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Layered Metal–Polymer Hybrid Laminates with Embedded Impact Sensors for Connected Automotive Panels

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Abstract

The increasing demand for lightweight, intelligent, and structurally reliable automotive components has accelerated the development of multifunctional hybrid materials capable of simultaneously providing superior mechanical performance and real-time structural health monitoring. In this study, a novel layered metal–polymer hybrid laminate incorporating an embedded flexible impact sensor was developed for connected automotive panel applications. The laminate was fabricated using AA6061-T6 aluminum alloy face sheets and a thermoplastic polyurethane interlayer through hot-press compression molding. A flexible graphene/CNT-based sensor was embedded at the neutral plane of the polymer core to monitor impact events without compromising structural integrity. Mechanical evaluation demonstrated that the TPU interlayer enhanced impact energy absorption, delayed crack propagation, and improved damage tolerance under low-velocity impact loading while maintaining high tensile and flexural performance. The sensor exhibited stable and repeatable voltage responses over impact energies ranging from 5 J to 30 J, showing excellent correlation between sensor output and impact severity. Furthermore, an ESP32-based wireless communication module established an Internet of Things enabled structural health monitoring framework capable of transmitting real-time impact data to cloud platforms for remote visualization and predictive maintenance. The proposed multifunctional hybrid laminate successfully combines lightweight structural reinforcement, impact sensing, and intelligent connectivity within a single integrated architecture, demonstrating strong potential for next-generation automotive body panels, enhanced passenger safety, and sustainable vehicle technologies for future connected mobility ecosystems and autonomous transportation worldwide.

Keywords: Thermoplastic polyurethane, graphene/carbon nano-tube, metal–polymer hybrid laminate, remote visualization, flexural performance.

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INTRODUCTION

The automotive industry is undergoing a rapid transformation driven by stringent environmental regulations, increasing demand for lightweight transportation systems, and the widespread adoption of connected and intelligent vehicle technologies. Modern vehicles are expected not only to exhibit superior structural performance and passenger safety but also to possess the capability to continuously monitor their structural condition throughout their service life. Consequently, lightweight multifunctional materials capable of simultaneously providing high mechanical performance and real-time structural health monitoring (SHM) have become a major focus of advanced automotive research. Among these materials, layered metal–polymer hybrid laminates (MPHLs) have attracted considerable attention owing to their excellent combination of high specific strength, corrosion resistance, impact tolerance, vibration damping, and design flexibility [1–3].

Conventional automotive body panels are primarily fabricated from steel or aluminum alloys because of their excellent load-bearing capability and established manufacturing infrastructure. However, these metallic structures contribute significantly to vehicle weight, thereby increasing fuel consumption and greenhouse gas emissions. Alternatively, polymer composites offer substantial weight reduction but often exhibit lower impact resistance and limited energy absorption under crash conditions [4, 5]. Layered metal–polymer hybrid laminates effectively combine the advantages of both materials by integrating thin metallic sheets with high-performance polymer layers, resulting in composites that exhibit improved stiffness-to-weight ratio, enhanced fatigue resistance, superior damage tolerance, and excellent vibration attenuation. Such hybrid architectures are increasingly being considered for automotive doors, engine hoods, roof panels, battery enclosures, and side-impact protection systems where lightweight construction and crashworthiness are equally important [6–8].

Although metal–polymer hybrid laminates possess outstanding mechanical characteristics, they remain susceptible to impact-induced damage during manufacturing, transportation, and in-service operation. Low-velocity impacts caused by road debris, parking collisions, hailstones, and minor accidents often produce barely visible impact damage (BVID), including internal delamination, matrix cracking, localized plastic deformation, and interfacial debonding. These defects frequently remain undetected during routine visual inspection while progressively reducing structural stiffness and long-term reliability [9–11]. Therefore, the development of intelligent hybrid structures capable of autonomously detecting impact events has become increasingly important for next-generation connected vehicles.

Recent advances in flexible electronics, printed sensors, and Internet of Things (IoT) technologies have enabled the integration of sensing elements directly within structural materials. Embedded impact sensors provide continuous monitoring of strain waves, vibration signatures, and impact energy without compromising the external geometry of automotive panels. Compared with externally mounted sensing systems, embedded sensors offer improved protection against environmental degradation, mechanical abrasion, moisture ingress, and accidental damage while delivering more accurate measurements from the interior of the laminate [12–14]. Flexible piezoresistive, piezoelectric, and capacitive sensors fabricated using conductive nanomaterials – such as graphene, carbon nanotubes (CNTs), MXenes, and metallic nanowires – have demonstrated remarkable sensitivity toward dynamic mechanical loading, making them attractive candidates for embedded structural sensing applications [15].

The selection of the polymer interlayer plays a decisive role in determining the overall performance of metal–polymer hybrid laminates. Thermoplastic polymers – such as polypropylene (PP), polyethylene terephthalate (PET), polyamide (PA), and thermoplastic polyurethane (TPU) – provide excellent formability, impact resistance, and recyclability, whereas thermosetting polymers including epoxy and polyurethane offer superior stiffness and interfacial adhesion with metallic substrates. Furthermore, advanced surface modification techniques – such as plasma treatment, anodization, laser texturing, and silane coupling – significantly improve metal–polymer interfacial bonding, thereby enhancing load transfer efficiency and suppressing premature delamination under cyclic and impact loading [16].

