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Bio-Inspired Energy Absorbers for Electric Vehicle Battery Pack Protection: Evolution, Materials, and Future Directions

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ABSTRACT

Electric vehicle (EV) battery packs positioned beneath the vehicle floor are particularly susceptible to structural damage during side pole impacts, frontal crashes, and rollover events. Conventional energy absorbers including hollow cylinders, square sections, and aluminum foam have historically been designed to manage predominantly axial loading, falling short under the complex, multi-directional force regimes encountered in real-world collisions. This has driven a paradigm shift toward bio-inspired energy absorber geometries that mimic high-performance natural structures such as bamboo hierarchies, bone microarchitectures, skeletal muscle arrangements, and the glass sponge Euplectella aspergillum lattice.

This review systematically traces the evolutionary trajectory of energy absorber design for EV battery protection, from conventional multi-cell configurations through three pillars of biological inspiration plant-inspired, animal-inspired, and microstructure-inspired geometries to advanced hybrid material systems combining aluminum and carbon fiber reinforced polymers (CFRP) via structural adhesive bonding. Performance benchmarks are synthesized across multiple loading conditions including axial, lateral, three-point bending, and oblique loading, demonstrating specific energy absorption (SEA) improvements of up to 98.96% under lateral loading and 43.73% under axial loading compared to simple baseline designs. The critical role of additive manufacturing in enabling geometrically complex bio-inspired absorbers is examined, alongside compliance requirements under international standards including SAE J2464, UN ECE R100, and USABC/FreedomCAR. Finally, key research gaps are identified encompassing scalable manufacturing, multi-physics crash-electrochemical coupling, solid-state battery compatibility, and circular economy compliance establishing a roadmap for the next generation of safer, lighter, and more sustainable EV battery containment systems.

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1. Introduction

The lithium-ion battery pack is the most structurally complex component of modern electric vehicles. Packs typically weigh between 500 and 900 kg. They account for more than 20% of the total vehicle weight. Most packs are mounted beneath the passenger floor in a "skateboard" configuration. This placement lowers the center of gravity and improves the vehicle stability. It also protects against frontal impacts. However, it leaves the pack exposed to side-pole impacts and road debris. These two scenarios produce the greatest penetration depths in standardized crash assessments [1,2].

Mechanical intrusion into battery cells triggers internal short-circuits. Short circuits generate heat rapidly. Unchecked heat generation causes thermal runaway, which can result in fires or explosions [3]. Therefore, the structural containment of battery cells during a crash is a public safety requirement and not only an engineering problem.

Energy absorbers are positioned between external crash forces and battery cells. They convert kinetic energy into plastic deformation. This limits the peak force that reaches the batteries. In underfloor battery packs, absorbers operate at two scales. At the module level, they surround individual cell groupings. At the pack level, they are integrated into crash protection frames and lattice structures [4].

Conventional absorbers use aluminum or polymer composites as their primary materials. Common configurations include honeycomb, foam, and thin-walled tubes. These perform adequately under axial loading, which dominates the frontal crash scenarios. Their performance decreased substantially under lateral, oblique, and three-point bending loads. The pole-side impact test produces greater pack penetration than any other standardized collision test [3,5]. This gap in lateral protection is a central weakness of current absorber designs.

Biological structures offer an alternative design basis for such applications. Bamboo culms, mammalian bone cortices, beetle elytra, and deep-sea sponge skeletons absorb energy at high specific values. This is achieved through hierarchical organization, functionally graded densities, and geometry-driven stress redistribution. Translating these principles into engineered absorbers is now termed a bio-inspired design. This has become one of the most active areas in crashworthiness research [6,7].

This review traces the development of energy absorbers for EV battery-pack protection. It covers (i) functional requirements and limitations of conventional designs; (ii) three biological structural principles and their translation into engineered geometries; (iii) hybrid material systems and additive manufacturing as fabrication routes; (iv) comparative performance across multiple loading conditions; (v) integration within evolving battery pack architectures; (vi) compliance with international safety standards; and (vii) open research gaps and future directions. This study serves as a reference for researchers and a design framework for engineers working on EV battery containment.

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1.1 Review Methodology

This review is based on a structured, though systematic, survey of the crashworthiness and battery-pack-protection literature. Studies were identified through Scopus, Web of Science, and ScienceDirect using combinations of the keywords "bio-inspired energy absorber," "battery pack crashworthiness," "specific energy absorption," "electric vehicle battery protection," "hybrid Al/CFRP absorber," and "additive manufacturing lattice absorber." The search was restricted to peer-reviewed journal articles and conference papers published in English, with an emphasis on the period from 2015 to 2026, reflecting the timeframe over which bio-inspired absorber research has become an active subfield of crashworthiness engineering. Studies were included if they reported experimental or numerical crashworthiness data (SEA, CFE, PCF, or intrusion) for absorber geometries, materials, or manufacturing routes relevant to battery pack protection; studies limited to non-automotive applications of bio-inspired structures, or lacking quantitative performance data, were excluded. Given the breadth of the topic, this review is best characterized as a narrative synthesis rather than a systematic review conducted to PRISMA-type protocols, and the selection and interpretation of studies reflect this scope.

2. Conventional Energy Absorber Designs for Battery Packs

2.1 Geometric Configurations and Materials

Conventional energy absorbers in EV battery packs fall into four geometric categories: hollow thin-walled sections, cellular honeycomb structures, metallic and polymeric foams, and multi-cell prismatic profiles. Each configuration produces a distinct combination of energy absorption, mass efficiency, and manufacturing feasibility values.

Hollow cylindrical and square thin-walled tubes are the simplest and most widely deployed absorber geometries. Manufacturers typically extrude them from aluminum alloys (Series 6000 or 7000) or form them from high-strength steel. Under axial compressive loading, these sections experience progressive plastic buckling. This folding sequence dissipated energy at a relatively uniform rate. Their main advantages are manufacturing simplicity and low cost. Energy absorption decreases sharply under off-axis or lateral loads [8].

