally that substantially enhances security for residents and prevents emergency services.[21] This synergy becomes even more impactful in conjunction with 3D printing technology, which arises from the layer-by-layer construction using Computer-aided design (CAD) models, and this technology is an awe-inspiring invention that has evolved into a fabrication platform.[22]

Technology development plays a vital role in improving business productivity in the construction field, and nowadays, 3D printing or additive manufacturing is a part of these innovations. This expression encompasses various technologies that utilize 3D printing to manufacture construction materials

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

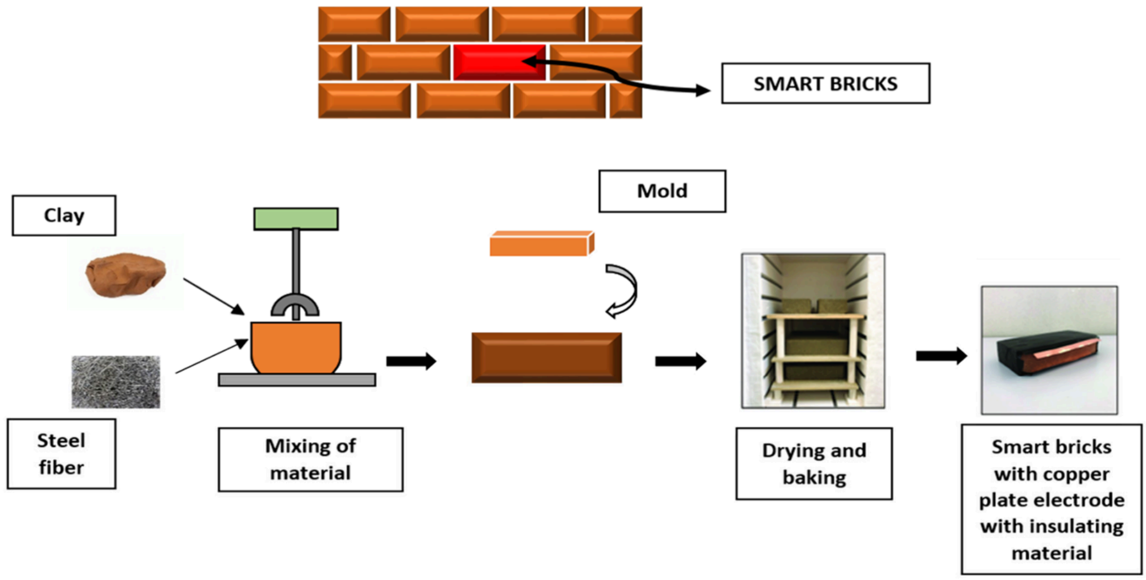


Figure 2. represents the manufacturing process of intelligent bricks. Reprinted with permission from ref 57. Copyright 2021, Elsevier.

and buildings.[24] A variety of materials can be applied using 3D techniques, but in the case of construction, additive manufacturing uses a unique blend. The utilization of 3D technologies in the manufacturing of buildings minimizes the reliance on manual labor, and it works at a low cost, as shown in Figure 1.[25] The innovative concept that the role of humans in construction relatively diminishes opens up novel possibilities for enormous communities, and the 3D technologies make it easier to construct buildings in any shape. It allows designers and architects to design without any restrictions from conventional constraints, and the construction period is shorter.[26]

Innovative materials are used in 4D printing and can be configured or programmed to modify their shape in response to external stimuli.[27] Many studies have been done recently to determine new items that can be used with 3D printing technology. 4D printing, a development over conventional 3D printing techniques, was developed due to this rise in interest.[28] The 4D technique includes creating three-dimensional things with the potential to change their form and function in reaction to outside stimuli, allowing printed objects to develop and change over time.[29] For 4D printing to become successful, two conditions must be satisfied. First, the materials employed should react to external stimuli so that the printed items are programmable. Second, an external stimulus that operates as a catalyst for transformation is required. Such stimuli include heat, pH shifts, light irradiation, or moisture. The 4D-printed object can be activated, providing its intended functionality when both conditions are satisfied.[30] Researchers have refined the definition to describe 3D-printed structures that exhibit targeted shape or property transformations when exposed to external stimuli.[28,31] Most studies now focus on 4D-printed structures' capability to alter shape, including bending, elongating, twisting, and corrugating. It is feasible to design these dynamic alterations further to produce valuable products like microtubes, robots, lifters, lockers, and toys.[32−34]

Compared with trivial uniform swelling, the 4D-printed object must display material anisotropy to achieve directional shape changes. This requires the precise and congruent printing of multiple materials in combination. A more specialized type of 3D printer is called a 4D printer. Currently, readily accessible methods for 4D printing include selective laser melting, laser-assisted bioprinting, stereolithography, fused deposition modeling, and direct inkjet curing. The specific types of innovative materials used should be considered when selecting a printer.[35]

This paper provides an idea about introducing bright bricks, an emergent study of additive manufacturing, portrays the different fabrication techniques using 3D printing, and focuses on 4D printing for construction applications. This newly developed approach to building construction has many advantages, including reduced material waste and improved sustainability and cost-effectiveness. Creating intelligent bricks, potentially transforming the building sector completely, is one of the field's most promising uses of 3D printing. Produced through 3D printing, intelligent bricks can integrate advanced functionalities such as self-monitoring, self-healing, and energy-harvesting capabilities, making them a game-changer in innovative and sustainable construction. These revolutionary bricks can speed up the building process and optimize resource usage, resulting in an eco-friendly and effective built environment. This work highlights the different types of intelligent bricks and their modification using sensors to provide better construction facilities. Modification methods by utilizing materials such as Graphene/PLA filament, 3D Graphene Nanosheet, 3D MXene, and Graphene nanoplatelets are described in this context. The efficiency of these smart bricks in various applications, including crack detection, Structural Health Monitoring, and Strain-sensing, is also illustrated.

2. SMART BRICK

A Smart brick is a clay brick that exhibits noticeable variations in electrical resistance when an external load is applied to it, and it also carries electrical conductivity and piezo-resistive features.[57] A proper conductive filler can be introduced throughout manufacturing to strengthen certain features of standard clay bricks. Presenting a monitoring method in an intelligent brick system is better since it provides high-fidelity data through natural brick traits used to record strain. This advancement offers long-term constancy since the sensors mimic the durability of the structural material.[58] Another remarkable attribute of bright bricks is architectural integration, which maintains the visual closeness to traditional neat brick. This is carried out by placing electrodes on the inside surface of the brick to cover them up, the manufacturing step of bright bricks demonstrated in Figure 2. Smart bricks in rugged sensor networks keep tabs on long-term tension changes, like those generated by earthquake impacts or variations in elevation, by contrasting the actual strain readings with those of the unaffected structures. When the strain data from the intelligent bricks can be examined to recreate patterns in masonry construction or structural components when the innovative sensors are dispersed throughout the load-bearing system, such as identifying anomalies in the built tension field maps facilitates efficient damage detection. The essential elements of intelligent brick designing are made from specialized ceramics that can conduct heat and electricity. These ceramics play a vital role in integrating sensors, circuits, and other smart devices by ensuring electronic parts are inside the bricks. Bright bricks typically contain sustainable materials like recycled plastics to improve their eco-friendliness further. Also, to enhance their environmental benefits, bright bricks may contain photovoltaic materials applied to their external surface to gather solar energy.[59] Implementing 3D-printed intelligent bricks significantly reduces material waste by 30–50% compared to traditional bricklaying methods, owing to enhanced precision and efficiency. A study by Zhiqiang Lai et al. presents an innovative approach to resource efficiency by transforming construction waste into high-performance thixotropic soils suitable for additive manufacturing. These engineered soils exhibit exceptional mechanical properties, achieving compressive strengths of 30 MPa (50% higher than traditional substrates) and flexural strengths of 5 MPa, ensuring their viability for construction. Life cycle assessments reveal a 20% reduction in carbon emissions and resource efficiency of 85%, far surpassing the 60% average of conventional materials. Additionally, fine-tuned 3D printing parameters achieve layer accuracy of $\pm$ 0.1 mm, reducing material wastage by 30% and accelerating construction timelines by 40%. These materials demonstrate excellent thermal stability, with only 0.1% variation at elevated temperatures, and maintain durability with less than 0.5 MPa degradation over 10 months, underscoring their potential for sustainable and efficient construction practices.[60] S. A. Khan and colleagues underscore the significant environmental benefits of incorporating circular materials derived from waste into construction practices, highlighting their potential to reduce carbon emissions and energy consumption compared to conventional materials. Their research reveals that 3D printing with circular materials enhances resource efficiency by minimizing waste generation through recycled products, paving the way for more sustainable construction methodologies. Through a comprehensive comparative analysis, the study demonstrates that construction methods employing circular materials substantially lower the overall ecological footprint, with metrics encompassing resource depletion, energy use, and greenhouse gas emissions. Several case studies illustrate the successful real-world implementation of 3D printing with circular materials, showcasing its practical feasibility and transformative potential in the construction sector. These examples emphasize the dual advantages of environmental sustainability and technological innovation, underscoring the pivotal role of integrating 3D printing technologies with circular economy principles. The findings strongly advocate for adopting these sustainable practices to foster a greener and more resilient construction industry.[61] Implementing intelligent bricks in infrastructure projects offers significant cost savings and environmental benefits. These innovations enhance durability, reduce energy consumption, and minimize greenhouse gas emissions, making them a sustainable choice for modern construction. Implementing a smart curing system represents a transformative advancement in enhancing the strength and durability of concrete bricks. Maintaining optimal moisture levels throughout the curing process mitigates the risk of cracks and structural failures commonly associated with traditional curing methods. Integrated sensors continuously monitor moisture and temperature levels within the bricks, enabling precise control over the curing environment to achieve ideal hydration conditions critical for developing concrete strength. Unlike conventional methods that rely on manual monitoring and are prone to human error, the smart system automates the process, ensuring consistency and minimizing potential inaccuracies. Moreover, research highlights the long-term advantages of this approach, including improved product quality and significant cost savings. Enhanced durability reduces material waste and lowers maintenance requirements, underscoring the smart curing system's potential to revolutionize concrete bricks' production and lifecycle performance.[62,63] Nanomaterials, including Graphene, might also be incorporated into intelligent bricks to improve their electrical and mechanical performance; bright bricks have enhanced conductivity, strength, and durability by including nanomaterials, making them excellent for various building applications.[64] Usually, recycled plastic material provides an essential component of these bricks; certain types of plastics, such as high-density polyethylene (HDPE), Polyethylene Terephthalate (PET), and Poly(vinyl chloride) (PVC) are frequently used in smart bricks.[65] 3D printing methods produce these bricks, enabling precise and adjustable designs. Embedded sensors are commonly used to track real-time energy consumption, ambient conditions, and structural integrity. Integrating intelligent technologies enhances maintenance and energy management through continuous data collection and analysis. While Lim et al.[66] concentrated on recent advancements in 3D printing, specifically the use of concrete as a printing material, Ghafar et al.[67] examined methods and materials used in 3D printing, highlighting benefits related to sustainability. The challenges and opportunities of 3D printing in the building industry were discussed by Labonnote et al.[68] and categorized into four areas: material science, engineering, building design, and market analysis. Bos et al.[37] identified the primary difficulties and chances associated with the 3D printing of concrete. In their study of 3D printing applications, Wu et al.[24] underlined the challenges in applying this technology to large-scale projects.