Beyond lightweight structural design, the emergence of connected vehicles has accelerated the integration of embedded sensing networks into automotive components. Smart body panels capable of detecting impact events and transmitting real-time structural information to onboard electronic control units (ECUs), vehicle gateways, or cloud-based diagnostic platforms represent an important step toward predictive maintenance and intelligent transportation systems. Such systems enable rapid accident detection, early identification of structural degradation, optimized maintenance scheduling, and improved passenger safety while supporting the broader vision of Industry 4.0 and intelligent mobility [17].

Despite considerable progress in hybrid laminates and embedded sensing technologies, limited research has focused on developing a unified metal–polymer laminate architecture that simultaneously combines lightweight structural performance, impact resistance, embedded sensing capability, and connected vehicle communication within a single multifunctional system. Most existing studies investigate either mechanical behavior or sensor performance independently, without addressing the interaction between embedded sensing elements and the structural integrity of the laminate under impact loading. Furthermore, maintaining strong interfacial adhesion while integrating flexible sensors remains a significant engineering challenge due to local stress concentrations and possible reductions in mechanical performance [18].

To address these challenges, this study proposes a layered metal–polymer hybrid laminate incorporating embedded flexible impact sensors for connected automotive body panels. The proposed architecture integrates thin metallic face sheets, a high-performance polymer core, and strategically positioned flexible impact sensors to achieve simultaneous structural reinforcement and real-time impact monitoring. The laminate is designed to exhibit high energy absorption, excellent interfacial integrity, reliable sensor response, and compatibility with connected vehicle communication systems. Comprehensive mechanical characterization, impact evaluation, sensor response analysis, and structural reliability assessment are performed to investigate the feasibility of the proposed smart laminate for next-generation automotive applications. The developed multifunctional hybrid panel is expected to contribute toward lightweight vehicle manufacturing, intelligent structural health monitoring, enhanced passenger safety, and sustainable automotive engineering.

MATERIALS AND METHODS

Materials

The layered metal–polymer hybrid laminates were fabricated using commercially available AA6061-T6 aluminum alloy sheets (0.5 mm thickness) as the outer metallic skins due to their excellent strength-to-weight ratio, corrosion resistance, and automotive-grade formability. A thermoplastic polyurethane (TPU) film with a thickness of 1.2 mm served as the polymer interlayer because of its high impact toughness, flexibility, vibration damping capability, and strong adhesion to metallic substrates. Prior to laminate fabrication, the aluminum sheets were mechanically polished using 800-grit silicon carbide paper, ultrasonically cleaned in acetone and ethanol, and finally dried using compressed air to remove surface contaminants.

Flexible polyimide (PI) films (50 µm thick) were selected as the substrate for the embedded impact sensors owing to their excellent thermal stability and mechanical durability. Silver nanoparticle conductive ink was screen-printed to form an interdigitated sensing electrode, while a graphene/carbon nanotube (CNT) nanocomposite coating was deposited as the active sensing layer. Copper micro-wires (100 µm diameter) were connected to the sensing electrodes to establish communication with the data acquisition unit. The detailed composition and specifications of all constituent materials used in the fabrication of the hybrid laminates are summarized in Table 1.

Fabrication of Layered Metal–Polymer Hybrid Laminates

The fabrication procedure of the smart hybrid laminate is illustrated in Figure 1. Initially, the cleaned aluminum sheets were surface-treated using atmospheric plasma to improve surface energy and enhance metal–polymer adhesion. The TPU film was then positioned between two aluminum sheets to form a symmetric laminate configuration.

The flexible impact sensor was carefully embedded at the neutral mid-plane of the polymer layer to minimize stress concentration during mechanical loading. The laminate assembly was consolidated using a hot-press compression molding process at 180°C under a pressure of 4 MPa for 25 min, followed by controlled cooling under constant pressure to ensure complete bonding and dimensional stability. Electrical leads from the embedded sensor were routed through the laminate edge without affecting structural continuity. The final laminate exhibited excellent interfacial bonding, uniform thickness, and complete encapsulation of the sensing element within the polymer core, as illustrated in Figure 1.

Table 1. Materials, constituent properties, and laminate configurations employed in the fabrication of the layered metal–polymer hybrid laminates.