Honeycomb structures are made of aluminum, polymer composites, or aramid paper. They exhibit a higher specific energy absorption (SEA) than solid or foam-filled tubes under out-of-plane compression. The hexagonal cell architecture distributes compressive stress uniformly across the cell walls. This promotes progressive layer-by-layer crushing. Battery pack designers often sandwich honeycomb absorbers between structural plates at the module level to reduce vibration. The performance is strongly anisotropic, with high absorption perpendicular to the cell axes and substantially lower in-plane absorption [9].

Aluminum and polymer foam absorbers provide energy absorption in multiple load directions. Closed-cell aluminum foam and open-cell polyurethane foam are both used in battery protection systems. Foams conform to irregular geometries and perform consistently under complex, nonuniform loading. Their SEA per unit mass is typically lower than that

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of equivalent structured absorbers. Manufacturing variability also affects the mechanical properties of these materials [10].

Multicell extruded profiles are the dominant commercial solution for side sill reinforcement in EV platforms. Partitioning the cross-section into multiple closed chambers increased the number of fold initiations per unit volume. This increases both the SEA and crushing force efficiency (CFE). The Tesla Model S Plaid uses a variant of multicore extrusion inserts in its side sills to improve the lateral energy absorption. Although multi-cell profiles outperform single-cell tubes, they still underperform under simultaneous multi-directional loading [1,4].

2.2 Key Performance Metrics

The performance of energy absorbers is quantified using several standardized metrics.

The Specific Energy Absorption (SEA) measures the total energy absorbed per unit mass. This is the primary metric for comparing absorbers across materials and geometries. Mass normalization is important in EV design, where weight budgets are tight. Commercial

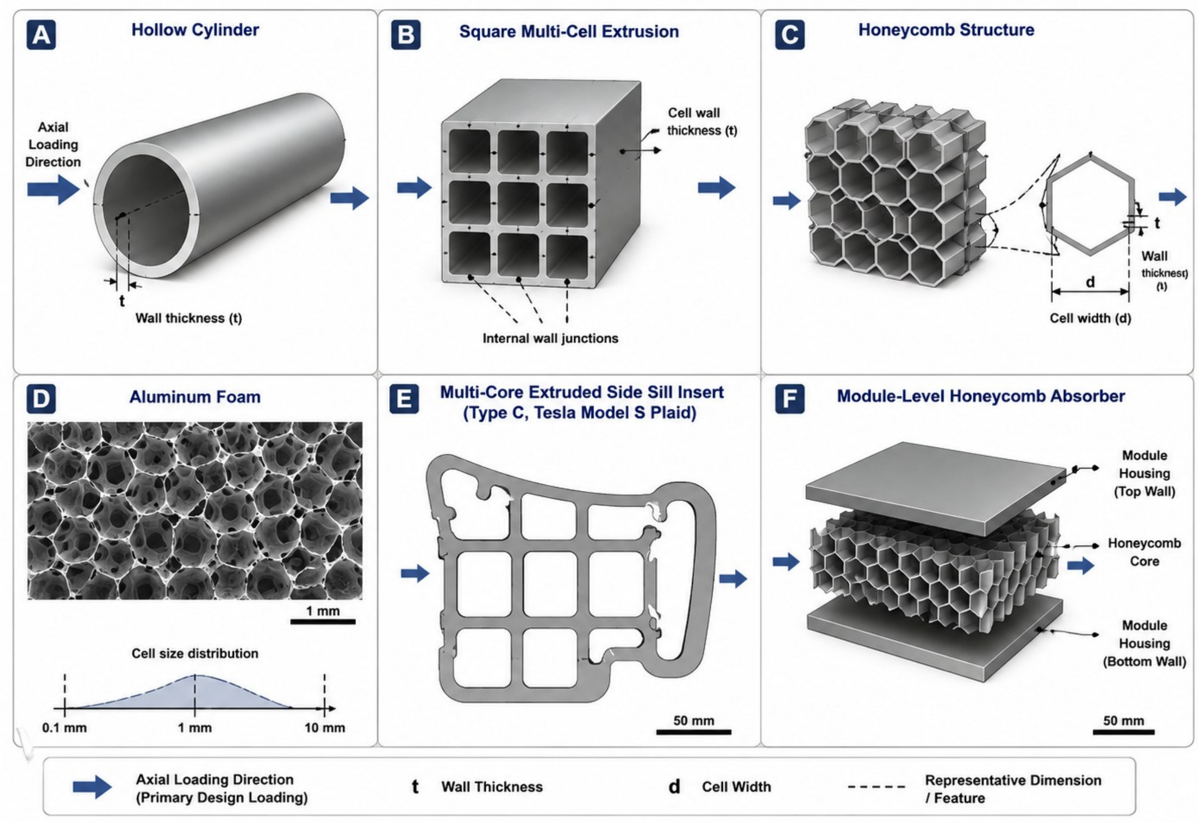

Fig. 1. Representative conventional energy absorber configurations used in EV battery pack protection systems: (A) hollow cylinder; (B) square multi-cell extrusion; (C) hexagonal honeycomb; (D) aluminum foam; (E) multi-core extruded side sill insert (Type C profile); (F) module-level sandwich honeycomb absorber. Arrows indicate primary design loading direction.

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aluminum absorbers typically achieve 15–45 kJ/kg.

The Crushing Force Efficiency (CFE) is the ratio of the mean crushing force to the peak crushing force, expressed as a percentage. A CFE approaching 100% indicates that the absorber maintains a near-constant force throughout its deformation stroke. This limits the injurious force spikes transmitted to the battery cells. Commercial honeycomb structures typically achieve CFE values ranging from 55% to 75%.

The Peak Crushing Force (PCF) is the maximum force generated during the initial contact before progressive folding begins. High PCF values can damage the battery cells before the absorber starts dissipating energy. Therefore, the PCF is a limiting parameter in battery protection design.