The exploration of materials like Graphene/PLA filament and 3D Graphene Nanosheet for intelligent bricks presents significant potential, yet it is essential to address the challenges and limitations associated with these materials. Understanding these obstacles is crucial for advancing the application of smart materials in construction. Despite their promising properties, these materials often present issues such as high production costs, scalability challenges, material degradation under specific environmental conditions, and compatibility with existing manufacturing processes. Moreover, there are potential

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

concerns regarding the ecological impact of large-scale production and disposal and technical difficulties in achieving uniform dispersion or integration of nanomaterials within the brick matrix. Addressing these challenges is essential for providing a balanced perspective on the feasibility and practicality of deploying such advanced materials in intelligent brick applications. Without this, the narrative may appear overly optimistic, overlooking critical factors that could affect real-world implementation.[69−71]

A smart brick is a technologically advanced construction unit that integrates multiple functional, structural, and interactive capabilities, distinguishing it from conventional bricks that serve only passive load-bearing or insulating roles. Beyond simply embedding sensors, smart bricks incorporate multifunctional materials like self-healing polymers, piezoresistive composites, and phase-change materials to enable autonomous damage repair, thermal regulation, and energy storage. Embedded sensing and monitoring systems, including strain gauges, fiber optics, and piezoelectric transducers, allow real-time structural health monitoring (SHM), detecting cracks, stress, and environmental variations. Some smart bricks feature energy-harvesting capabilities, using triboelectric generators, thermoelectric materials, or photovoltaic coatings to contribute to decentralized energy storage. Unlike static materials, they exhibit adaptive properties, such as thermochromic or hydrogel-based responses to temperature and humidity changes, improving energy efficiency and indoor comfort. Additionally, modular connectivity and IoT integration enable wireless communication for remote diagnostics and predictive maintenance. Advanced self-healing mechanisms, including microcapsules with repair agents or vascular networks, enhance structural durability, while nanoreinforcements (e.g., graphene-enhanced cement) improve mechanical strength. The true innovation of smart bricks lies in their synergistic impact on building performance—enhancing safety through early damage detection, reducing energy consumption via active thermal regulation, improving sustainability by extending material lifespan, and facilitating automation in smart infrastructure. Ultimately, smart bricks represent a paradigm shift toward intelligent, interactive, and self-sustaining construction materials that redefine modern architecture and infrastructure.[72−74]

3. VARIOUS TYPES OF SMART BRICK

Smart bricks, a creative advancement in technology that combines functionality with conventional building materials, have the potential to impact urban development significantly. Their adaptability and potential effect in several fields, from urban infrastructure to sustainable building, make them crucial in influencing design and urban development as technology evolves. As smart bricks become increasingly important, they will shape the future of construction and urban planning.

Integrating multiple functionalities—structural health monitoring (SHM), strain sensing, crack detection, self-healing, and thermal sensing—into a single smart brick requires careful consideration of material compatibility, functional trade-offs, and structural integrity. Strain-sensing elements, often utilizing piezoresistive nanocomposites, carbon-based networks, or embedded fiber optic sensors, may affect mechanical performance by introducing weak interfaces or stress concentrations. Similarly, crack-detection mechanisms based on conductive fillers or acoustic emission sensors require precise placement to avoid interference with load-bearing capacities.[75] Self-healing technologies, such as polymeric microcapsules, vascular networks, or bacterial-based healing agents, enhance long-term durability but may reduce initial compressive strength due to the presence of voids or inclusions.[76] Thermal sensing, which typically relies on phase-change materials, thermochromic coatings, or infrared-sensitive additives, can impact the insulation properties of the brick, potentially reducing energy efficiency in residential applications. In optimizing these trade-offs, residential construction would benefit from prioritizing energy efficiency and self-healing capabilities, integrating coatings for thermal sensing, and localized microcapsules in nonload-bearing regions to maintain strength.[77] In contrast, industrial applications demand higher structural reliability and real-time SHM, necessitating robust sensor networks, advanced piezoelectric or resistive sensing grids, and minimal use of self-healing to avoid compromising load-bearing capacity. Furthermore, multifunctional integration should consider environmental exposure, cyclic loading conditions, and long-term durability by employing hybrid material formulations, gradient architectures, or layered composites that compartmentalize functions without compromising overall performance.[78] By strategically optimizing material placement and functional synergy, smart bricks can be tailored to meet the specific demands of different construction environments while ensuring long-term reliability and sustainability.

Optimizing the structural integrity of smart bricks while incorporating functionalities like strain-sensing and crack detection involves innovative material design and integration of advanced monitoring technologies. Recent advancements highlight the potential of smart bricks to enhance structural health monitoring (SHM) in masonry buildings, addressing challenges such as localized damage detection and environmental influences. While these innovations present significant advancements in smart brick technology, challenges remain in achieving widespread adoption and integration into existing structures, particularly in terms of cost and scalability.[79,80]

3.1. Structural Health Monitoring (SHM). One of the most significant actions in maintaining the conservation of heritage constructions is to keep a close eye on their condition and preservation. An efficient and precise structural health monitoring (SHM) system is crucial for determining structural performance while providing relevant data for planning maintenance and retrofitting affordable and environmentally friendly strategies, as shown in Figure 3.[81] SHM in bricks integrates advanced sensor technologies to detect and address early signs of structural damage, ensuring the longevity and safety of built environments. By embedding diverse sensors, including accelerometers,[82] strain sensors,[83] inclinometers,[84]

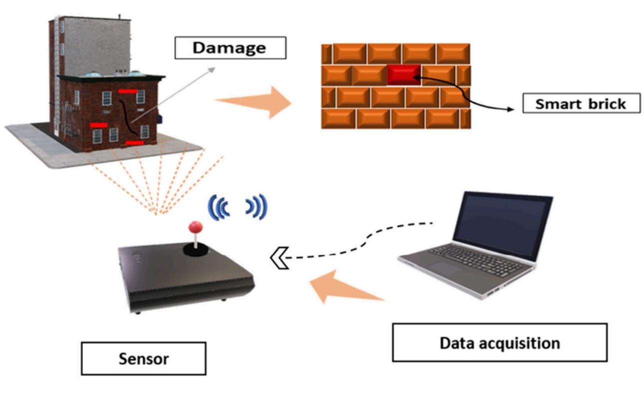


Figure 3. Structural health monitoring of smart bricks.

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

environmental sensors,[84] and tilt sensors,[85] SHM bricks provide continuous, real-time data on structural integrity under various operational conditions. These sensors collectively monitor parameters such as stress, strain, vibrations, and environmental influences, offering valuable insights into the health and stability of structures. However, implementing SHM systems presents challenges, such as sensor faults, signal interference, and complexities in data correlation, which can hinder precise damage detection and analysis. To overcome these obstacles, significant progress has been made in sensor miniaturization, reliability, and data processing algorithms. Machine learning and artificial intelligence techniques now enable the identification of subtle anomalies within large data sets, improving the accuracy of damage assessment and forecasting.[86] These technological advancements enhance SHM efficiency and contribute to the broader adoption of intelligent construction practices, paving the way for safer, more resilient, and sustainable infrastructure systems. By transforming bricks into self-monitoring entities, SHM systems exemplify the synergy between material innovation and digital technology, addressing critical challenges in modern construction and urbanization. By incorporating stainless steel microfiber as conductive material into the clay and adding superficial horizontal copper plates as electrodes to the brick surface after it has been baked at 900 °C, Antonella D. Alessandro et al. demonstrated a novel formulation for a clay brick that can sense and monitor the structural health of masonry structures.[87] According to the investigation, the same preparation strategy was used for casting bricks using nano titania.[58] The researcher investigates the configuration of two advanced stress sensors, especially ceramic and capacitive sensors, on prestressed masonry walls made of clay and calcarenite, which the researcher is exploring. With two alternative postinstallation processes, two types of sensors, and two kinds of configuration, the sensors are attached to existing walls under load circumstances, stimulating a real-world scenario[88]—the first postinstallation technique detected issues related to the sensors' placement. Due to installation faults, ceramic sensors mounted on calcarenite and clay brick masonry specimens failed to precisely record the load cell reference curve. In the content of the postinstallation system, P2 was a comparison between load cells, capacitive sensors, and ceramic sensors. When rigid mortar was implemented during sensor installation, capacitive stress sensor sensitivity decreased at lower load values. Experiments on calcarenite and clay brick masonry fitted with ceramic and capacitive stress sensors indicated that the ceramic sensors curve differed significantly from the load cell reference curve; the resultant showed that both types of sensors were able to record the change of stress state, with no appreciable difference between the two types of masonry. Remarkably, the first postinstallation system had a problem with ceramic sensors in terms of reliability, while the second system had a problem with fluctuation in stiffness.[88,89] Research on an Atmel SAM-based wireless sensor node for bridge SHM highlights significant advancements in continuous monitoring and data accuracy. Key findings include precise modal parameter measurement using accelerometer sensors calibrated with the VCD21D vibration tool to achieve a minimal error of 0.3%. The study also demonstrated the effectiveness of Reference Broadcast Synchronization (RBS) in wireless sensor networks, achieving a synchronization error of just 2049.5 μs. These results underscore the importance of accurate sensor calibration and robust synchronization in ensuring reliable, real-time SHM data, contributing to safer and more resilient infrastructure.[82] Jyrki Kullaa and the team explored using autocovariance function (ACF) estimates for damage detection in structural health monitoring (SHM). By analyzing response data from diverse sensors measuring displacement, velocity, acceleration, and strain under stationary random excitation, functionally similar ACFs were derived, enabling unified data analysis. A spatiotemporal correlation model was developed using ACFs at various lags, with violations of the model serving as reliable indicators of structural damage. Validated using a finite element model of a bridge deck, the method demonstrated effective damage detection without requiring excitation or environmental measurements. The integration of diverse sensor types maintained detection accuracy while enhancing system robustness. The study highlights ACF estimates and spatiotemporal models as practical tools for scalable, accurate SHM, offering innovative solutions for monitoring structural integrity in modern infrastructure.[83]

Figure 3 illustrates the integration of damage detection, smart brick sensors, and data acquisition systems to monitor and analyze the performance of smart bricks for masonry buildings. The system begins with identifying potentially damaged areas within the structure, where smart bricks with embedded strain sensors are strategically installed. These sensors detect real-time deformations and transmit the data wirelessly to a central hub. The collected data is then forwarded to a data acquisition system for further processing, typically represented by a computer or server. The raw sensor data undergoes preprocessing to filter out noise and ensure accuracy, followed by strain analysis to detect deformation patterns and assess the magnitude and location of abnormal stresses. Advanced algorithms compare the results against baseline thresholds to evaluate the structural integrity, providing actionable insights into the building's condition. Visualizations, such as heatmaps or 3D models, are generated to display the findings intuitively. Additionally, predictive analytics can leverage historical and real-time data to forecast potential failures, enabling proactive maintenance strategies. This integrated approach ensures real-time monitoring, accurate damage detection, and data-driven decision-making to enhance the safety and longevity of masonry structures.