Component	Material/specification	Key properties	Purpose in hybrid laminate
Outer Metal Skin	AA6061-T6 Aluminum Alloy (0.5 mm)	Density: 2.70 g/cm³; Tensile Strength: 310 MPa; Young's Modulus: 68.9 GPa; Excellent corrosion resistance	Provides structural rigidity, impact resistance, and lightweight metallic reinforcement.
Polymer Core	Thermoplastic Polyurethane (TPU) (1.2 mm)	Density: 1.18 g/cm³; High flexibility; Excellent impact toughness; Good vibration damping	Functions as the energy-absorbing core and bonding layer between metal skins.
Sensor Substrate	Polyimide (PI) Film (50 µm)	High thermal stability (up to 400°C); Flexible; Electrically insulating	Supports the embedded impact sensing element without affecting laminate flexibility.
Conductive Electrode	Screen-Printed Silver Nanoparticle Ink	Electrical conductivity: ~6×10^6 S/m; Excellent adhesion; High signal stability	Forms the interdigitated electrode (IDE) for impact signal acquisition.
Active Sensing Layer	Graphene/Carbon Nanotube (CNT) Nanocomposite	High piezoresistive sensitivity; Fast electrical response; High mechanical flexibility	Detects impact-induced deformation through resistance variation.
Electrical Interconnects	Copper Micro-Wires (100 µm diameter)	High electrical conductivity; Low signal loss	Transfers sensor signals to the embedded data acquisition system.
Surface Treatment	Atmospheric Plasma Treatment	Increases surface energy; Improves metal–polymer adhesion	Enhances interfacial bonding and suppresses delamination.
Bonding Process	Hot Compression Molding	180°C; 4 MPa; 25 min curing	Consolidates the laminate and encapsulates the sensor within the polymer core.
Data Acquisition System	National Instruments (NI) DAQ	Sampling frequency: 10 kHz	Acquires real-time electrical signals generated during impact loading.
Wireless Communication Module	ESP32 Microcontroller with Wi-Fi	2.4 GHz Wi-Fi; Low power consumption	Enables wireless transmission of impact data to cloud-based monitoring platform.

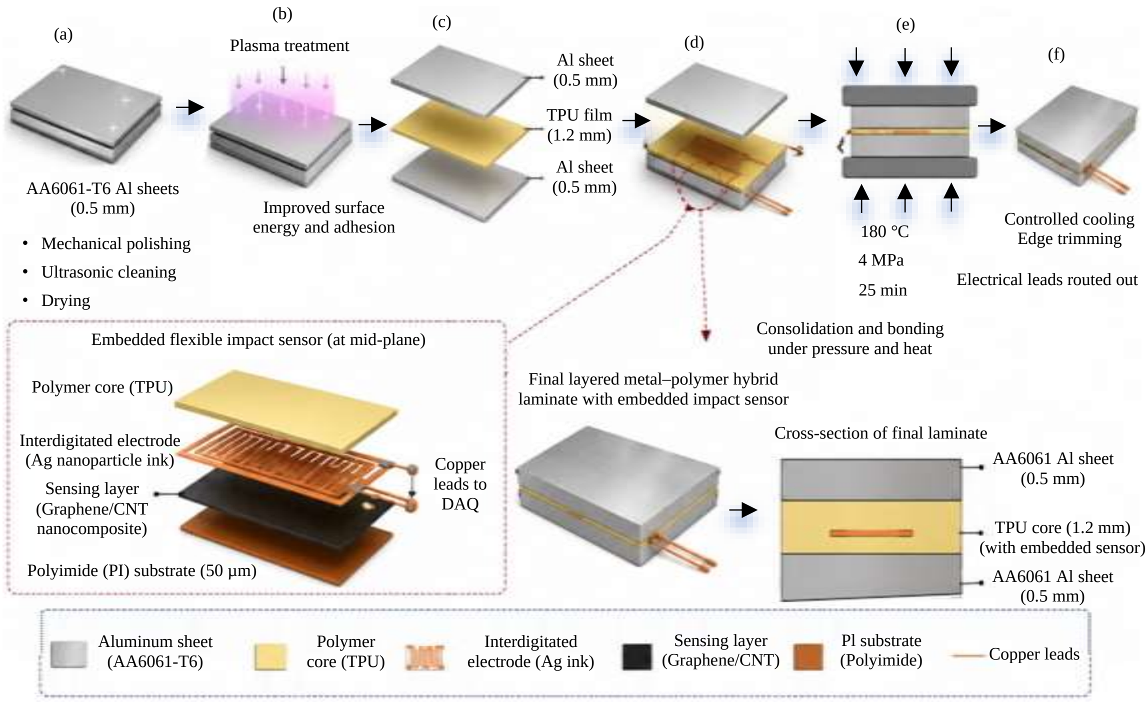

Figure 1. Schematic illustration of the fabrication process of the layered metal–polymer hybrid laminate incorporating an embedded flexible impact sensor. (a) Material preparation and cleaning. (b) Surface treatment (plasma). (c) Lay-up of metal–polymer preform. (d) Embedding of flexible impact sensor. (e) Hot-press compression molding. (f) Cooling and edge trimming.

Structural, Mechanical, and Sensor Characterization

The structural integrity and interfacial morphology of the fabricated laminates were examined using Scanning Electron Microscopy (SEM) to evaluate metal–polymer bonding and sensor integration. Optical microscopy was further employed to inspect laminate quality and identify possible voids or delamination around the embedded sensing region. The overall laminate thickness was measured using a digital micrometer with an accuracy of ±1 μm.

Mechanical characterization included tensile testing according to ASTM D3039, three-point flexural testing based on ASTM D790, and low-velocity impact testing following ASTM D7136. An instrumented drop-weight impact tester equipped with a hemispherical impactor was used to investigate the energy absorption characteristics and impact resistance of the hybrid laminates. The experimental arrangement adopted for structural and impact characterization is presented in Figure 2.