Conventional absorbers are typically optimized for a single dominant loading direction. Loading them off-axis reduced the SEA by 40–60%. This performance drop motivated the study of bio-inspired geometries. The goal is to maintain a high SEA and CFE across multiple simultaneous loading axes [6].

3. The Evolution of Bio-Inspired Energy Absorber Designs

Hierarchical architectures have developed in natural structures subjected to complex, multidirectional mechanical loading over evolutionary timescales. These architectures balance the strength, toughness, and energy absorption at a minimal mass. Bio-inspired absorber designs translate these biological principles into engineered geometries. Recent literature has identified three primary pillars of this translation [6,7].

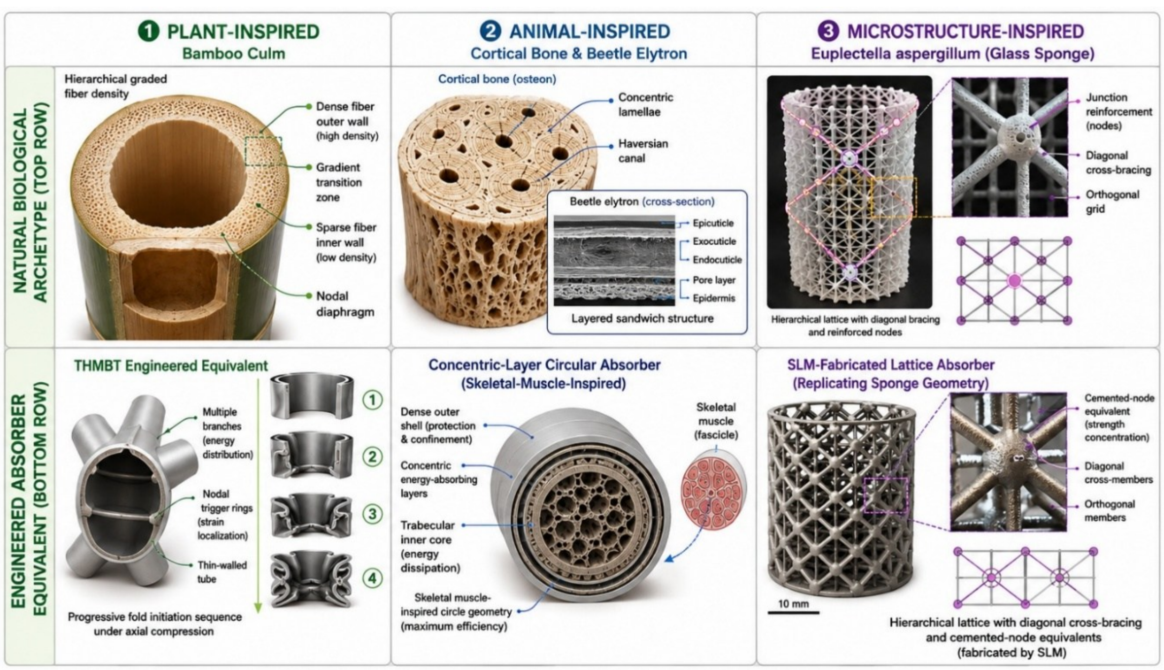

Fig. 2. The three pillars of biological inspiration for EV battery energy absorber design.

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3.1 Plant-Inspired Structures

Plant tissues resist bending, compression, and torsional loading from wind and their own weight. This is achieved through hierarchical fiber arrangements that resist buckling and promote progressive and stable deformation. Two plant archetypes have informed the energy absorber design for battery protection:

Bamboo Hierarchical Architecture: The bamboo culm achieves high bending stiffness and fracture toughness through two structural features: First, the fiber density grades ranged from dense at the outer surface to sparse at the center. Second, periodic nodal diaphragms reinforce the segmented hollow cross sections. These nodes act as the fold initiators. They control the location and sequence of buckling to produce progressive and stable energy dissipation. Absorbers replicating this geometry, particularly the tube-with-hollow-multiple-branches-and-tubes (THMBT) configuration, exhibit higher CFE and stable crushing over larger deformation strokes than plain hollow tubes [6,7].

Tree Branching Hierarchies: Tree structures distribute stress across multiple parallel load paths. This prevents stress concentration and allows for controlled distributed deformation. Absorbers incorporating branched internal webs replicate this mechanism in nature. The webs transition from primary trunk members to multiple secondary branches. This creates multiple simultaneous fold initiation sites and increases the effective crushing area per unit mass [6].

Plant-inspired absorbers promote progressive crushing, a fold-by-fold deformation mode that maintains a near-constant crushing force. This resulted in CFE values of 65–80%. It also avoids the sharp initial force spike observed in conventional multi-cell designs [7].

The bamboo-inspired THMBT configuration and tree-branching web architectures both derive from plant hierarchies, but the reported gains are not interchangeable: THMBT studies emphasize CFE and stable stroke length as the primary benefit [6,7], whereas branched-web studies emphasize the number of simultaneous fold initiation sites and effective crushing area rather than CFE directly [6]. This distinction matters because a design optimized for CFE stability does not necessarily maximize crushing area, and the two studies do not report a common metric that would allow one geometry to be ranked above the other. Reconciling these findings requires a shared test protocol reporting both CFE and crushing-area utilization for the same loading rate, which the current literature does not provide.

3.2 Animal-Inspired Structures

The skeletal and integumentary systems of animals provide design templates for energy absorption under dynamic, multidirectional forces.

Skeletal-Inspired Circular Sections: Mammalian long bones achieve high bending stiffness and energy absorption through a cortical shell of dense bone surrounding a trabecular open-cell lattice core. The periosteal membrane controls the crack propagation. Absorbers replicating this concentric layer architecture, with a dense outer shell transitioning to a lower-density inner lattice, outperform conventional hollow tubes in three-point bending. They also exhibit greater resistance to fracture initiation [7].

Bone and Beetle Wing Microstructures: Beetle elytra achieve high-impact resistance relative to their mass through a layered sandwich structure.