3.2. Strain-Sensing Brick. The combined effect of the contact resistance developed in the electrodes of bright bricks, and the piezo resistivity found in the doped clay matrices provides their strain-sensing prowess. Although contact resistance plays a role, these innovative sensors primarily use piezo-resistive behavior as their sensing mechanism. The specially engineered mix design of bright bricks involves certain fillers that transport electricity into the clay matrix. Using the piezo resistive concept, bright bricks help assess strain variation when integrated into masonry structures because they can monitor electrical outputs like electrical resistance.[90] Enrique Garcia et al. delve into the operational details of bright bricks and examine matters like the requirement of electrical separation for sensors and their working phenomena in various construction conditions.[91] Bright brick performs at peak efficiency in an electrically isolated environment, demonstrating high sensitivity. Within the masonry shear walls, the electrical responses of bright brick are deliberately using electrochemical Finite Element(FE) simulations. During earthquake simulation, a shaking table was employed with the smart bricks to test an unreinforced

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

masonry (URM) building. The test was conducted in a higher-intensity sequence to destroy the structure gradually. After every phase of earthquake simulation, smart brick was implemented to detect long-term changes when the load is distributed within the building by tracking strain variation, and the strain outputs from the smart bricks can be analyzed to reconstruct the strain field in masonry construction, which facilitates the damage detection by identifying variations in the strain field maps. An electromechanical finite element (FE) simulation framework was created to mimic the shaking table test and correctly comprehend the experiments' outcome. Strain-sensing technologies are vital in monitoring the structural integrity of masonry buildings, particularly brick structures. Recent innovations have led to the development of a range of sensor technologies that enhance strain detection and enable the assessment of potential damage. Shaking table tests and electromechanical finite element (FE) simulations offer complementary approaches for assessing the accuracy and reliability of strain data obtained from bright bricks under earthquake scenarios. Shaking table tests provide realistic, empirical validation, capturing actual seismic forces, multi-directional accelerations, and material interactions, making them effective in evaluating sensor performance under dynamic conditions. They also account for masonry imperfections, sensor-mortar bonding variability, and environmental influences. However, these tests are costly, time-consuming, and subject to scaling limitations, making large-scale validation challenging. In contrast, FE simulations enable controlled parametric analysis, allowing systematic variation of earthquake intensities, material properties, and sensor placements while providing detailed strain distribution and internal stress states that may not be directly measurable in experiments. They are cost-effective and efficient but rely on modeling assumptions that may not fully capture real-world effects such as material degradation, nonuniform sensor bonding, or dynamic damping variations. Discrepancies between the two methods can arise due to idealized vs real-world conditions, where FE models assume uniform material properties and perfect boundary conditions. At the same time, experimental tests account for actual construction defects and sensor inconsistencies. Additionally, sensor calibration differences and limitations in capturing high-frequency earthquake effects can lead to variations in strain measurements. By integrating these two methods, researchers can refine simulation models for better predictive accuracy while using experimental data as ground truth, ultimately enhancing bright bricks' design, optimization, and real-world applicability for seismic resilience in masonry structures.[76,92,93] Microbiologically induced crack healing smart clay bricks, for example, have been designed to integrate strain sensors directly within the masonry, enabling diffuse strain monitoring and providing real-time data on structural health without the need for external sensors. Traditional strain sensors, such as electrical strain gauges and fiber-optic sensors, incorporate long gauge and distributed sensing capabilities, which expand their applicability in structural health monitoring. Additionally, concrete-based sensors, incorporating multi-walled carbon nanotubes, offer high sensitivity and durability, making them promising candidates for embedding in brick structures to ensure continuous strain monitoring. Flexible and textile-based sensors are emerging as a versatile solution, especially for applications requiring adaptability to irregular surfaces. These sensors can be integrated into wearable technologies, broadening their potential use in structural and human health monitoring.

Bright bricks with piezoresistive properties offer a well-balanced solution for strain monitoring in masonry structures, combining high sensitivity, durability, and seamless integration without requiring external adhesives or complex installation. Compared to electrical strain gauges, which are cost-effective and precise but prone to environmental degradation and complex wiring, bright bricks provide a more robust and scalable alternative. Fiber-optic sensors, while offering superior accuracy and immunity to electromagnetic interference, suffer from high costs and difficult installation, making them less practical for large-scale masonry applications. Carbon nanotube (CNT)-based concrete sensors provide high durability and integration potential, but their long-term stability and cost-effectiveness remain challenges. Overall, bright bricks stand out for their ease of deployment, cost-efficiency, and ability to be mass-produced, making them an ideal choice for real-time strain sensing in masonry structures. Table 3 detailed comparison of ″bright bricks″ with piezoresistive properties against electrical strain gauges, fiber-optic sensors, and carbon nanotube (CNT)-based concrete sensors for strain monitoring in masonry structures.[94−96]

3.3. Crack Detection Brick. Individual masonry blocks' sacrificial mortar and modular structures can maintain a long service lifetime because they allow progressive repair and lower maintenance costs than monolithic materials, including concrete slabs. Thermal stress from freezing and thawing cycles, unsuitable material proximity, hygroscopic stress from rainfall or increasing dampness, and mechanical stress from settlement or earthquake may cause cracking in the masonry buildings.[97] The brick is equipped with sensors showcasing piezo-resistive characteristics, so it is feasible for them to detect the notable variation in electrical resistance in response to compression forces, as exhibited in Figure 4. These modern facility sensors are meticulously crafted from a composite material that blends fresh clay with electrically conductive microfillers to amplify this distinctive electromechanical feature. Improving the specific characteristics of the conventional clay brick requires adding an appropriate conductive filler in the production process. Downey et al. explore the promising application of titania doped clay brick as a tempting filler choice, considering their electrical resistivity ranging from 0.1 to 10Ωcm and their resilience to high temperatures. Linear variable differential transformers (LVDTs) and smart bricks were used to identify cracks in masonry walls, and the cracking pattern mainly affected both the front and back sides of the wall, which occurred in the squeezed diagonal. As the applied load developed, smart bricks developed an increase in compressive stresses. At the crack forming point, a noticeable decrease in their compressive strain levels of 0.2 MPa was mentioned when employed on masonry structural elements exposed to in-plane shear loading; smart brick technology demonstrated performance in the rapid detection of cracks.[90]

Two cases are applied to calculate the crack width. Case 1: crack orientation <45° and case 2: crack orientation >45°. A Crack object resembles a horizontal crack in crack 1, and a crack object leans vertical crack in crack 2. The crack width at the crack section 's' of the crack object is denoted as $W(\mathrm{s})$.

$$\text{Case 1: } W(\mathrm{s}) = L_{\mathrm{v}}(\mathrm{s})\cdot\sin(90 - \alpha)$$

$$\text{Case 2: } W(\mathrm{s}) = L_{\mathrm{h}}(\mathrm{s})\cdot\sin(\alpha)$$

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

Table 3. Comparison of "Smart Bricks" with Piezoresistive Properties against Conventional Strain-Sensing Technologies for Masonry Structures in Terms of Cost, Ease of Integration, Sensitivity, Durability, and Scalability

Feature	Bright Bricks (Piezoresistive)	Electrical Strain Gauges	Fiber-Optic Sensors	CNT-Based Concrete Sensors
Cost	Moderate cost depends on the piezoresistive material used (e.g., graphene, carbon black).	Low: widely available and inexpensive but requires additional wiring and signal processing.	High fiber-optic cables and interrogation units are expensive.	Moderate to high CNTs are costly, but scalable manufacturing could lower costs.
Ease of Integration	High; directly incorporated into masonry without additional mounting or adhesives.	Low to moderate; requires careful surface preparation and adhesion.	Low installation is complex, requiring precise positioning and alignment.	High; integrated within the concrete, eliminating external installation.
Sensitivity	High; piezoresistive materials exhibit strong resistance change under strain.	High, precise, and widely used in structural health monitoring.	Very high; capable of detecting microstrain with minimal signal noise.	High; CNTs offer good strain sensitivity, though signal consistency can vary.
Durability	High; robust against environmental factors, embedded in masonry for protection.	Moderate; prone to degradation from moisture, temperature variations, and surface wear.	Very high; resistant to environmental degradation, corrosion, and electromagnetic interference.	High; CNTs enhance concrete durability, but long-term stability of conductive pathways is still being studied.
Scalability	High; modular and mass-producible for large-scale masonry applications.	Moderate; effective for small-scale applications but impractical for widespread deployment.	Low; expensive and challenging to install over large areas.	High; can be seamlessly incorporated into large concrete structures.

L_v (s) and L_h(s) are denoted as the number of crack pixels measured in the vertical and horizontal direction at sections, ′ and α is the orientation of a crack object.

Therefore, crack length (L_c) is:[98]

$$L_c = \frac{\mathrm{Per} - 2\cdot W_{\mathrm{avg}}}{\alpha}$$

where Per denotes crack perimeter, and W_{avg} is the average value of crack width.

3.4. Self-Healing Brick.

There is a wide variety of self-healing materials belonging to the category of intelligent structures since they contain encapsulated healing compounds that are released when damage occurs, "healing" the "injury" and improving the material that is useful in life. Self-healing is done to reduce cracks, reduce maintenance expenses, and increase strength and durability. Skin and additional damaged tissue tend to mend themselves because the host may absorb nutrients and develop new alternatives that help the injured parts heal.[99] Microbiologically induced crack healing is a valuable method to heal such cracks found in bricks; it entails inserting certain bacteria that can generate calcium carbonate, which helps caulk the gap. The bacteria serve as an inducer of mineralization and cause the formation of calcium carbonate under the presence of a calcium supply. Concurrently, calcium particles provide bacteria energy and act as precursors of calcium carbonate. Dormant bacterial spores become activated when the entry of air and water forms cracks, and these spores immediately begin to precipitate CaCO3 by utilizing the calcium substance as a source of energy.[100] Microbiologically induced crack healing (MICH) in bricks, facilitated by bacteria that precipitate calcium carbonate ($CaCO_3$), represents a promising self-healing approach to enhance the durability and lifespan of masonry materials. In this process, bacteria such as *Bacillus subtilis* are embedded within the brick matrix, where they remain dormant until activated by environmental moisture and nutrients. Upon activation, the bacteria metabolize the available nutrients and produce calcium carbonate, which fills microcracks, effectively "healing" the material and restoring its mechanical properties.[101] This self-healing mechanism can reduce the need for external repairs and maintenance, offering significant cost savings and improved longevity. However, several limitations hinder the widespread application of this approach. The rate of crack healing is relatively slow, which could be problematic for large cracks or when rapid restoration of structural integrity is required. The bacteria's activity is heavily reliant on specific environmental conditions, such as moisture, temperature, and nutrient availability, which may not be present in all locations or during all seasons, limiting the geographical applicability of this technology. Furthermore, MICH is primarily effective for small cracks, typically a few microns to millimeters, and may not adequately address larger structural damage.[102] The long-term viability of the bacteria is another concern, as they may lose their functionality over time due to environmental degradation or insufficient nutrient supply, potentially reducing the self-healing efficacy as the brick ages. Additionally, embedding bacteria within bricks increases the production complexity and cost, potentially limiting the scalability of this technology in commercial applications. Finally, while the ecological impact of using bacteria in bricks is generally considered positive, there may be concerns regarding introducing non-native microorganisms into the environment, raising potential regulatory issues. Despite these challenges,

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

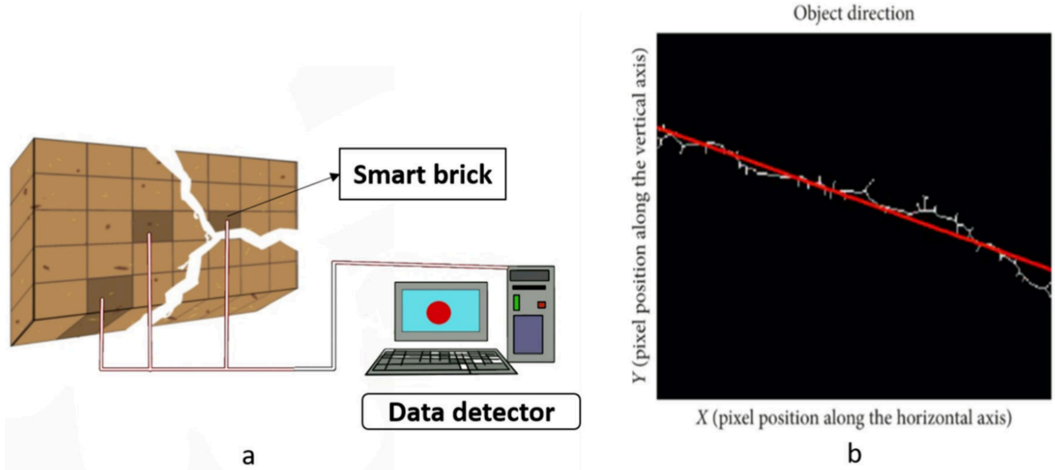


Figure 4. Crack detection of bright bricks. (a) Cracked wall contains smart bricks with sensors. (b) Determination of crack orientation, Reprinted with permission from ref 98. Copyright 2018, John Wiley & Sons.