(a) (b)

Figure 2. Experimental setup for tensile, flexural, and low-velocity impact characterization of the layered metal–polymer hybrid laminates. (a) mechanical testing laboratory drops weight impact tensile testing machine. (b) flexural 3 point bending test universal testing machine and drop weight low-velocity impact testing machine.

Embedded Impact Sensor Evaluation

The performance of the embedded impact sensor was evaluated under repeated impact loading and cyclic mechanical deformation. During impact events, the sensor continuously recorded variations in electrical resistance, voltage response, and signal amplitude corresponding to different impact energies. Signal acquisition was performed using a National Instruments (NI) DAQ system operating at a sampling frequency of 10 kHz. Multiple impact energies ranging from 5 J to 30 J were applied to establish the relationship between impact severity and sensor response.

The repeatability, sensitivity, response time, and stability of the sensing system were evaluated through repeated loading cycles. The acquired signals were processed using MATLAB to eliminate environmental noise and accurately identify impact events. The processed sensor outputs were further correlated with the measured impact force and absorbed energy to assess the effectiveness of the embedded sensing system for structural health monitoring.

Connected Automotive Monitoring Framework

To demonstrate intelligent monitoring capability, the embedded impact sensor was interfaced with an ESP32 microcontroller integrated with a Wi-Fi communication module. The processed impact data were transmitted wirelessly to a cloud-based monitoring dashboard, enabling real-time visualization of impact location, signal intensity, and structural condition. The proposed connected monitoring architecture provides continuous health assessment of automotive body panels while supporting predictive maintenance strategies for next-generation intelligent vehicles. The overall sensing, wireless communication, cloud analytics, and remote monitoring framework is illustrated in Figure 3.

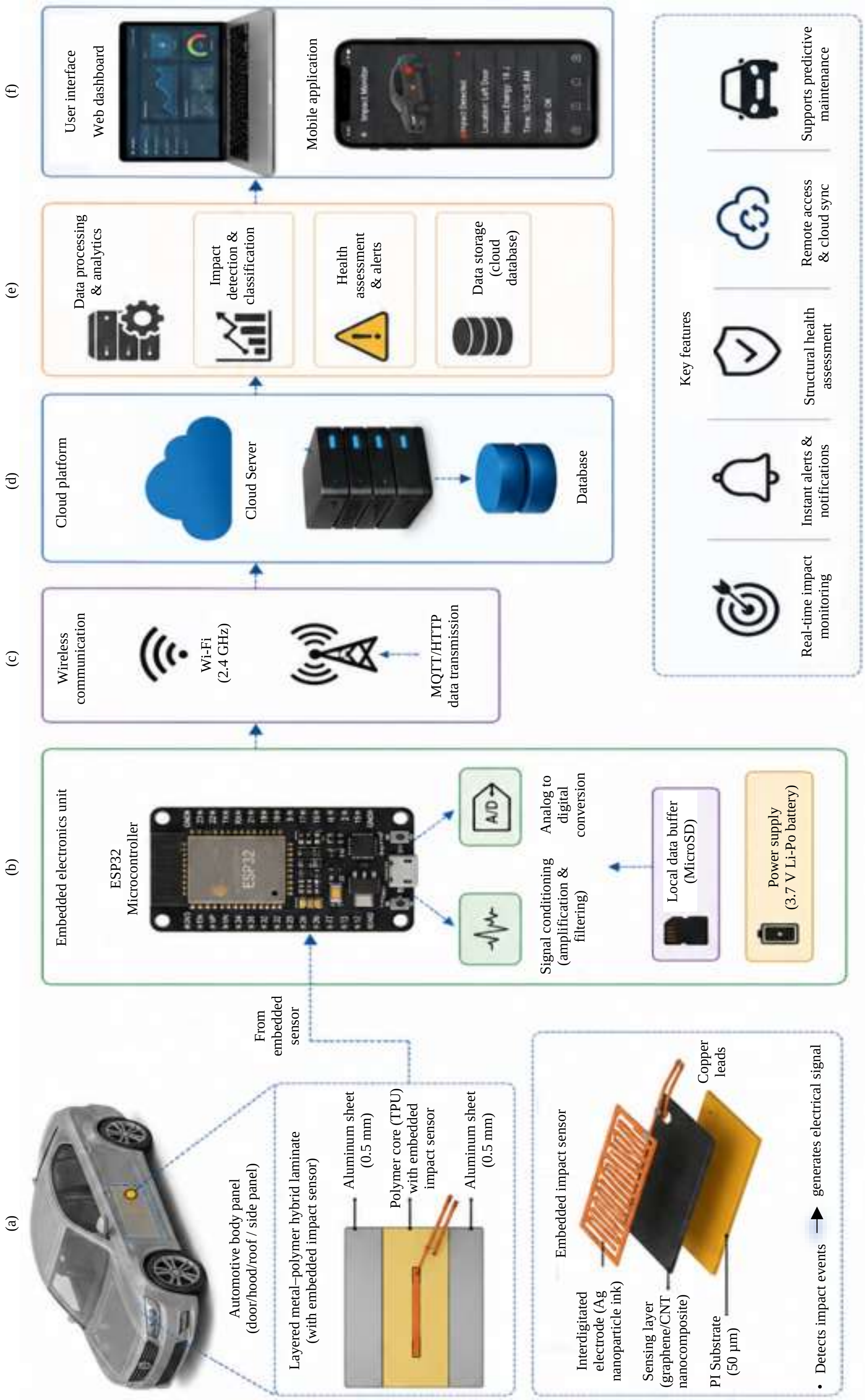

Figure 3. IoT-enabled connected automotive monitoring framework incorporating. (a) embedded impact sensor. (b) ESP32 controller. (c) wireless communication. (d) cloud dashboard. (e) data analytics and storage and. (f) user interface.