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This structure incorporates anisotropic fiber orientation and interlocking surface features. Shell nacre uses a cross-laminar aragonite structure arranged in hierarchical tablet formations, bonded by organic adhesive layers. This arrangement produces progressive microcracking that dissipates energy without fracture. These mechanisms have informed absorbers with structured surface textures and internal partitions. These features trigger distributed progressive deformation under multidirectional impact [6,7].

Animal-inspired designs perform well under oblique and lateral loadings. The multidirectional symmetry of biological archetypes translates directly to improved multi-axis performance in engineered equivalents. Lateral SEA improvements above 93% relative to simple baseline designs have been reported for animal-inspired configurations [7].

The animal-inspired lateral SEA gain of above 93% exceeds the 88.60% reported for plant-inspired designs under the same loading mode [6,7], which at first appears to establish a clear ranking between the two pillars. However, the underlying mechanisms differ in ways the reported percentages do not capture: plant-inspired gains are attributed primarily to fold-initiation control (a geometric mechanism), whereas animal-inspired gains are attributed to graded density and fracture-resistance mechanisms operating at the material microstructure level. Because the two families of studies vary geometry and material simultaneously rather than isolating one variable, the reported gap cannot be attributed with confidence to the biological archetype itself rather than to differences in specimen scale, wall thickness, or loading rate between the underlying experiments.

3.3 Microstructure-Inspired Designs

The most demanding tier of biological inspiration is drawn from the microscale architecture of materials shaped by sustained mechanical loading at the cellular level.

Euplectella Aspergillum (Glass Sponge) Lattice: The deep-sea glass sponge *Euplectella aspergillum* builds its skeleton from a hierarchically organized silica lattice. The diagonal cross-bracing members overlay an orthogonal grid. Cemented junctions prevent stress concentration and redistribute the load. This architecture performs well under multidirectional loading. Absorbers replicating this lattice geometry, particularly those produced by additive manufacturing, exhibit the highest SEA and CFE gains among all bio-inspired categories. Lateral SEA improvements of over 98% over simple baseline designs have been reported [6,36].

Honeycomb–sponge hybridization: Combining the hexagonal honeycomb geometry with sponge-inspired lattice cross-bracing produces a hybrid cellular architecture. It retains the manufacturing simplicity of a honeycomb while adding the multidirectional load redistribution of sponge microstructures. These hybrid designs occupy a practical position between high-performance bio-inspired lattices and commercially deployable honeycomb absorbers [6].

Microstructure-inspired designs currently yield the highest recorded bio-inspired absorption metrics. They also face significant manufacturing constraints. The realization of complex three-dimensional lattice geometries requires precision additive manufacturing [6].

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The progression from plant-inspired (+88.60% lateral SEA) to animal-inspired (+93.40%) to microstructure-inspired (+98.96%) designs [6,7,36] reads as a smooth performance hierarchy across the three pillars, but this ordering is confounded by manufacturing route: the plant- and animal-inspired studies are drawn predominantly from conventionally manufactured (extruded or stamped) specimens, whereas the highest microstructure-inspired results are drawn from additively manufactured lattices. It is therefore unclear from the current literature whether the reported gains reflect the superiority of the sponge-lattice geometry itself, or the greater geometric freedom that AM affords regardless of which biological archetype is being replicated. Isolating the manufacturing-route variable, by fabricating a sponge-lattice geometry and a comparable animal-inspired geometry with the same process, would be needed to settle this question.

4. Manufacturing Approaches and Advanced Material Systems

4.1 Conventional Manufacturing Pathways

Most energy absorbers in production EV battery packs are made using aluminum extrusion, stamping, or die casting. Extruded multi-cell aluminum profiles (series 6000 and 7000 alloys) are the dominant commercial solutions. They offer low cost, corrosion