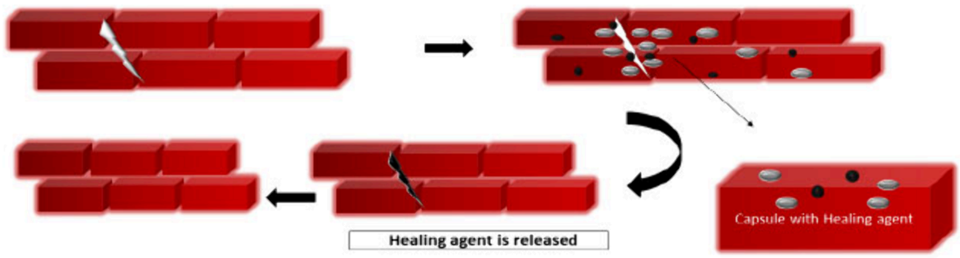


Figure 5. Self-healing mechanism working flowchart in smart bricks.

MICH remains a promising avenue for improving the sustainability and resilience of brick-based structures, especially when combined with other complementary materials or technologies for crack repair and prevention.[103]

The presence of mineral precipitates like calcite or healing agents may slowly fill up the small fissures, which is one mechanism of self-healing in brick mentioned in Figure 5; in addition, certain bacteria added to the material of the brick can help in self-healing through the formation of calcite or other kinds of minerals which can close the crack.[99]

3.5. Thermal Sensing Brick. Smart multifunctional material represents a potential advancement in technology in the building sector to meet the need for thermal-energy efficiency to attain mechanical performance standards and environmental sustainability.[104] In addition to providing advanced data logging functions, the thermal sensing brick can easily connect with current technologies, giving valuable information for analysis and monitoring. Its rugged construction and user-friendly design also made it an ideal choice for various industrial and commercial applications. The thermal sensing brick offers a reliable and effective solution for thermal management needs because of its preciseness in measuring and monitoring thermal changes. There are different types of thermal sensing for various applications; the sensing and image acquisition block is used to capture images and acquire data, the preprocessing and fusion block works on the acquired images and data, and the communication block is used to transfer data between the sensor brick and the remote host computer. Finally, the power block maintains the power supply for the entire brick. The wall's visibility was superimposed with the thermal infrared images, which captured the details and characteristics of the building wall from various angles indicated in Figure 6. To verify the effectiveness of infrared thermal imaging technology in identifying wall damage after a disaster, collect images from the postearthquake site photos that indicated various building types at the earthquake emergency rescue base.[105]

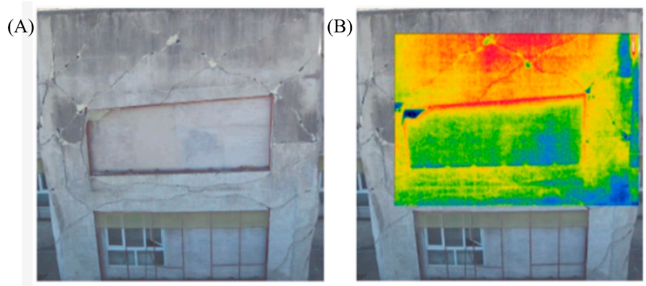


Figure 6. Thermal infrared image of window damages. (A) Visible image of wall. (B) Thermal infrared image of wall. Reprinted with permission from ref 105. Copyright 2020, MDPI.

4. FABRICATION OF SMART BRICKS USING 3D PRINTING

Building construction uses bricks for several reasons, such as soundproofing, strength, and durability. The construction field has different types of bricks, as illustrated in Figure 7A. In contrast, concrete bricks offer excellent durability and consistency, while traditional clay bricks are utilized in residential and commercial buildings.[106] While engineering bricks offer low water absorption and high density, fly ash bricks are lightweight and eco-friendly.[107] Bricks constructed

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

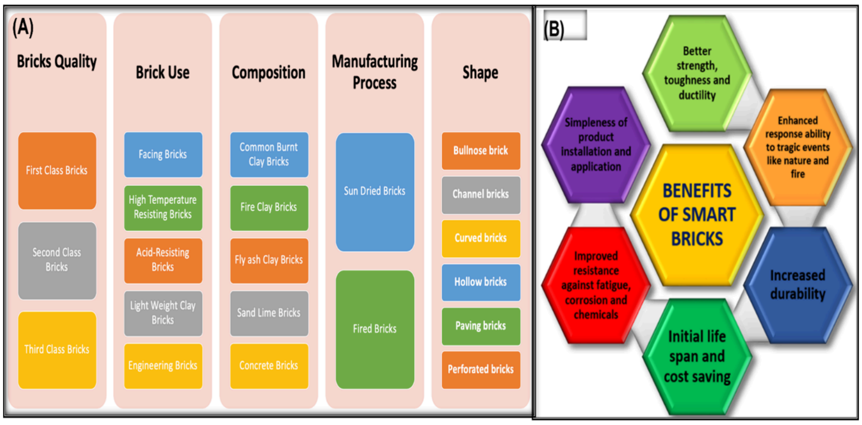


Figure 7. (A) Schematic illustration of types of intelligent bricks, use, composition, shape, and manufacturing of commercial bricks. (B) Merits of incorporating smart bricks.

from sand lime provide soundproofing and a smooth surface.[108] Three-dimensional printed bright bricks are an essential advancement in environmentally friendly construction methods. The utilization of 3D printing technology in construction has a chance to enhance the sustainability of building construction significantly. It is currently possible to construct houses using materials whose life cycle has been evaluated, which helps to protect the environment. One of the significant strengths of architects is their capability to develop complex structures. In the construction industry, this method has several advantages, it may build complicated geometries that are impossible with standard technologies and enhance design flexibility and material efficiency.[109] Additionally, it prevents excessive material use, reduces building time and expense, and improves safety by lowering the need for physical labor in hazardous areas. Technology can entirely change the construction sector and make it more adaptable, efficient, and sustainable as it develops.[110] Additive manufacturing helps lower injury rates and fatalities at work sites, as printers can handle many risky tasks. Today, the growth in the size and scale of structures impacts surface conditions, enhances land use, and threatens water availability.[111] The present additive manufacturing techniques are compatible with advanced sensor manufacturing for smart bricks, and they are promising for intricate brick production with numerous designs. Soil debris, concrete-based masonry, and clay-based masonry are the most common types of trash produced from building sector waste.[112] The "smart bricks" are notably extensively used, and depending on the situation, they could allude to many technologies or ideas, depending on the context, each offering numerous benefits, as shown in Figure 7B. The conventional method of fabricating smart bricks in building materials and brick employs several drawbacks, and the intelligent bricks are suppressed with many sensors, connectivity, and intelligent features that are incredibly costly to produce and install.[113] The use of sensors and electronic constituents in smart brick needs regular maintenance, and to check that they work correctly, there is any wrong or failure for these elements, which could result in extra maintenance costs and inconvenience. Building-connected materials and smart bricks face cybersecurity risks because these systems could be dangerous to hacking if they are not adequately secured. This may result in privacy violations or interfere with intelligent functions. The hybrid technology of smart bricks demands regular support, updates, or possibly replacement over time, and because of the need for energy to operate their integrated technologies containing sensors and illumination, many smart bricks utilize alternative energy sources. Reliance on energy sources could significantly create barriers to resilience and sustainability when the power supply is disrupted. They could also require complex installation processes to impact the environment negatively, leading to problems in compatibility with traditional building methods.[114,115]

3D printing is more effective than traditional manufacturing methods; engineers and designers can quickly iterate and improve their designs by changing them into physical models, which increases the process of creating a new product. Conventional subtractive production techniques generate waste material; using 3D printing, minimal waste occurs because the material is dropped layer-by-layer, and the development can be performed quickly and cost-effectively.[116] The structural flexibility of additive manufacturing makes it feasible to develop intricate designs and complex shapes, making it easier to incorporate electrical parts into the brick structure seamlessly. The value of the brick is enhanced by the ability to place the sensor directly during the process of printing, which allows for continuous monitoring and collection of data. During the production process, 3D printing enables the inclusion of sensors and electronic components right into the structures of bricks, improving the brick's "smart" abilities. The methodology of 3D printing involves meticulously constructing buildings one layer at a time. This method provides exact control and can produce bright bricks with improved structural qualities, increasing their durability and robustness.[117] Similarly, the shape memory effect (SME) explains in 4D printing the ability of a material that has been significantly and quasi-plastically predeformed to return to its original form after applying a suitable stimulus.[118] SME can be observed in metal alloys such as nitinol and several polymers. Numerous stimuli, including direct or indirect heating or cooling; exposure to light (photoresponsive) without causing significant temperature changes; chemical agents (chemo-responsive), such as water, moisture, or pH shifts; or mechanical stress (mechano-responsive), among others, may trigger this shape recovery.[119] Zang et al. demonstrate that the materials that respond to water or moisture are fascinating due to their wide variety of applications and ubiquitous stimulation. For example, hydrogels have exceptional moisture response due to their hydrophilicity, allowing them to expand up to 200% of their initial volume.

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

Additionally, hydrogels, as a class of polymer materials, exhibit excellent printability, providing features such as biocompatibility and simplicity in printing through direct ink writing.[120] Piezoelectric materials are an essential category of innovative materials with widespread application. They can generate electrical charge or voltage in response to external stress and vice versa.[121] Similarly, Fremond and Miyazaki et al. demonstrate a different type of intelligent material known as shape memory alloys (SMAs) displays the shape memory effect (SME), which is the direct conversion of thermal energy into mechanical work. The transition between low- and high-temperature phases, two distinct crystalline phases in SMAs, increases SME. Super elasticity, the capacity of the alloy to display an essential recoverable strain during loading and unloading, is another notable characteristic of SMAs; in comparison to SME, where variations in Temperature cause reversible martensitic phase transformation, the stage transformation in super elasticity is a result of mechanical processes.[122] Nickel−titanium (NiTi) SMA is a perfect instance of an SMA that contains both super elasticity (mechanical memory) and SME (thermal memory). Because of its excellent functional features, NiTi SMA has become popular in engineering applications.[123]

The most widely used method in 3D printing of intelligent brick is fused fragment fabrication (FFF), one of the most popular, inexpensive, and user-friendly methods. FFF 3D printer is accessible to anybody with computer-aided design (CAD) knowledge, and the method can be used to create high-quality, functionally engineered parts and prototypes. The fabrication process of this method includes spooling, and the thermoplastic filament is fed into the 3D printer and then melted under controlled conditions. The filament is extruded into the build system. It is built layer-by-layer, and the build system is increased after each layer is placed, producing a 3D structure. Each layer is placed, cools down, solidifies, and ensures the material adheres to the previous one. Usually, the printed item will be removed from the build platform and let cool down.[124,125] The common FFF material includes Poly(lactic acid) (PLA), Acrylonitrile butadiene styrene (ABS), Polyamide 6 (PA 6, Nylon-6), Polycarbonate and thermoplastic polyurethane (TPU). PLA is the most conventional printed material in FFF technology, but PLA cannot be applied to structural applications because it shows a highly brittle nature. Using PLA filament, Vaghasiya et al. demonstrate that the inclusion of 3D printed electrochemical devices filled into the inside of the construction brick is a creative concept that illustrates that electrochemical energy storage could be easily integrated into the basic structure of a home. Researchers print supercapacitor electrodes by the 3D printer using affordable Graphene/Poly(lactic acid) (PLA filament) to improve capacitive performance, as demonstrated in Table 4; this 3D printed electrodes are coated with electroplating of Ti_3C_2 polypyrrole (PPy) and demonstrate exceptional electrical conductivity, high energy density, capacitive performance, and cycle life. Furthermore, the bricks themselves provide enormous underutilized thermal insulation spaces, electrical insulation, and fire resistance, thereby providing a suitable scaffold for the electrochemical energy system, and the integration of sophisticated energy storage into the fabric of building material is carried out seamlessly.[126]