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RESULTS AND DISCUSSION

Interfacial Morphology and Mechanical Integrity

The interfacial characteristics of the layered metal–polymer hybrid laminate play a significant role in determining its structural performance under mechanical loading. SEM observations (Figure 4) revealed strong adhesion between the plasma-treated AA6061 aluminum sheets and the TPU polymer core, with no noticeable interfacial voids or delamination. The enhanced surface energy produced by plasma treatment promoted effective wetting of the polymer, resulting in improved interfacial stress transfer and mechanical compatibility.

The embedded flexible impact sensor remained fully encapsulated within the polymer layer without disrupting laminate continuity. The sensor placement at the neutral plane minimized stress concentration and preserved the structural integrity of the laminate [19]. These observations indicate that the proposed fabrication approach successfully integrates sensing functionality while maintaining excellent interfacial bonding, making the laminate suitable for lightweight automotive structures.

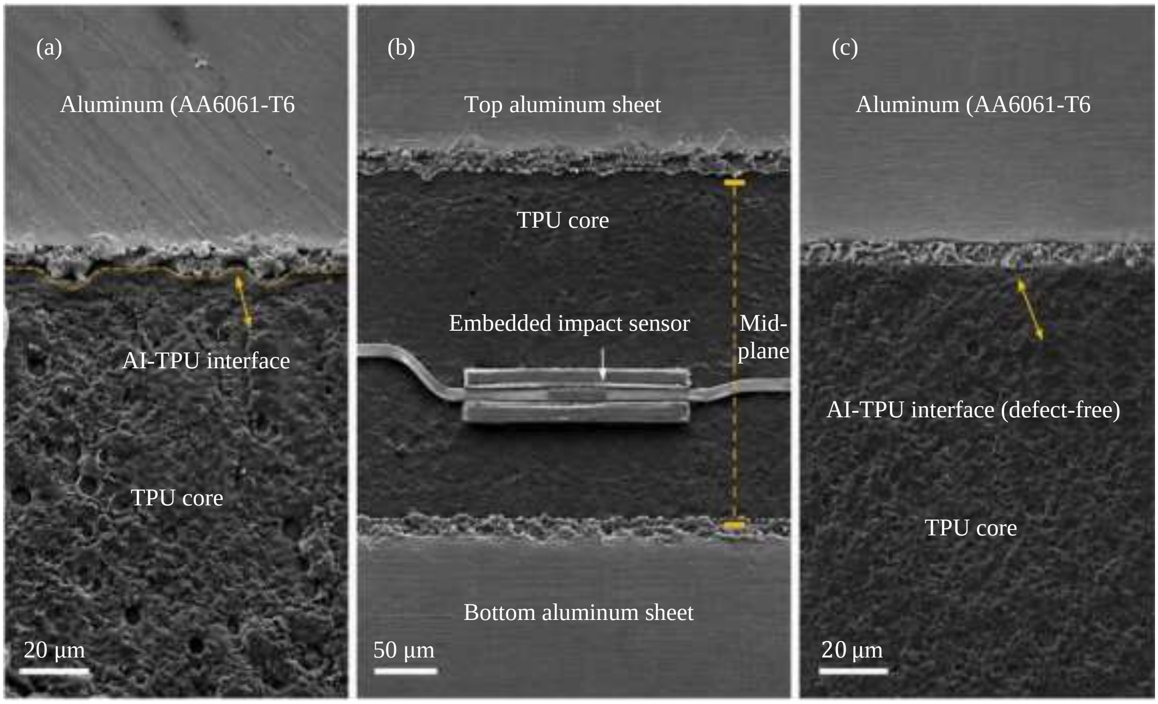


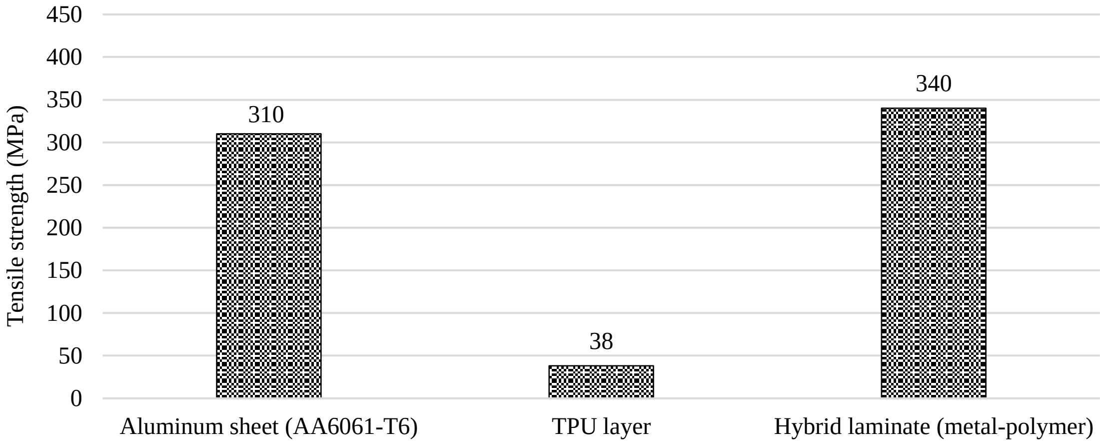
Figure 4. SEM micrographs showing. (a) aluminum–TPU interface, (b) embedded impact sensor at the laminate mid-plane, and (c) defect-free aluminum–polymer interfacial bonding.