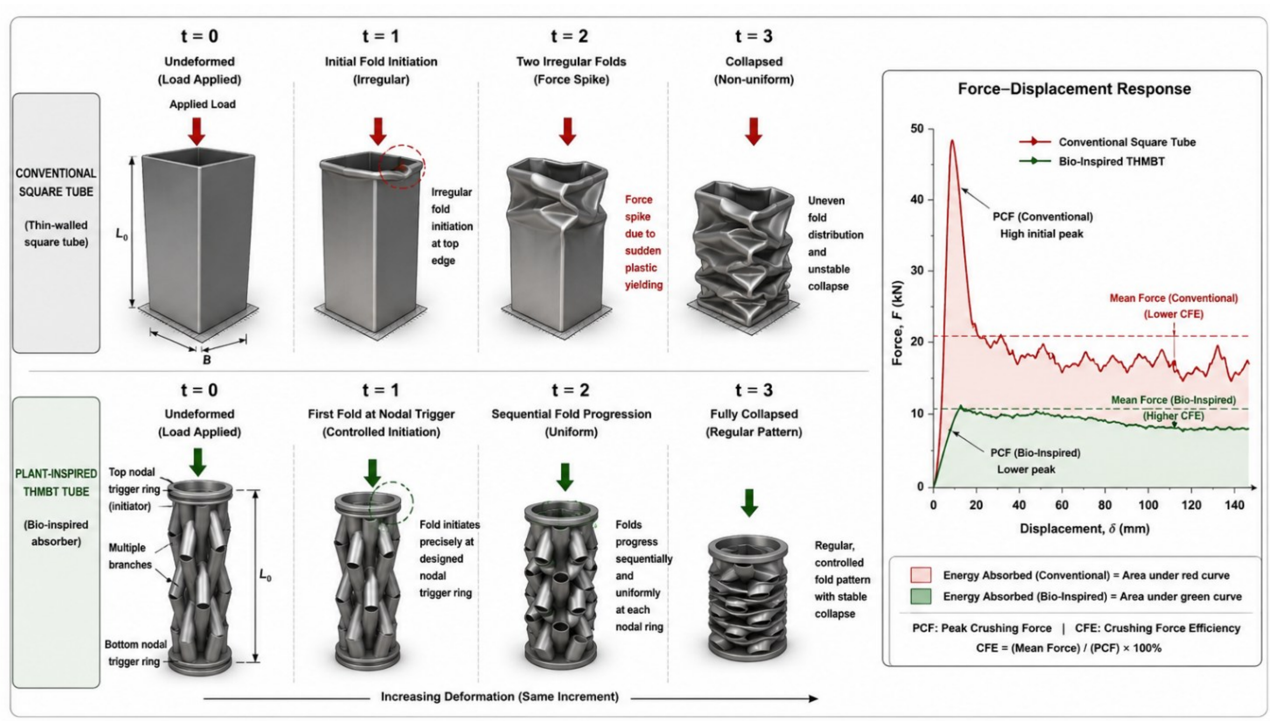

Fig. 3. Comparison of progressive crush deformation sequences between a conventional square thin-walled tube (top row) and a plant-inspired THMBT bio-inspired absorber (bottom row) at equivalent deformation increments (t = 0–3).

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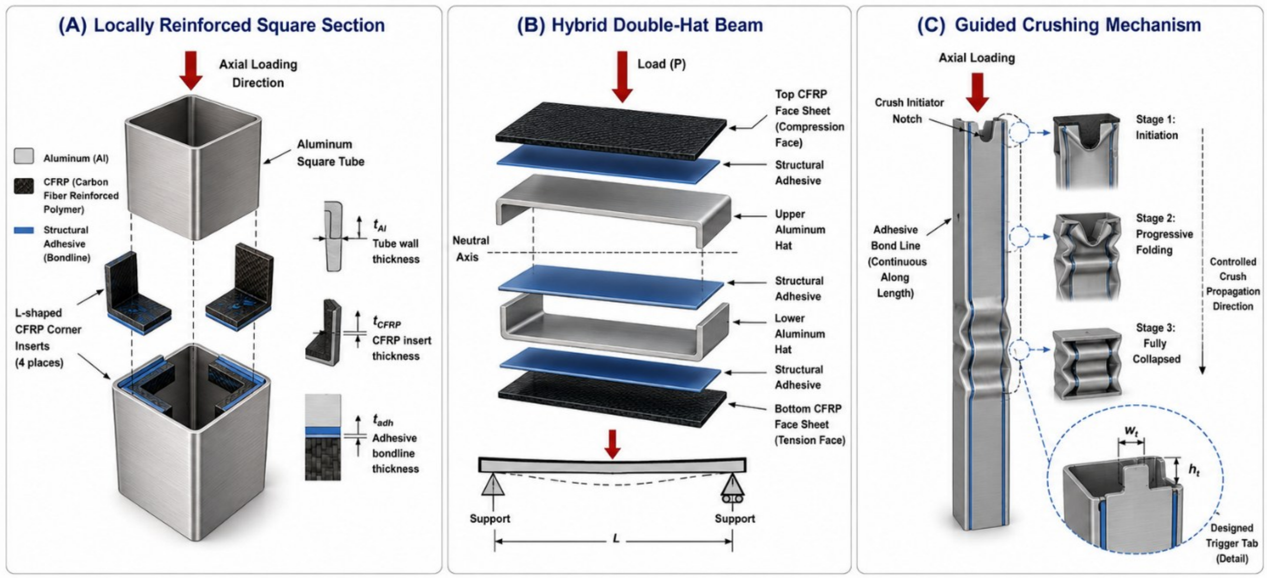

Fig. 4. Hybrid aluminum/CFRP energy absorber constructions joined by structural adhesive bonding

resistance, high heat transfer efficiency, and adequate crashworthiness under axial loads. Stamped steel inserts are used where higher stiffness-to-volume ratios are required in confined geometries [1].

These manufacturing routes are suitable for high-volume automotive production. They also impose geometric constraints on the achievable absorber architectures. Extrusion limits cross-sections to prismatic profiles without an internal curvature. Stamping constrains the design of developable surface geometries. Both restrictions limit the bio-inspired geometries that can be produced using conventional manufacturing.

4.2 Hybrid Aluminum/CFRP Constructions via Structural Adhesive Bonding

The most immediate fabrication advance for bio-inspired absorbers in EV battery applications is hybrid aluminum and carbon fiber-reinforced polymer (CFRP) construction, joined by structural adhesive bonding. Aluminum contributes to ductile, progressive plastic deformation. CFRP contributes to high specific stiffness and strength. Structural adhesives transfer loads between two materials and prevent delamination-driven premature failure [11].

Several hybrid configurations have been developed and validated for the protection of battery packs.

Locally Reinforced Square Sections with L-Shaped CFRP Inserts: Standard aluminum square tubes receive L-shaped CFRP inserts bonded at the corner regions, where the stress concentration is highest during axial crushing. This reinforcement delayed the local buckling initiation, increased the fold initiation force, and improved the progressive crushing stability. SEA improvements of 40–55% over unreinforced aluminum baselines under axial loading have been reported [11].

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Hybrid Double-Hat Beams: Two stamped aluminum hat-sections bond with CFRP outer face sheets and structural adhesive to form a multi-layer sandwich beam. Under three-point bending, which is a loading mode representative of lateral pole impacts, the CFRP face sheets experience tensile and compressive bending stresses. The aluminum core absorbs shear and prevents premature face sheet buckling. This configuration has been validated for battery module housing protection under pole-side impact conditions [12].

Guided Crushing Mechanisms in Adhesively Bonded Structures: Pre-designed crush initiators, including geometric notches, thickness transitions, and pre-bonded trigger tabs, control the location and sequence of fold initiation in hybrid Al/CFRP absorbers. Guided crushing produces stable and progressive deformation from the initiation point. Without these features, buckling is unpredictable and can generate high peak forces or incomplete energy dissipation [11,13].

Bonded hybrid absorbers face durability problems at the adhesive interface. In-vehicle battery packs experience combined thermal cycling, vibrations, and humidity. Structural adhesives must retain their mechanical properties across the full operational temperature range of the battery pack (−40°C to +75°C). They must also resist degradation by electrolyte vapors during cell venting events. Toughened epoxy and polyurethane adhesive formulations improved the long-term reliability of bonded hybrid joints under these conditions.