Another method used for the fabrication of 3D printing is known as the Direct Ink Writing method; it allows the exact and precise deposition of substance to produce a three-dimensional structure and is comparable to a typical 3D printer; the melted filament is applied layer-by-layer through a nozzle to extrude a viscous ink or paste in DIW.[130] By this method, Bolin et al. describe that the 3D Nanosheet has excellent potential for utilization in electrochemical energy storage because of the distinctive electronic structure and geometric features of layered 3D Nanosheet. The material possesses an exceptionally high specific surface area, excellent electron migration rate, and incredible structural stability. Recent advancements in 3D printing technology, particularly in ink direct writing, have greatly improved microstructure devices' design and control accuracy. This article aims to create a solid capacitor with a flexible design using 3D Graphene and 3D MXene nanosheets, which serve as active materials due to their high specific capacitance discussed in Table 4. In this literature, additive manufacturing technology can create stable and readily dispersed slurry or ink using various 3D Nanosheet powder components. Typically, a potential 3D design and colloidal 2D nanosheet solution are employed to initiate the 3D printing process, and a mixed ink is then formulated to enable the printing of specific shapes based on a predetermined design. In this work, they enhance the 3D printing of flexible supercapacitor electrodes by applying the DIW method and exploring three different electrode types: interdigital electrodes, multilayer skeleton electrodes, and fibers.[129]

Table 4. Various Materials with Their Properties and Temperature for Smart Brick Applications

Sl No	Material	Properties	Temperature	Reference
1	Graphene/ Polylactic acid	Good capacitance performance	220 °C	126
2	Alkali − Activated materials(AAMs)	Quick setting time and faster strength growth	20 °C	127
3	Graphene Nanoplatelets	Improved multifunctional characteristics	−	128
4	3D Graphene Nanosheet	Excellent specific capacitance	−	129
5	3D MXene	Enhance the rate of utilization of surface-active sites.	180 °C	129

Electron beam melting (EBM) AM is another method to fabricate intelligent parts. Sensors can be easily integrated into structures while preserving the integrity and functionality of their structures. This embedding property effectively enables end users to monitor crucial sections, like extreme temperatures and pressures. This technique encompasses sensor functionality characterization through the EBM AM production process. EBM is a powder bed fusion AM technique widely used to manufacture metallic parts utilizing an electron beam and precursor powder.[131] Piezoelectric ceramic materials show the potential to work as pressure sensors in dynamic loading situations. Because they can generate an electric charge when exposed to force or contrast to apply force when an electric charge is induced.[132]

The integration of creativity and advances in the area of modern architecture resulted in the rise of a revolutionary approach called 3D printing of intelligent bricks, and the materials used in the bricks convert the static components to dynamic supports in the frameworks of construction via the incorporation of intelligent features and structural integrity. Compared to conventional substrates for construction, the materials used in the 3D printing of intelligent bricks are

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

Table 5. Comparison of 3D Printing and Traditional Brick Manufacturing for Smart Brick Production in Terms of Cost-Effectiveness and Scalability

Factor	3D Printing	Traditional Methods
Cost-Effectiveness	High initial investment in printers, materials, and software; cost per unit can be high due to use of advanced materials (e.g., conductive composites, self-healing agents)	Lower cost for mass production; low material costs; economies of scale make it cost-effective for large volumes
Material Flexibility	High material flexibility, enabling customization with smart features like sensors, self-healing mechanisms, and thermal regulation	Limited flexibility; embedding smart functionalities requires additional postproduction steps, increasing cost
Production Speed	Relatively slow, with time-consuming layer-by-layer deposition, especially for multimaterial or embedded sensor printing	Fast production with established, high-speed molding/extrusion processes, suitable for large-scale outputs
Dimensional Accuracy	High precision for complex designs, but accuracy may be affected by warping, shrinkage, and interlayer bonding	High consistency and accuracy, especially for standard brick shapes, with fewer dimensional issues
Scalability	Faces challenges in scaling due to slower print speeds and the complexity of multimaterial integration; ideal for custom or small-scale production	Highly scalable for mass production with well-established supply chains and production facilities
Customization	Excellent for custom designs, specialized shapes, and integration of advanced functionalities	Limited customization typically focuses on standardized designs with some potential for postproduction modifications
Post-Processing	Minimal postprocessing is required for custom designs; however, embedding electronics or sensors postprinting can add complexity	Significant postprocessing is required for adding smart features, such as embedding sensors or coatings, which increase time and cost
Labor Cost	Potentially lower due to automation, but higher costs for skilled labor to operate and maintain the printers	Low labor costs, as processes are highly automated and widely practiced

various novel substances that cater to the printing process and final structures based on their specific needs.[133]

One of the most common polymeric ingredients that are readily available, biodegradable, low-cost, and nontoxic is Poly(lactic acid) (PLA); this material can be readily reshaped and reformed because of its thermoplastic properties and poor melting point, so it is a good choice for Fused Filament Fabrication (FFF), an adaptable 3D printing process. The graphene PLA filament used in 3D printing provides improved structural integrity, and when graphene is combined with PLA, the filament has better electrical conductivity.[134] The second material is Alkali-Activated material (AAMs), which is an environmentally friendly material; it became one of the key benefits of using the 3D printing technique by using industrial products like fly ash or slag, diminishing the need for traditional production of cement and carbon footprint associated with construction operations. Alkali-activated materials showcase outstanding mechanical qualities and endurance, rendering these materials suited for structural components having excellent strength and resilience.[135] Other materials used in the 3D printing of intelligent bricks are the 3D Nanosheet and 3D MXene. A notable advantage of using 3D Nanosheet and 3D MXene is to build a very accurate and complex pattern. These materials can make lightweight and robust elements according to their nanoscale size, and they are mainly used in medical, aerospace, and automotive areas.[136]

The large-scale production of 3D-printed smart bricks faces bottlenecks in material cost, production speed, dimensional accuracy, and the integration of complex sensors and electronics. High-performance materials such as conductive composites, self-healing polymers, and phase-change materials significantly increase costs compared to conventional construction materials, while ensuring sustainability further complicates material selection. Production speed is limited by the layer-by-layer deposition process, which requires curing time and precise material transitions, making multimaterial printing for smart functionalities even slower. Dimensional accuracy remains a challenge due to potential warping, shrinkage, and interlayer bonding issues, necessitating postprocessing steps like machining to meet industry tolerances. Embedding fragile sensors and electronics, such as fiber optics or thermal sensors, is difficult within an automated printing process without compromising structural integrity, often requiring hybrid approaches that increase complexity and costs. Addressing these challenges requires innovations in cost-effective printable composites, high-speed robotic extrusion, AI-driven real-time monitoring for precision control, and hybrid manufacturing techniques that integrate sensors seamlessly, all of which are crucial for making 3D-printed smart bricks viable for large-scale construction. Table 5 summarizes the trade-offs between 3D printing and traditional methods for producing smart bricks, highlighting the strengths and weaknesses of each approach in terms of cost, speed, scalability, and functionality.

5. FUTURE SCOPE

The future scope of 3D-printed bright bricks presents a multitude of promising advancements and applications that have the potential to revolutionize the construction industry, drive sustainability, and enhance urban development. These innovations encompass the integration of multiple functionalities, such as energy harvesting, self-repairing capabilities, and improved thermal characteristics, paving the way for more durable, efficient, and intelligent buildings. The advancements in 3D printing technology, coupled with breakthroughs in materials science, are expected to significantly impact how structures are designed, built, and maintained. One of the most compelling prospects for smart bricks is their potential for energy harvesting. By directly incorporating solar panels or thermoelectric generators into the bricks, buildings can become more self-sufficient in meeting their energy needs. This integration could reduce reliance on external power sources, lower energy costs, and contribute to a building's sustainability. Additionally, energy-harvesting smart bricks can be instrumental in developing net-zero energy buildings, aligning with global efforts to combat climate change and reduce carbon footprints.

Another critical aspect of smart bricks is their self-repairing capabilities. Advances in materials science have led to the development of self-healing materials that can autonomously repair minor cracks and damages. By integrating these materials into smart bricks, the lifespan and durability of buildings can be significantly enhanced. This self-repairing feature reduces maintenance costs and ensures the structural integrity of buildings over time, making them safer and more reliable. Improved thermal characteristics of smart bricks

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322

represent another area of significant advancement. Bricks with enhanced thermal insulation properties can help maintain optimal indoor temperatures, reducing the need for extensive heating and cooling systems. This energy efficiency contributes to lower utility bills and a reduced environmental impact, promoting more sustainable living environments. Incorporating phase-change materials, for example, can store and release thermal energy, further optimizing the energy performance of buildings.

The use of 3D-printed smart bricks is poised to accelerate construction projects, particularly in remote or disaster-stricken areas where traditional building methods may be impractical. For instance, in remote areas with limited access to construction materials, 3D-printed smart bricks can be used to build emergency shelters quickly. In disaster-stricken areas, these bricks can be used to construct temporary housing that is both durable and quickly assembled. The ability to rapidly produce and assemble customized bricks on-site can expedite the construction of emergency shelters, housing, and infrastructure. This flexibility in design and production allows for innovative architectural solutions that adapt to specific needs and challenges, fostering resilience in vulnerable communities. Smart bricks also open up new possibilities for automation and connectivity in smart cities and homes. By embedding sensors and IoT technology within the bricks, real-time monitoring and control of building systems such as lighting, heating, and security become feasible. This connectivity enhances the responsiveness and efficiency of smart homes, providing occupants with greater comfort and convenience.

Additionally, the data collected by these sensors can offer valuable insights into structural health, environmental conditions, and energy usage, informing maintenance strategies and optimizing building performance. Advancements in 3D printing technology and materials science are central to the continued evolution of smart bricks. Developing innovative materials with superior properties, such as greater strength, flexibility, and environmental sustainability, will enhance the performance and applicability of smart bricks. Furthermore, improvements in 3D printing techniques, such as increased printing speeds and precision, will enable the mass production of high-quality smart bricks, making them more accessible and cost-effective. In conclusion, integrating smart technology and 3D printing in developing smart bricks holds immense potential for transforming the construction industry. These advancements promise to drive significant progress in building techniques, sustainability, and urban development. By harnessing the capabilities of smart bricks, we can look forward to a future where buildings are more efficient, resilient, and responsive to the needs of their occupants and the environment. This field's continued exploration and innovation will undoubtedly lead to even more groundbreaking applications, paving the way for smarter and more sustainable built environments.

6. CONCLUSION

The growth of 3D printing technology has significantly improved smart brick production, giving unprecedented possibilities and innovative approaches. 3D printing plays a crucial role in producing smart bricks, allowing for the rapid and cost-effective creation of complex brick designs. According to technological and material science developments, multifunctional sensing devices were developed, providing intelligent techniques for monitoring occupant safety and continuously analyzing civil constructions throughout their life. A real-time structural health monitoring technology can be set up to access structural performance. Bright bricks are made up of coated stainless steel fibers and have been applied in many industries to gather in situ data on environmental conditions such as stress, moisture, tilt, force, and Temperature. Using wireless communication links, sensors, and signal processors embedded within them, these bricks operate as vigilant guardians, capable of detecting pressure and damage beneath the surface. Sensors measure force, stress, moisture, chemicals, humidity, and sound. In addition, they are attached to walls to monitor temperature, vibration, and motion. Additive manufacturing has developed into remarkable inventions that act as a platform for the manufacturing process, which originated from layer-by-layer creation with Computer-aided design (CAD) designs. This technology reduces the requirement for physical labor, and shorter timelines for construction can be accomplished. Architects and designers make buildings with any design without any traditional constraints.