Mechanical and Impact Performance

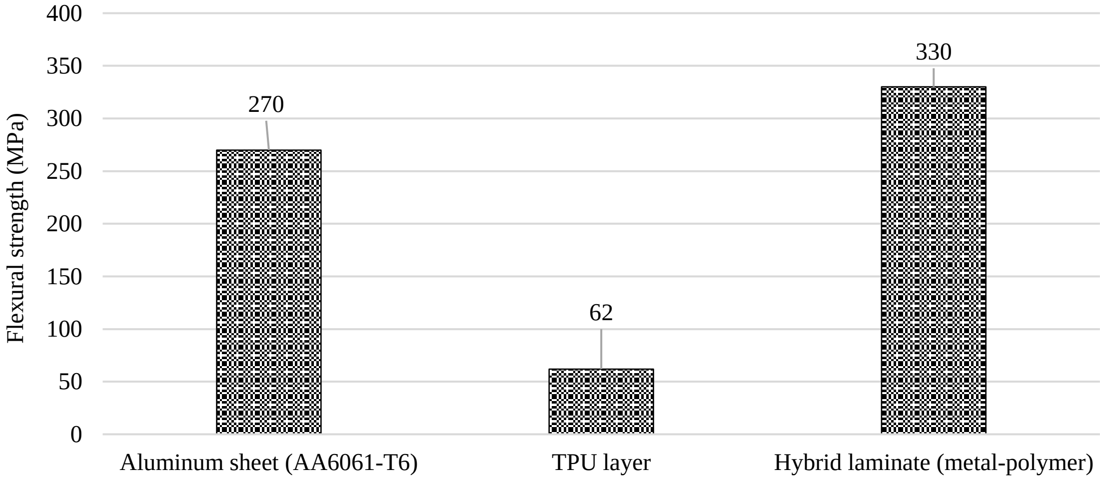
The incorporation of the TPU interlayer significantly enhanced the energy absorption capability of the hybrid laminate while maintaining high structural stiffness. Tensile and flexural testing demonstrated that the metal–polymer configuration effectively distributes applied loads through the polymer core, reducing localized stress concentration and delaying crack propagation.

Under low-velocity impact loading, the TPU layer dissipated a considerable portion of the impact energy through elastic deformation, thereby reducing permanent damage to the aluminum face sheets. The improved impact resistance can be attributed to the combined effects of polymer deformation, strong interfacial bonding, and efficient load redistribution across the laminate [20].

Comparative tensile strength, flexural strength, and absorbed impact energy are presented in Figures 5 and 6, respectively.



(a)



(b)

Figure 5. Comparison of tensile strength and flexural strength for aluminum sheet, TPU layer, and layered metal–polymer hybrid laminate. (a) Tensile strength. (b) Flexural strength.

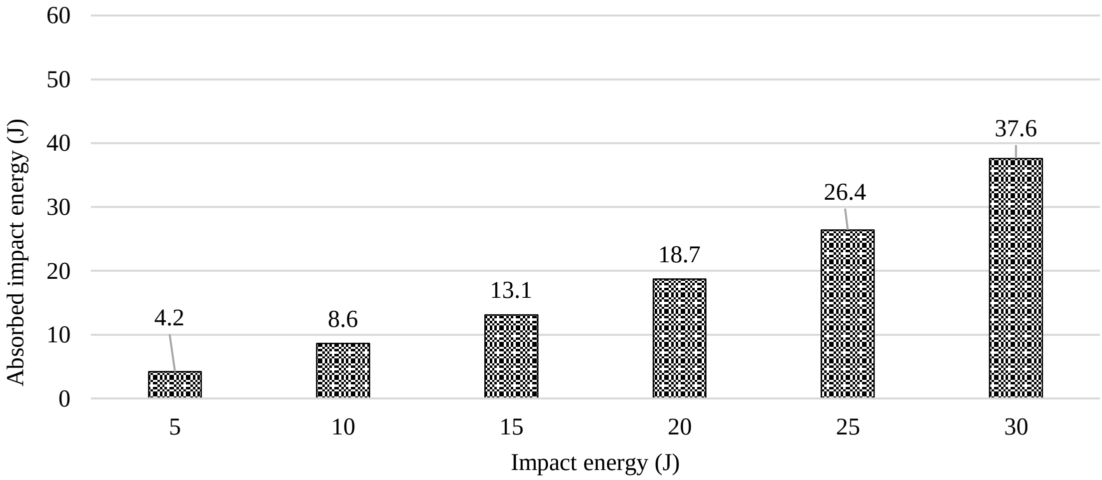


Figure 6. Absorbed impact energy of the layered metal–polymer hybrid laminate under different low-velocity impact energies.