The three hybrid Al/CFRP configurations reviewed above are not directly comparable on a single performance axis: L-shaped CFRP inserts are validated under axial loading (SEA improvements of 40–55% [11]), double-hat beams are validated under three-point bending [12], and guided crushing features are evaluated primarily on deformation stability rather than SEA [11,13]. Because each configuration has been characterized under a different loading mode, the literature does not currently support ranking these three approaches against one another; a design choosing between them must rely on which loading mode dominates the target application rather than on a single superior SEA figure.

4.3 Additive Manufacturing for Complex Bio-Inspired Geometries

Additive manufacturing (AM), including selective laser melting (SLM) for metallic lattices and fused deposition modelling (FDM) for polymeric and composite structures, eliminates the geometric constraints of conventional subtractive and forming processes. This has made AM the primary fabrication route for bio-inspired absorber studies.

Hierarchical lattice geometries inspired by *Euplectella aspergillum* incorporate diagonal cross-members, nodal reinforcements, and graded density distributions. Extrusion and casting cannot produce these characteristics. SLM builds them directly from aluminum alloy powder (AlSi10Mg) or titanium alloy (Ti-6Al-4V) powders. AM-fabricated lattice absorbers have shown SEA values 50–100% higher than those of equivalent-mass conventional foam or honeycomb absorbers.

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This gain is attributed to the precisely controlled deformation sequence produced by the designed lattice topology [6].

AM also enables functionally graded lattices in which the cell geometry, strut diameter, or relative density varies continuously through the absorber volume. This allows the absorber to match the spatially nonuniform loading distribution of an actual crash event. The impact-facing surface presented a high resistance, where the loading was the most severe. The core transitioned to a more compliant structure that absorbed residual energy at lower force levels. This limits the force transmission to the battery cells.

SLM processing of metallic parts currently costs 5–20× more than extrusion. The build chamber dimensions also constrain the part size. Large-format AM systems are advancing, and powder and machine costs are decreasing. AM-fabricated bio-inspired absorbers may become cost-competitive for deployment in premium EV platforms within the next decade.

AM-fabricated lattices report SEA gains of 50–100% over conventional foam or honeycomb absorbers [6], nominally larger than the 40–55% gains reported for adhesively bonded hybrid Al/CFRP inserts [11]. Taken at face value, this would favor AM as the higher-performance route; however, the AM comparison baseline is foam or honeycomb, while the hybrid Al/CFRP comparison baseline is unreinforced aluminum tube, so the two percentage gains are not measured against the same reference and cannot be compared directly.

4.4 Performance Comparison of Material Systems

Table 1. Comparative performance and characteristics of conventional and bio-inspired energy absorber material systems for EV battery pack protection.

Material System	Manufacturing Method	SEA Potential	Cost	Repairability
Aluminum alloys (6000/7000)	Extrusion, Stamping	Moderate	Low	Good
Carbon Fiber (CFRP)	Layup, Pultrusion	High	High	Poor
Hybrid Al/CFRP (adhesive)	Bonding + Forming	Very High	Medium	Moderate
Aluminum Foam	Casting, Sintering	Moderate	Medium	Poor
Polymer Composites (GFRP)	Injection Moulding	Moderate	Low-Med	Poor
3D-Printed Lattice	Additive Mfg (SLM/FDM)	Very High	High	Poor
Bio-inspired Hybrid (3D)	Additive + Bonding	Excellent	Very High	Poor

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In addition, the AM route carries a 5–20× cost penalty over extrusion that the hybrid bonding route does not, so the manufacturing-cost gap identified in Section 4.1 works against AM adoption even where its reported SEA gain is nominally larger. A performance-per-cost comparison, rather than SEA gain alone, would be needed to determine which route is preferable for near-term production.

5. Comparative Performance Under Multi-Directional Loading

5.1 Overview of Loading Scenarios

Energy absorbers in EV battery packs must perform across the full range of loading conditions encountered in real-world crash events. Standardized crash tests define four loading scenarios relevant to battery pack protection: (i) frontal impact, dominated by axial compressive loading on longitudinal energy absorbers; (ii) pole side impact, imposing lateral bending and shear on module-level absorbers with a concentrated contact area; (iii) three-point bending, imposed by objects beneath the vehicle floor; and (iv) oblique and combined loading in rear and offset frontal impacts [3].

Conventional absorbers designed for axial loading lose 40–60% of their SEA under lateral or oblique loads. Bio-inspired designs can resist this degradation. Hierarchical cross-bracing, graded density, and distributed fold initiation each improved the axial SEA. They also improve resistance under non-axial loading modes through similar geometric mechanisms [6,7].

5.2 Axial Loading Performance

Axial loading, dominant in frontal impacts, is the design condition for which conventional absorbers (hollow tubes, multi-cell extrusions) were originally optimized, and it remains the loading mode under which bio-inspired designs show the smallest relative improvement over conventional baselines. Bamboo-inspired THMBT and tree-branching geometries improve axial SEA by 38.20% over simple baselines, and microstructure-inspired sponge lattices reach the highest reported axial gain at 43.73% (Table 2); the hybrid Al/CFRP category, drawing on both ductile aluminum folding and controlled CFRP fragmentation, extends this further to an estimated 55–70% [30].

That axial gains are consistently the smallest of the four loading conditions reported in Table 2, well below the lateral and three-point bending gains discussed in Section 5.3, is itself informative: it indicates that conventional multi-cell geometry was already reasonably well optimized for axial crushing before bio-inspired principles were introduced, and that the practical value of bio-inspired designs lies predominantly in closing the lateral and oblique performance gap rather than in further improving an axial mode that was not the weakest link to begin with [6,7].