AUTHOR INFORMATION

Corresponding Authors

Balasubramanian Kandasubramanian − *Additive Manufacturing Laboratory, Department of Metallurgical and Materials Engineering, Defence Institute of Advanced Technology (DU), Ministry of Defence, Pune 411025, India;* orcid.org/0000-0003-4257-8807; Email: meetkbs@googlemail.com

Mohamed Kchaou − *Department of Industrial Engineering, College of Engineering, University of Bisha, Bisha 67714, Saudi Arabia*; Email: kchaou.mohamed@yahoo.fr

Authors

Aiswarya Kallayil − *Polymer Science, Central Institute of Petrochemical Engineering and Technology (IPT), Kochi 683501 Kerala, India*

Jigar Patadiya − *Additive Manufacturing Laboratory, Department of Metallurgical and Materials Engineering, Defence Institute of Advanced Technology (DU), Ministry of Defence, Pune 411025, India; Institute for Frontier Materials, Deakin University, Geelong, Victoria 3216, Australia*

Aleksey Adamtsevich − *Research Institute of Construction Materials and Technologies (CM&T), Moscow State University of Civil Engineering, 129337 Moscow, Russia;* orcid.org/0000-0003-4878-2737

Faisal Khaled Aldawood − *Department of Industrial Engineering, College of Engineering, University of Bisha, Bisha 67714, Saudi Arabia*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.4c04943

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors sincerely acknowledge Dr. C. P. Ramanarayanan, Vice Chancellor, DIAT-DU Pune, and Mr. K. A. Rajesh, Joint Director & Head CIPET: IPT Kochi, for their continuous and unwavering support. The authors are thankful to the Deanship of Graduate Studies and Scientific Research at University of Bisha for supporting this work through the Fast-Track Research Support Program. The first author also acknowledges Ms. Alsha Subash, Ms. Neelaambhigai Mayilswamy, and Ms.

Shruti Gupta for their technical support throughout the review writing.

■ REFERENCES

(1) Oesterreich, T. D.; Teuteberg, F. Understanding the Implications of Digitisation and Automation in the Context of Industry 4.0: A Triangulation Approach and Elements of a Research Agenda for the Construction Industry. *Comput. Ind.* **2016**, *83*, 121−139.
(2) Pan, Y.; Zhang, Y.; Zhang, D.; Song, Y. 3D Printing in Construction: State of the Art and Applications. *Int. J. Adv. Manuf. Technol.* **2021**, *115* (5−6), 1329−1348.
(3) Kristiawan, R. B.; Imaduddin, F.; Ariawan, D.; Ubaidillah; Arifin, Z. A Review on the Fused Deposition Modeling (FDM) 3D Printing: Filament Processing, Materials, and Printing Parameters. *Open Eng.* **2021**, *11* (1), 639−649.
(4) Popescu, D.; Zapciu, A.; Amza, C.; Baciu, F.; Marinescu, R. FDM Process Parameters Influence over the Mechanical Properties of Polymer Specimens: A Review. *Polym. Test.* **2018**, *69*, 157−166.
(5) Delgado Camacho, D.; Clayton, P.; O'Brien, W. J.; Seepersad, C.; Juenger, M.; Ferron, R.; Salamone, S. Applications of Additive Manufacturing in the Construction Industry − A Forward-Looking Review. *Autom. Constr.* **2018**, *89*, 110−119.
(6) Dudek, P. FDM 3D Printing Technology in Manufacturing Composite Elements. *Arch. Metall. Mater.* **2013**, *58* (4), 1415−1418.
(7) Bici, A.; Yunitsyna, A. Analysis of 3D Printing Techniques for Building Construction: A Review. *Constr. Robot.* **2023**, *7* (2), 107−123.
(8) Hager, I.; Golonka, A.; Putanowicz, R. 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? *Procedia Eng.* **2016**, *151*, 292−299.
(9) D'Alessandro, A.; Ubertini, F.; García-Macías, E.; Castro-Triguero, R.; Downey, A.; Laflamme, S.; Meoni, A.; Materazzi, A. L. Static and Dynamic Strain Monitoring of Reinforced Concrete Components through Embedded Carbon Nanotube Cement-Based Sensors. *Shock Vib.* **2017**, *2017*, 1−11.
(10) Coppola, L.; Buoso, A.; Corazza, F. Electrical Properties of Carbon Nanotubes Cement Composites for Monitoring Stress Conditions in Concrete Structures. *Appl. Mech. Mater.* **2011**, *82*, 118−123.
(11) Zhang, Z. J. Goals and Operation of Green Building. *Appl. Mech. Mater.* **2013**, *438*−*439*, 1706−1709.
(12) Zuo, J.; Zhao, Z.-Y. Green Building Research−Current Status and Future Agenda: A Review. *Renew. Sustain. Energy Rev.* **2014**, *30*, 271−281.
(13) Ding, Z.; Fan, Z.; Tam, V. W. Y.; Bian, Y.; Li, S.; Illankoon, I. M. C. S.; Moon, S. SC. *Build. Environ.* **2018**, *133*, 32.
(14) Taylor, P.; Wang, N.; Adeli, H. *Sustainable Building Design* **2014**, *20*, 37−41.
(15) Tarfiei, M.; Branch, N. Smart Building Materials in Sustainable Architecture: A Case Study in Electrochromic Glass. *Eur. Online J. Nat. Soc. Sci.: Proc* **2015**, *3* (3), 408−416.
(16) Çiner, F.; Doğan-Sağlamtimur, N. Environmental and Sustainable Aspects of Green Building: A Review. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *706* (1), No. 012001.
(17) Kryzia, K.; Radziejowska, A.; Sobotka, A. Analysis of Factors Influencing Carbon Footprint Reduction in Construction Projects. *Arch. Min. Sci.* **2024**, 327−347.
(18) Tashkov, L.; Zlateva, P.; Penkova, N. Reducing the Carbon Footprint in the Construction Sector By Replacing Ceramic Bricks With Alternative Materials. *J. Chem. Technol. Metall.* **2024**, *59* (6), 1347−1352.
(19) Mohamed, S.; Elattar, S. Smart Structures and Material Technologies in Architecture Applications. *Acad. J.* **2013**, *8* (31), 1512−1521.
(20) Javaid, M.; Haleem, A.; Rab, S.; Pratap Singh, R.; Suman, R. Sensors for Daily Life: A Review. *Sensors Int.* **2021**, *2* (July), No. 100121.
(21) Mohamed, A. S. Y. Smart Materials Innovative Technologies in architecture; Towards Innovative design paradigm. *Energy Procedia* **2017**, *115*, 139−154.
(22) Low, Z.-X.; Chua, Y. T.; Ray, B. M.; Mattia, D.; Metcalfe, I. S.; Patterson, D. A. Perspective on 3D Printing of Separation Membranes and Comparison to Related Unconventional Fabrication Techniques. *J. Membr. Sci.* **2017**, *523*, 596−613.
(23) Pessoa, S.; Guimarães, A. S.; Lucas, S. S.; Simões, N. 3D Printing in the Construction Industry - A Systematic Review of the Thermal Performance in Buildings. *Renew. Sustain. Energy Rev.* **2021**, *141*, No. 110794.
(24) Wu, P.; Wang, J.; Wang, X. A Critical Review of the Use of 3-D Printing in the Construction Industry. *Autom. Constr.* **2016**, *68*, 21−31.
(25) Ngo, T. D.; Kashani, A.; Imbalzano, G.; Nguyen, K. T. Q.; Hui, D. Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. *Compos. Part B Eng.* **2018**, *143*, 172−196.
(26) Science, E. *Using of Additive Manufacturing (AM) in Construction Economics − Shortcomings, Advantages, Prospects Using of Additive Manufacturing (AM) in Construction Economics − Shortcomings, Advantages, Prospects* **2021**, DOI: 10.1088/1755-1315/751/1/012170.
(27) Ge, Q.; Dunn, C. K.; Qi, H. J.; Dunn, M. L. Active Origami by 4D Printing. *Smart Mater. Struct.* **2014**, *23* (9), No. 094007.
(28) Momeni, F.; M.Mehdi Hassani.N, S.; Liu, X.; Ni, J. A Review of 4D Printing. *Mater. Des.* **2017**, *122*, 42−79.
(29) Khoo, Z. X.; Teoh, J. E. M.; Liu, Y.; Chua, C. K.; Yang, S.; An, J.; Leong, K. F.; Yeong, W. Y. 3D Printing of Smart Materials: A Review on Recent Progresses in 4D Printing. *Virtual Phys. Prototyp.* **2015**, *10* (3), 103−122.
(30) Jadhav, R. G.; Das, A. K. Four Dimensional Printing in Healthcare. In *3D Printing in Medicine*; Elsevier, 2017; pp 207−218. DOI: 10.1016/B978-0-08-100717-4.00010-7.
(31) Mao, Y.; Yu, K.; Isakov, M. S.; Wu, J.; Dunn, M. L.; Jerry Qi, H. Sequential Self-Folding Structures by 3D Printed Digital Shape Memory Polymers. *Sci. Rep.* **2015**, *5* (1), 13616.
(32) Liu, Y.; Zhang, W.; Zhang, F.; Lan, X.; Leng, J.; Liu, S.; Jia, X.; Cotton, C.; Sun, B.; Gu, B.; Chou, T.-W. Shape Memory Behavior and Recovery Force of 4D Printed Laminated Miura-Origami Structures Subjected to Compressive Loading. *Compos. Part B Eng.* **2018**, *153*, 233−242.
(33) Kuribayashi-Shigetomi, K.; Onoe, H.; Takeuchi, S. Cell Origami: Self-Folding of Three-Dimensional Cell-Laden Micro-structures Driven by Cell Traction Force. *PLoS One* **2012**, *7* (12), No. e51085.
(34) An, B.; Rus, D. Programming and Controlling Self-Folding Robots. In *2012 IEEE International Conference on Robotics and Automation*; IEEE, 2012; pp 3299−3306. DOI: 10.1109/ICRA.2012.6224789.
(35) Ge, Q.; Qi, H. J.; Dunn, M. L. Active Materials by Four-Dimension Printing. *Appl. Phys. Lett.* **2013**, *103* (13), No. 131901.
(36) Khorramshahi, M. R.; Mokhtari, A. Automatic Construction by Contour Crafting Technology. *Emerg. Sci. J.* **2017**, *1* (1), 28.
(37) Bos, F.; Wolfs, R.; Ahmed, Z.; Salet, T. Additive Manufacturing of Concrete in Construction: Potentials and Challenges of 3D Concrete Printing. *Virtual Phys. Prototyp.* **2016**, *11* (3), 209−225.
(38) Lim, S.; Buswell, R.; Le, T.; Wackrow, R.; Austin, S.; Gibb, A.; Thorpe, T. Development of a Viable Concrete Printing Process. *2011 Proc. 28th ISARC, Seoul, Korea* **2011**, DOI: 10.22260/ISARC2011/0124.
(39) Fratello, V. S. 3D Printing Architecture. In *TMS 2021 150th Annual Meeting & Exhibition Supplemental Proceedings*; Minerals, Metals and Materials Series; Springer: Cham, 2021. DOI: 10.1007/978-3-030-65261-6_4.
(40) ICON. *Meet Vulcan: Our Home-Sized 3D Printer*.
(41) Apis Cor. *Construction with Robotic Precision. Technologies*.
(42) IaaC. *Small Robots Printing Big Structures*. 2015.
(43) Hoffman, D. W. *Robotic construction - FBR*.

(44) Giftthaler, M.; Sandy, T.; Dörfler, K.; Brooks, I.; Buckingham, M.; Rey, G.; Kohler, M.; Gramazio, F.; Buchli, J. Mobile Robotic Fabrication at 1:1 Scale: The In Situ Fabricator. *Constr. Robot.* **2017**, *1* (1−4), 3−14.

(45) Sandy, T.; Giftthaler, M.; Dorfler, K.; Kohler, M.; Buchli, J. Autonomous Repositioning and Localization of an in Situ Fabricator. *Proc. - IEEE Int. Conf. Robot. Autom.* **2016**, 2852−2858.

(46) Gardiner, J. B.; Janssen, S.; Kirchner, N. A Realisation of a Construction Scale Robotic System for 3D Printing of Complex Formwork. *ISARC 2016 - 33rd Int. Symp. Autom. Robot. Constr.* **2016**, 515−521.

(47) Herrmann, E.; Mainka, J. L. C.; Lindemann, H.; Wirth, F.; Kloft, H. Digitally Fabricated Innovative Concrete Structures. *ISARC 2018 - 35th Int. Symp. Autom. Robot. Constr. Int. AEC/FM Hackathon Futur. Build. Things* **2018**, DOI: 10.22260/isarc2018/0077.