Embedded Impact Sensor Performance

The embedded flexible impact sensor exhibited stable and repeatable electrical responses under different impact energies. As the impact energy increased, the peak sensor voltage increased proportionally, demonstrating excellent sensitivity toward dynamic loading conditions. The sensor showed rapid response with minimal signal drift during repeated impact cycles, indicating reliable long-term performance.

Embedding the sensor within the polymer core effectively protected it from external mechanical damage while enabling direct monitoring of internal stress-wave propagation [21–24]. The close agreement between impact force and sensor output confirms the capability of the sensing system for real-time structural health monitoring of automotive body panels.

The typical voltage response corresponding to different impact energies is shown in Figure 7.

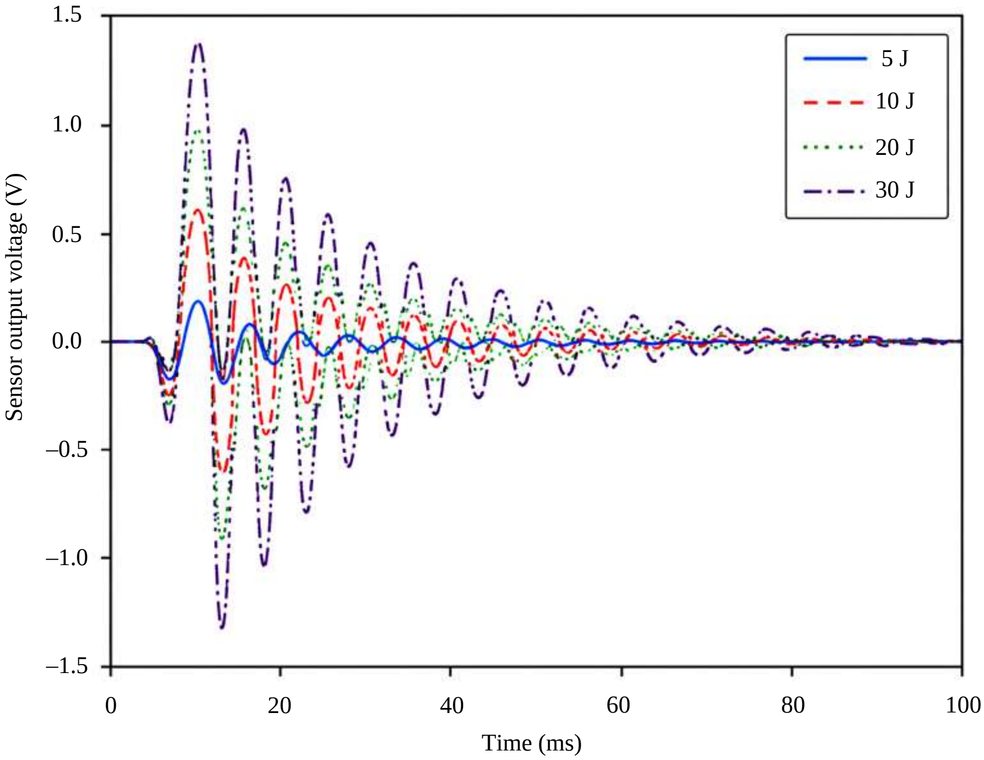


Figure 7. Voltage response of the embedded flexible impact sensor under different impact energies.

IoT-Based Structural Health Monitoring

The integration of the embedded impact sensor with the ESP32 controller enabled continuous wireless monitoring of the laminate condition. Impact signals were processed locally before being transmitted via Wi-Fi to a cloud-based dashboard for real-time visualization [25]. The proposed monitoring framework provides immediate notification of impact events together with their severity, enabling predictive maintenance and early damage detection.

The lightweight metal–polymer architecture combined with embedded sensing technology demonstrates the feasibility of intelligent automotive body panels capable of autonomous condition monitoring without compromising structural performance. Such multifunctional laminates offer significant potential for next-generation connected vehicles where lightweight construction, impact resistance, and smart monitoring are simultaneously required.

The overall monitoring workflow and cloud communication architecture are illustrated in Figure 8.