5.3 Lateral and Three-Point Bending Performance

Lateral loading from the pole-side impact scenario is the primary performance differentiator between conventional and bio-inspired absorber designs. Simple tubes and standard multicell profiles offer limited lateral bending resistance. Their thin walls cannot prevent global beam bending without local

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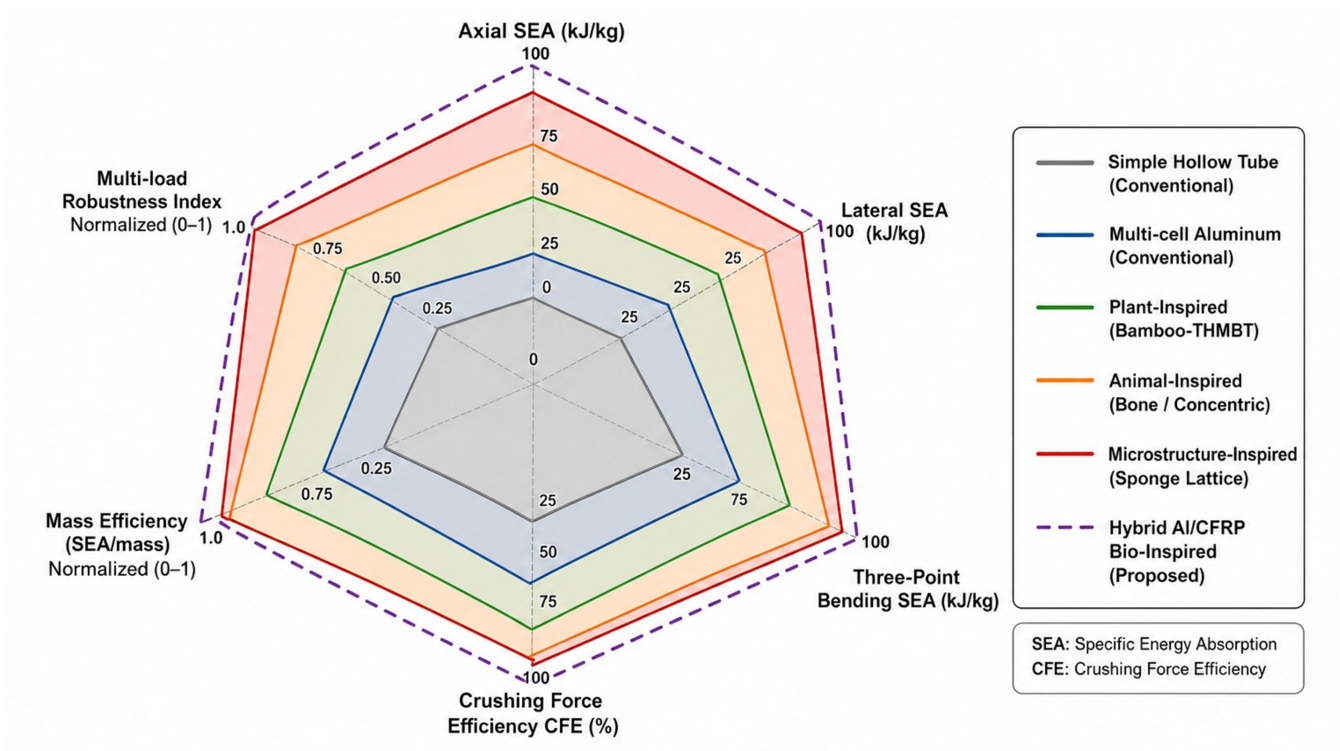

Fig. 5. Radar chart comparing multi-dimensional performance of energy absorber design categories across six metrics

buckling interventions. Under lateral loading, conventional absorbers may deliver less than 50% of their axial SEA.

Bio-inspired designs produce the largest performance gains under lateral and bending loads. Animal-inspired absorbers, drawing from the concentric-layer architecture of the bone cortex, show SEA improvements above 93% over simple baselines under lateral loading. Microstructure-inspired sponge lattice absorbers achieved a 98.96% improvement in the lateral SEA compared to simple designs. This represents a near doubling of the energy absorption in the loading direction, which is the most demanding for battery pack protection [6,7].

The three-point bending performance, relevant to underbody impact scenarios, showed comparable gains. Plant- and animal-inspired configurations achieve improvements of 62–80% over simple baselines [6,7].

5.4 Consolidated Performance Comparison

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Table 2. Comparative SEA performance of energy absorber design categories across loading conditions (* estimated ranges for hybrid Al/CFRP bio-inspired systems based on constituent material benchmarks).

Design Category	Axial SEA Gain	3-Pt Bending	Lateral SEA	Oblique	Ref.
Simple Shapes (baseline)	0%	0%	0%	0%	[26]
Multi-cell Configurations	+29.74%	+62.53%	+81.99%	+35%	[36]
Plant-Inspired (Bamboo/Tree)	+38.20%	+58.40%	+88.60%	+42%	[36]
Animal-Inspired (Bone/Beetle)	+41.50%	+61.80%	+93.40%	+47%	[37]
Microstructure (Sponge lattice)	+43.73%	+62.86%	+98.96%	+51%	[36]
Hybrid Al/CFRP Bio-Inspired	+55–70%*	+70–80%*	+100–120%*	+60%*	[30]

Note: Values represent approximate SEA improvements relative to simple hollow tube baseline. Specific values depend on geometry, material, and loading rate. References [6,7,11,36,37] provide detailed experimental and numerical data.

Table 2b. Comprehensive study-level comparison of bio-inspired and hybrid energy absorber designs reviewed in Sections 3 and 4, summarizing geometry, material, manufacturing method, loading condition, reported performance, advantages, and limitations for each individually reviewed design.