(48) Fonda, C.; Canessa, E.; Zennaro, M. *Low-Cost 3D Printing for Science, Education and Sustainable Development*; 2013.

(49) Anbarasi, A.; Ishwarya, M. Design and Implementation of Smart Home Using Sensor Network. In *2013 International Conference on Optical Imaging Sensor and Security (ICOSS)*; IEEE, 2013; pp 1−6. DOI: 10.1109/ICOISS.2013.6678399.

(50) Ho, V. T. T.; Hoang, A. N. T.; Thu, T. D.; Thi, N. D. Design and Fabrication the Smart Irrigation Technology Using Soil Moisture Sensor System for Vine in Ninh Thuan, Vietnam. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *991* (1), No. 012143.

(51) Hancke, G.; Silva, B.; Hancke, G., Jr. The Role of Advanced Sensing in Smart Cities. *Sensors* **2013**, *13* (1), 393−425.

(52) Sun, M.; Staszewski, W. J.; Swamy, R. N. Smart Sensing Technologies for Structural Health Monitoring of Civil Engineering Structures. *Adv. Civ. Eng.* **2010**, *2010*, 1−13.

(53) Sobczyk, M.; Wiesenhütter, S.; Noennig, J. R.; Wallmersperger, T. Smart Materials in Architecture for Actuator and Sensor Applications: A Review. *J. Intell. Mater. Syst. Struct.* **2022**, *33* (3), 379−399.

(54) Rosell-Polo, J. R.; Auat Cheein, F.; Gregorio, E.; Andújar, D.; Puigdomènech, L.; Masip, J.; Escolà, A. *Advances in Structured Light Sensors Applications in Precision Agriculture and Livestock Farming* **2015**, *133*, 71−112.

(55) Jang, Y.; Kim, S. M.; Spinks, G. M.; Kim, S. J. Carbon Nanotube Yarn for Fiber-Shaped Electrical Sensors, Actuators, and Energy Storage for Smart Systems. *Adv. Mater.* **2020**, DOI: 10.1002/adma.201902670.

(56) Abegaz, B. W.; Datta, T.; Mahajan, S. M. Sensor Technologies for the Energy-Water Nexus − A Review. *Appl. Energy* **2018**, *210*, 451−466.

(57) Meoni, A.; D'Alessandro, A.; Kruse, R.; De Lorenzis, L.; Ubertini, F. Strain Field Reconstruction and Damage Identification in Masonry Walls under In-Plane Loading Using Dense Sensor Networks of Smart Bricks : Experiments and Simulations. *Eng. Struct.* **2021**, *239*, No. 112199.

(58) Downey, A.; D'Alessandro, A.; Laflamme, S.; Ubertini, F. Smart Bricks for Strain Sensing and Crack Detection in Masonry Structures. *Smart Mater. Struct.* **2018**, *27* (1), 015009.

(59) Konarzewska, B. Smart Materials in Architecture : Useful Tools with Practical Applications or Fascinating Inventions for Experimental Design. *IOP Conf. Ser.: Mater. Sci. Eng.* **2017**, *245*, 052098.

(60) Lai, Z.; Chen, Y. From Wreckage to Resource: Advanced 3D Printing Materials from Construction Waste for Energy Infrastructure. *J. Renew. Sustain. Energy* **2024**, DOI: 10.1063/5.0201775.

(61) Khan, S. A.; Jassim, M.; Ilcan, H.; Sahin, O.; Bayer, I. R.; Sahmaran, M.; Koc, M. Sustainable 3D Printing in the Construction Industry: Environmental Benefits of Comparative Analysis of Circular Materials from Waste and Conventional Construction Methods. *Case Stud. Constr. Mater.* **2023**, *18*, No. e02059.

(62) Elarmathi, S.; Purusothaman, C.; Prasanth, N.; Harishkumar, P. K.; Mohammed Reyan, A. Smart Bricks Curing System Using IoT. *J. ISMAC* **2024**, *6* (2), 165−175.

(63) Shubhananda Rao, P.; Chandar, K. R. Development of Energy Efficient Organic Bricks in Construction Using IOT and Perlite. *Int. J. Sustain. Eng.* **2021**, *14* (4), 865−873.

(64) Shamsaei, E.; de Souza, F. B.; Yao, X.; Benhelal, E.; Akbari, A.; Duan, W. Graphene-Based Nanosheets for Stronger and More Durable Concrete: A Review. *Constr. Build. Mater.* **2018**, *183*, 642−660.

(65) Mak, S.-L.; Wu, T. M. Y.; Tang, F. W. F.; Li, J. C. H.; Lai, C. W. A Review on Utilization of Plastic Wastes in Making Construction Bricks. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *706* (1), No. 012001.

(66) Lim, S.; Buswell, R. A.; Le, T. T.; Austin, S. A.; Gibb, A. G. F.; Thorpe, T. *Automation in Construction Developments in Construction-Scale Additive Manufacturing Processes* **2012**, *21*, 262−268.

(67) Hamidreza, S.; Corker, J.; Fan, M. Additive Manufacturing Technology and Its Implementation in Construction as an Eco-Innovative Solution. *Automation in Construction* **2018**, *93*, 1−11.

(68) Labonnote, N.; Rønnquist, A.; Manum, B.; Rüther, P. Automation in Construction Additive Construction : State-of-the-Art, Challenges and Opportunities. *Autom. Constr.* **2016**, *72*, 347−366.

(69) Bhattacharjee, J.; Roy, S. Smart Materials for Sustainable Energy. *Nat. Resour. Conserv. Res.* **2024**, *7* (1), 5536.

(70) Behera, A. Smart Materials Based Additive Manufacturing. *Mater. Horizons Nat. Nanomater.* **2024**, 153−175.

(71) Massaro, A. Intelligent Materials and Nanomaterials Improving Physical Properties and Control Oriented on Electronic Implementations. *Electron.* **2023**, *12* (18), 3772.

(72) Liu, M.; Chen, C.; Jin, X.; Xue, C.; Zhang, S.; Feng, P.; Luo, Y. Smart Building Material with Near-Infrared-Triggered Reversible Color Switching. *Adv. Eng. Mater.* **2024**, DOI: 10.1002/adem.202400618.

(73) Lee, S. Y.; Chae, D.; Kim, J.; Oh, S.; Lim, H.; Kim, J.; Lee, H.; Oh, S. J. Smart Building Block with Colored Radiative Cooling Devices and Quantum Dot Light Emitting Diodes. *Nanoscale* **2024**, *16* (4), 1664−1672.

(74) Wu, M.; Yao, F.; Wang, H. An End-to-End Solution for Spatial Inference in Smart Buildings. *In Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation*; ACM: New York, NY, USA, 2023; pp 110−119. DOI: 10.1145/3600100.3623736.

(75) Kontiza, A.; Kartsonakis, I. A. Smart Composite Materials with Self-Healing Properties: A Review on Design and Applications. *Polymers (Basel)* **2024**, *16* (15), 2115.

(76) Meoni, A.; D'Alessandro, A.; Virgulto, G.; Buratti, N.; Ubertini, F. Smart Bricks for Monitoring Strain in Full-Scale Masonry Structures: Recent Advances and First Field Application. *Lect. Notes Civ. Eng.* **2023**, *253*, 835−843.

(77) Vaghasiya, J. V.; Mayorga-Martinez, C. C.; Pumera, M. Smart Energy Bricks: Ti3C2@Polymer Electrochemical Energy Storage inside Bricks by 3D Printing. *Adv. Funct. Mater.* **2021**, DOI: 10.1002/adfm.202106990.

(78) Vasconcelos, A. R. C.; de Matos, R. A.; Silveira, M. V.; Mesquita, E. Applications of Smart and Self-Sensing Materials for Structural Health Monitoring in Civil Engineering: A Systematic Review. *Buildings* **2024**, *14* (8), 2345.

(79) Ubertini, F. Advancing Seismic Monitoring of Masonry Structures with Smart Bricks: Recent Developments and Future Prospects. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2024*; Limongelli, M. P., Ng, C. T., Glisic, B., Eds.; SPIE, 2024; p 6. DOI: 10.1117/12.3010112.

(80) Jung, Y.-J.; Jang, S.-H. Crack Detection of Reinforced Concrete Structure Using Smart Skin. *Nanomaterials* **2024**, *14* (7), 632.

(81) Meoni, A.; D'Alessandro, A.; Cavalagli, N.; Gioffré, M.; Ubertini, F. Shaking Table Tests on a Masonry Building Monitored Using Smart Bricks: Damage Detection and Localization. *Earthq. Eng. Struct. Dyn.* **2019**, *48* (8), 910−928.

(82) Purnomo, R. D.; Trilaksono, B. R.; Riyansyah, M.; Triwibowo, H. Development of Atmel SAM-Based Wireless Sensor Node for