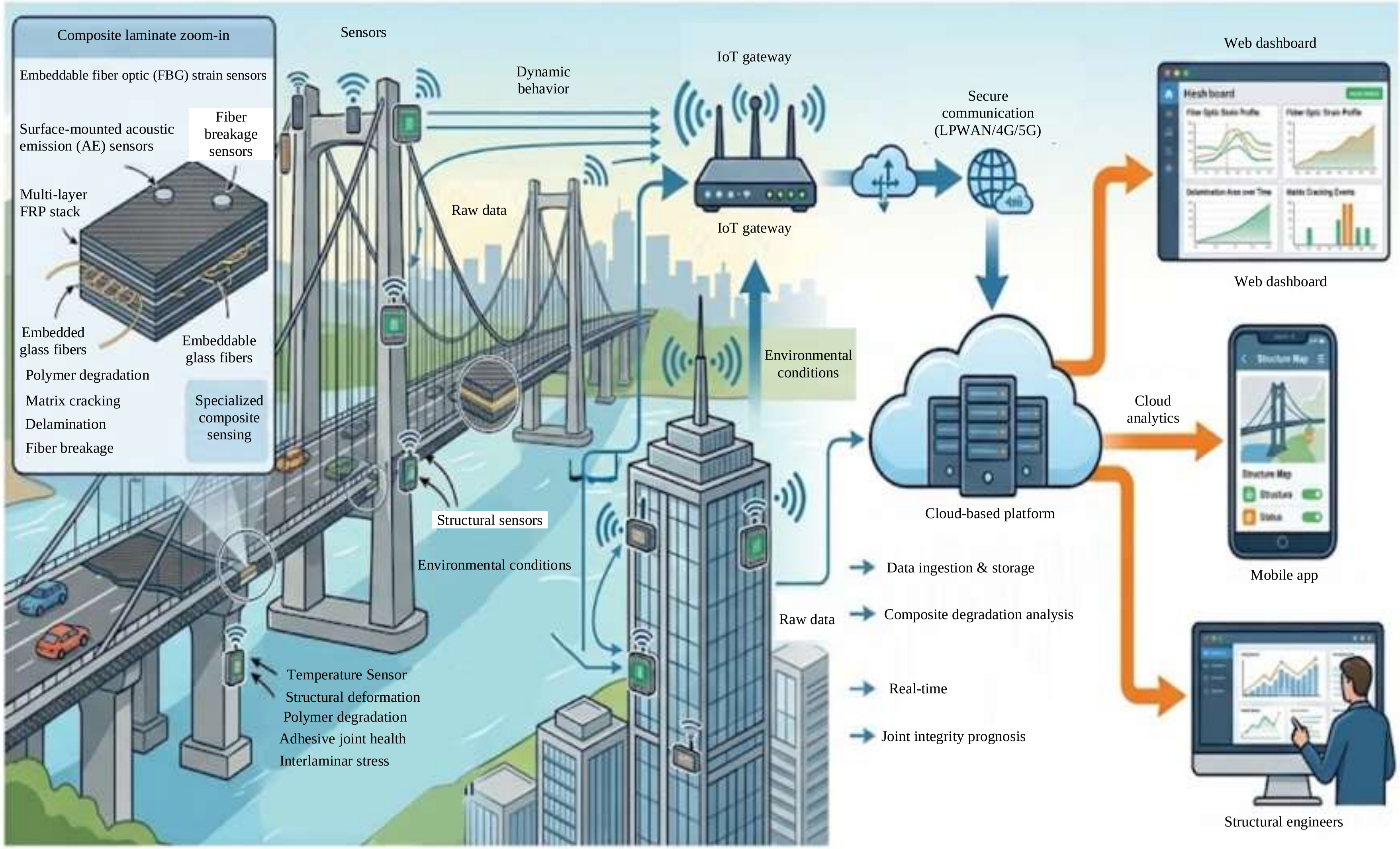


Figure 8. IoT-enabled structural health monitoring system for connected automotive panels incorporating the embedded impact sensor, ESP32 controller, cloud platform, and user dashboard.

CONCLUSION

The present study demonstrated the feasibility of developing layered metal–polymer hybrid laminates with embedded flexible impact sensors for next-generation connected automotive body panels. By integrating lightweight metallic face sheets, a TPU polymer core, and an embedded sensing element within a single multifunctional laminate, the proposed structure combines improved mechanical performance with real-time structural health monitoring. The polymer core not only enhances energy absorption and impact resistance but also provides a protective environment for the embedded sensor, enabling reliable wireless monitoring without compromising structural integrity.

- Lightweight hybrid laminate architecture was successfully developed by integrating AA6061 aluminum sheets with a TPU polymer core for improved structural efficiency.
- Strong metal–polymer inter-facial bonding was achieved through plasma surface treatment, resulting in effective load transfer and enhanced laminate durability.
- The TPU interlayer significantly improved impact energy absorption, thereby increasing the damage tolerance and crashworthiness of the hybrid automotive panel.
- The embedded flexible impact sensor remained fully encapsulated within the laminate and provided stable, repeatable, and highly sensitive responses under different impact loading conditions.
- Real-time structural health monitoring was successfully demonstrated using an ESP32-based wireless communication system, enabling continuous transmission of impact information to a cloud-based dashboard.
- The integrated IoT monitoring framework supports remote damage detection, predictive maintenance, and intelligent condition assessment for connected automotive structures.
- The multifunctional metal–polymer hybrid laminate offers a promising solution for future lightweight vehicles by combining structural reinforcement, impact sensing, and smart connectivity within a single integrated material system.
- The proposed approach has strong potential for applications in automotive doors, side panels, roof structures, engine hoods, battery enclosures, and other intelligent transportation components, contributing toward safer, lighter, and more sustainable connected vehicles.

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