Bridge Structural Health Monitoring (SHM). *Proc. Int. Conf. Electr. Eng. Informatics* **2023**, DOI: 10.1109/ICEEI59426.2023.10346654.
(83) Kullaa, J. Damage Detection Using Different Types of Sensors. *J. Phys. Conf. Ser.* **2024**, *2647* (18), 182006.
(84) Fertitta, G.; Yang, W.; Costanza, A.; Martino, C.; Macaluso, F.; Patane, D. Design and Test of a Smart Sensor Box for Structural and Seismological Monitoring with a High-Performance QMEMS Accelerometer. *2024 IEEE Int. Work. Metrol. Ind. 4.0 IoT* **2024**, 541−546.
(85) Andò, B.; Greco, D.; Navarra, G.; Lo Iacono, F. A Low-Cost Sensing Solution for SHM, Exploiting a Dedicated Approach for Signal Recognition. *Sensors* **2024**, *24* (12), 4023.
(86) Al-Nasser, H.; Al-Zuriqat, T.; Dragos, K.; Geck, C. C.; Smarsly, K. Identification of Combined Sensor Faults in Structural Health Monitoring Systems. *Smart Mater. Struct.* **2024**, *33* (8), 085026.
(87) Alessandro, A. D.; Meoni, A.; Ubertini, F. *Stainless Steel Microfibers for Strain-Sensing Smart Clay Bricks*, 2018.
(88) La Mendola, L.; Oddo, M. C.; Cucchiara, C.; Granata, M. F.; Barile, S.; Pappalardo, F.; Pennisi, A. Experimental Investigation on Innovative Stress Sensors for Existing Masonry Structures Monitoring. *Appl. Sci.* **2023**, *13* (6), 3712.
(89) La Mendola, L.; Oddo, M. C.; Papia, M.; Pappalardo, F.; Pennisi, A.; Bertagnoli, G.; Di Trapani, F.; Monaco, A.; Parisi, F.; Barile, S. Performance of Two Innovative Stress Sensors Imbedded in Mortar Joints of New Masonry Elements. *Constr. Build. Mater.* **2021**, *297*, No. 123764.
(90) Meoni, A.; D'Alessandro, A.; Saviano, F.; Lignola, G. P.; Parisi, F.; Ubertini, F. Strain Monitoring and Crack Detection in Masonry Walls under In-Plane Shear Loading Using Smart Bricks: First Results from Experimental Tests and Numerical Simulations. *Sensors* **2023**, *23* (4), 2211.
(91) García-Macías, E.; Ubertini, F. Earthquake-induced Damage Detection and Localization in Masonry Structures Using Smart Bricks and Kriging Strain Reconstruction: A Numerical Study. *Earthq. Eng. Struct. Dyn.* **2019**, *48* (5), 548−569.
(92) Meoni, A.; D'Alessandro, A.; Cavalagli, N.; Gioffré, M.; Ubertini, F. Shaking Table Tests on a Masonry Building Monitored Using Smart Bricks: Damage Detection and Localization. *Earthq. Eng. Struct. Dyn.* **2019**, *48* (8), 910−928.
(93) D'Alessandro, A.; Meoni, A.; Ubertini, F. Stainless Steel Microfibers for Strain-Sensing Smart Clay Bricks. *J. Sensors* **2018**, *2018*, 1−8.
(94) Lin, H.; Xu, Z.; Hong, W.; Yang, Z.; Wang, Y.; Li, B. Long-Gauge Fiber Optic Sensors: Strain Measurement Comparison for Reinforced Concrete Columns. *Sensors* **2025**, *25* (1), 220.
(95) Downey, A.; D'Alessandro, A.; Laflamme, S.; Ubertini, F. Smart Bricks for Strain Sensing and Crack Detection in Masonry Structures. *Smart Mater. Struct.* **2018**, *27* (1), No. 015009.
(96) Ubertini, F.; D'Alessandro, A.; Materazzi, A. L.; Laflamme, S.; Downey, A. Novel Nanocomposite Clay Brick for Strain Sensing in Structural Masonry. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*; IEEE, 2017; pp 1−4. DOI: 10.1109/EEEIC.2017.7977598.
(97) Hallee, M. J.; Napolitano, R. K.; Reinhart, W. F.; Glisic, B. Crack Detection in Images of Masonry Using CNNs. *Sensors* **2021**, *21* (14), 4929.
(98) Hoang, N.-D. Detection of Surface Crack in Building Structures Using Image Processing Technique with an Improved Otsu Method for Image Thresholding. *Adv. Civ. Eng.* **2018**, *2018*, 1−10.
(99) Van Tittelboom, K.; De Belie, N. Self-Healing in Cementitious Materials—A Review. *Materials (Basel)* **2013**, *6* (6), 2182−2217.
(100) Saleem, B.; Hussain, A.; Khattak, A.; Khan, A. Performance Evaluation of Bacterial Self-Healing Rigid Pavement by Incorporating Recycled Brick Aggregate. *Cem. Concr. Compos.* **2021**, *117*, No. 103914.
(101) Elgendy, I. M.; Elkaliny, N. E.; Saleh, H. M.; Darwish, G. O.; Almostafa, M. M.; Metwally, K.; Yahya, G.; Mahmoud, Y. A.-G. *J. Ind. Microbiol. Biotechnol.* **2024**, DOI: 10.1093/jimb/kuae051.
(102) Maurente-Silva, D. G.; Borowski, J. V. B.; Cappellesso, V. G.; Vainstein, M. H.; Masuero, A. B.; Dal Molin, D. C. C. Effect of Exposure Environment and Calcium Source on the Biologically Induced Self-Healing Phenomenon in a Cement-Based Material. *Buildings* **2024**, *14* (12), 3782.
(103) Mitra, A.; Sreedharan, S. M.; Singh, R. Concrete Crack Restoration Using Bacterially Induced Calcium Metabolism. *Indian J. Microbiol.* **2021**, *61* (2), 229−233.
(104) Pisello, A. L.; D'Alessandro, A.; Sambuco, S.; Rallini, M.; Ubertini, F.; Asdrubali, F.; Materazzi, A. L.; Cotana, F. Multipurpose Experimental Characterization of Smart Nanocomposite Cement-Based Materials for Thermal-Energy Efficiency and Strain-Sensing Capability. *Sol. Energy Mater. Sol. Cells* **2017**, *161*, 77−88.
(105) Zhang, R.; Li, H.; Duan, K.; You, S.; Liu, K.; Wang, F.; Hu, Y. Automatic Detection of Earthquake-Damaged Buildings by Integrating UAV Oblique Photography and Infrared Thermal Imaging. *Remote Sens.* **2020**, *12* (16), 2621.
(106) Maia de Souza, D.; Lafontaine, M.; Charron-Doucet, F.; Chappert, B.; Kicak, K.; Duarte, F.; Lima, L. Comparative Life Cycle Assessment of Ceramic Brick, Concrete Brick and Cast-in-Place Reinforced Concrete Exterior Walls. *J. Clean. Prod.* **2016**, *137*, 70−82.
(107) Bygness, R. World of Coal Ash. *Geosynthetics* **2015**, *33* (3), 1−13.
(108) Fang, Y.; Gu, Y.; Kang, Q.; Wen, Q.; Dai, P. Utilization of Copper Tailing for Autoclaved Sand−Lime Brick. *Constr. Build. Mater.* **2011**, *25* (2), 867−872.
(109) Žujovi, M. *3D Printing Technologies in Architectural Design and Construction : A Systematic Literature Review*, 2022.
(110) Schuldt, S. J.; Jagoda, A.; Hoisington, A. J.; Delorit, J. D.; Administration, V. H.; Mountain, R.; Illness, M.; Mountain, R.; Veterans, R.; Medical, A. A Systematic Review and Analysis of the Viability of 3D-Printed Construction in Remote Environments. *Automation in Construction* **2021**, DOI: 10.1016/j.autcon.2021.103642.
(111) Sakin, M.; Kiroglu, Y. C. 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. *Energy Procedia* **2017**, *134*, 702−711.
(112) Shufrin, I.; Pasternak, E.; Dyskin, A. Environmentally Friendly Smart Construction—Review of Recent Developments and Opportunities. *Appl. Sci.* **2023**, *13* (23), 12891.
(113) Shakir, A. A.; Mohammed, A. A.; Mohammed, A. A. Manufacturing of Bricks in the Past, in the Present and in the Future : A State of the Art Review. *Int. J. Adv. Appl. Sci.* **2013**, *2* (3), 145−156.
(114) Iyer, S. *Cyber Security for Smart Grid, Cryptography, and Privacy*, 2011. DOI: 10.1155/2011/372020.
(115) Lee, C. C. A Basic Principle of Physical Security and Its Link to Cybersecurity. *Zenodo* **2020**, *14*, 203−219.
(116) Wu, P.; Wang, J.; Wang, X. Automation in Construction A Critical Review of the Use of 3-D Printing in the Construction Industry Material Finished. *Autom. Constr.* **2016**, *68*, 21−31.
(117) Shahrubudin, N.; Lee, T. C.; Ramlan, R. An Overview on 3D Printing Technology: Technological, Materials, and Applications. *Procedia Manuf.* **2019**, *35*, 1286−1296.
(118) Huang, W. M.; Yang, B.; Zhao, Y.; Ding, Z. Thermo-Moisture Responsive Polyurethane Shape-Memory Polymer and Composites: A Review. *J. Mater. Chem.* **2010**, *20* (17), 3367.
(119) Sun, L.; Huang, W. M.; Ding, Z.; Zhao, Y.; Wang, C. C.; Purnawali, H.; Tang, C. Stimulus-Responsive Shape Memory Materials: A Review. *Mater. Des.* **2012**, *33*, 577−640.
(120) Zhang, Y. S.; Yue, K.; Aleman, J.; Mollazadeh-Moghaddam, K.; Bakht, S. M.; Yang, J.; Jia, W.; Dell'Erba, V.; Assawes, P.; Shin, S. R.; Dokmeci, M. R.; Oklu, R.; Khademhosseini, A. 3D Bioprinting for Tissue and Organ Fabrication. *Ann. Biomed. Eng.* **2017**, *45* (1), 148−163.
(121) Uchino, K. The Development of Piezoelectric Materials and the New Perspective. In *Advanced Piezoelectric Materials*; Elsevier, 2017; pp 1−92. DOI: 10.1016/B978-0-08-102135-4.00001-1.

(122) Miyazaki, S. Development and Characterization of Shape Memory Alloys. In *Shape Memory Alloys*; Springer Vienna: Vienna, 1996; pp 69−147. DOI: 10.1007/978-3-7091-4348-3_2.
(123) Dadbakhsh, S.; Speirs, M.; Kruth, J.; Schrooten, J.; Luyten, J.; Van Humbeeck, J. Effect of SLM Parameters on Transformation Temperatures of Shape Memory Nickel Titanium Parts. *Adv. Eng. Mater.* **2014**, *16* (9), 1140−1146.
(124) Goyanes, A.; Buanz, A. B. M.; Basit, A. W.; Gaisford, S. Fused-Filament 3D Printing (3DP) for Fabrication of Tablets. *Int. J. Pharm.* **2014**, *476* (1−2), 88−92.
(125) Steuben, J.; Van Bossuyt, D. L.; Turner, C. Design for Fused Filament Fabrication Additive Manufacturing. In *Vol. 4:20th Design for Manufacturing and the Life Cycle Conference; 9th International Conference on Micro- and Nanosystems*; American Society of Mechanical Engineers, 2015. DOI: 10.1115/DETC2015-46355.
(126) Vaghasiya, J. V.; Mayorga-martinez, C. C.; Pumera, M. Smart Energy Bricks : Ti 3 C 2 @ Polymer Electrochemical Energy Storage inside Bricks by 3D Printing. *Adv. Funct. Mater.* **2021**, *2106990*, 1−9.
(127) Al-Noaimat, Y. A.; Chougan, M.; Albar, A.; Skibicki, S.; Federowicz, K.; Hoffman, M.; Sibera, D.; Cendrowski, K.; Techman, M.; Pacheco, J. N.; Chung, S.-Y.; Sikora, P.; Al-Kheetan, M.; Ghaffar, S. H. Recycled Brick Aggregates in One-Part Alkali-Activated Materials: Impact on 3D Printing Performance and Material Properties. *Dev. Built Environ.* **2023**, *16*, No. 100248.
(128) Yang, Y.; Li, X.; Chu, M.; Sun, H.; Jin, J.; Yu, K.; Wang, Q.; Zhou, Q.; Chen, Y. Electrically Assisted 3D Printing of Nacre-Inspired Structures with Self-Sensing Capability. *Sci. Adv.* **2019**, DOI: 10.1126/sciadv.aau9490.
(129) Li, B.; Yu, M.; Li, Z.; Yu, C.; Wang, H.; Li, Q. Constructing Flexible All-Solid-State Supercapacitors from 3D Nanosheets Active Bricks via 3D Manufacturing Technology: A Perspective Review. *Adv. Funct. Mater.* **2022**, DOI: 10.1002/adfm.202201166.
(130) Yang, G.; Sun, Y.; Li, M.; Ou, K.; Fang, J.; Fu, Q. Direct-Ink-Writing (DIW) 3D Printing Functional Composite Materials Based on Supra-Molecular Interaction. *Compos. Sci. Technol.* **2021**, *215*, No. 109013.
(131) Terrazas, C. A.; Gaytan, S. M.; Rodriguez, E.; Espalin, D.; Murr, L. E.; Medina, F.; Wicker, R. B. Multi-Material Metallic Structure Fabrication Using Electron Beam Melting. *Int. J. Adv. Manuf. Technol.* **2014**, *71* (1−4), 33−45.
(132) Sirohi, J.; Chopra, I. Fundamental Understanding of Piezoelectric Strain Sensors. *J. Intell. Mater. Syst. Struct.* **2000**, *11* (4), 246−257.
(133) Jerzy, S. Application of Smart Materials in Civil Engineering and Architecture. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *958* (1), No. 012006.
(134) Kim, M.; Jeong, J. H.; Lee, J.; Capasso, A.; Bonaccorso, F.; Kang, S.; Lee, Y.; Lee, G. Electrically Conducting and Mechanically Strong Graphene − Polylactic Acid Composites for 3D Printing. *ACS Appl. Mater. Interfaces* **2019**, *11*, 11841−11848.
(135) Luukkonen, T.; Abdollahnejad, Z.; Yliniemi, J.; Kinnunen, P.; Illikainen, M. One-Part Alkali-Activated Materials : A Review. *Cement Concrete Res.* **2017**, DOI: 10.1016/j.cemconres.2017.10.001.
(136) Tian, W.; Vahidmohammadi, A.; Reid, M. S.; Wang, Z.; Ouyang, L.; Erlandsson, J.; Pettersson, T.; Wågberg, L.; Beidaghi, M.; Hamedi, M. M. Multifunctional Nanocomposites with High Strength and Capacitance Using 2D MXene and 1D Nanocellulose. *Adv. Mater.* **2019**, *31*, No. 1902977.

https://doi.org/10.1021/acsomega.4c04943
ACS Omega 2025, 10, 22305−22322