Geometry (Study)	Material	Manufacturing Method	Loading Condition	SEA / CFE Reported	Advantages	Limitations	Ref.
Bamboo THMBT (plant-inspired)	Aluminum tube (THMBT profile)	Extrusion-equivalent test geometry	Axial	CFE 65–80%	High CFE, stable crushing stroke	Complex branched-tube tooling	[6,7]
Tree-branching web insert (plant-inspired)	Aluminum / polymer web insert	Extrusion + internal web insert	Axial	Increased fold-initiation sites (qualitative)	More crushing area per unit mass	No CFE value reported	[6]
Skeletal circular section (animal-inspired)	Al shell with graded-density lattice core	AM lattice core + conventional outer shell	3-point bending	Outperforms hollow tube (qualitative)	High resistance to fracture initiation	Requires dual-material / dual-process construction	[7]
Beetle elytra / nacre microstructure (animal-inspired)	Textured or partitioned Al / composite	Surface texturing, internal partitioning	Oblique / lateral	Lateral SEA >93%	Strong multi-axis performance	Micro-feature fabrication complexity	[6,7]

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Euplectella sponge lattice (microstructure-inspired)	AlSi10Mg or Ti-6Al-4V lattice	Selective laser melting (SLM)	Lateral	Lateral SEA >98.96%	Highest SEA/CFE of all reviewed categories	5–20× cost vs. extrusion; build-volume limits	[6,36]
Honeycomb–sponge hybrid (microstructure-inspired)	Aluminum / polymer composite	Honeycomb tooling + lattice cross-bracing	Multi-axis	Between honeycomb and pure lattice (qualitative)	Retains honeycomb manufacturability	Performance below pure sponge lattice	[6]
L-shaped CFRP corner insert (hybrid)	Al square tube + CFRP inserts	Structural adhesive bonding	Axial	SEA +40–55%	Delays buckling; low added mass	Validated under axial loading only	[11]
Hybrid double-hat beam (hybrid)	Al hat-sections + CFRP face sheets	Stamping + adhesive bonding	3-point bending	Validated for module housing (qualitative)	Strong bending / pole-impact performance	Not validated under axial loading	[12]
Guided crushing trigger features (hybrid)	Al/CFRP with notches or trigger tabs	Bonding + geometric crush initiators	Axial / oblique	Improves deformation stability (qualitative)	Predictable, repeatable fold initiation	Requires precise trigger-feature tolerancing	[11,13]

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5.5 Design Trade-offs and Selection Framework

Selecting an energy absorber for a specific battery pack application requires balancing the SEA and CFE against the manufacturing cost, integration constraints, mass budget, and durability requirements. Figure 1 shows the SEA against the manufacturing cost for each absorber type. Extruded aluminum multi-cell profiles are at the low-cost extreme. AM-fabricated sponge lattices exhibit high-performance extremes. Bio-inspired designs occupy progressively higher positions on both axes within these bounds. Hybrid Al/CFRP bonded constructions currently offer the most favorable near-term trade-off between performance and manufacturability in premium EV applications.

5.6 Beyond SEA: Force and Intrusion Metrics

SEA quantifies how much energy an absorber removes per unit mass, but it says nothing about the force pulse actually transmitted to the battery cells or the distance the crash structure intrudes before that energy is dissipated. Peak Crushing Force (PCF), defined in Section 2.2, is the more directly safety-relevant metric: a high-SEA absorber that reaches its peak force early in the stroke can still transmit a damaging force spike to adjacent cells before progressive crushing begins. This is why CFE, the ratio of mean to peak force, is reported alongside SEA throughout this review rather than SEA alone.

Table 3 (Section 6) reports CFE ranges alongside SEA for each design category, and the trend across categories mirrors the SEA

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trend rather than diverging from it: hollow cylinders and square sections show the lowest CFE (40–60%), commercial honeycomb and aluminum foam sit at 55–75%, plant- and animal-inspired designs reach 65–82%, and microstructure-inspired and hybrid Al/CFRP designs reach the highest range at 70–92%. Because CFE improves in step with SEA rather than trading off against it in this dataset, the bio-inspired categories that lead on SEA also transmit a comparatively flatter, lower-peak force pulse to the battery pack, which is the more direct indicator of cell protection than SEA alone.

Intrusion depth and battery protection effectiveness are reported far less consistently across the reviewed studies than SEA and CFE. Section 7.1 notes that UN ECE R100 and ISO 12405 apply a fixed 100–105 kN static crush load precisely because vehicle structure, not absorber mass, governs the force actually transmitted in a real collision, which makes pack-level intrusion the ultimate test of absorber effectiveness rather than a laboratory SEA figure. However, the individual absorber-level studies synthesized in Sections 3–5 predominantly report coupon- or component-level SEA and CFE rather than intrusion depth or cell-level protection outcomes measured in a full pack assembly. This is a genuine limitation of the current bio-inspired absorber literature rather than of this review: absorber-level and pack-level test data are rarely published together for the same design, which is also why Table 2b above records several entries qualitatively rather than with a directly comparable intrusion figure. Closing this gap is one of the motivations for the component-level testing standard proposed in Section 8.6.

6. Integration into EV Battery Pack Architecture

6.1 Module-Level Integration

At the battery module level, energy absorbers surround the groups of cells. They provide mechanical protection and facilitate the thermal management. The absorber geometry must fit the cell form factor (cylindrical, prismatic, or pouch), remain within the available packaging envelope, and achieve the required SEA under multidirectional loading.

Table 3. Conventional vs bio-inspired energy absorber performance comparison across key metrics.

Absorber Type	SEA (kJ/kg)	CFE (%)	Multi-load Capability	Key Limitation
Hollow Cylinder	15–25	40–55	Poor	Low lateral performance
Square Section	18–30	45–60	Moderate	Unstable collapse modes
Honeycomb (Al)	25–45	55–70	Moderate	Anisotropic behavior
Al Foam	10–20	60–75	Good	High cost, low SEA

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Absorber Type	SEA (kJ/kg)	CFE (%)	Multi-load Capability	Key Limitation
Plant-Inspired (Bamboo)	40–60	65–80	Good	Complex manufacturing
Animal-Inspired	45–65	68–82	Very Good	Material sensitivity
Microstructure-Inspired	55–80	70–88	Excellent	Fabrication precision
Hybrid Al/CFRP Bio	65–100+	75–92	Excellent	Bonding durability

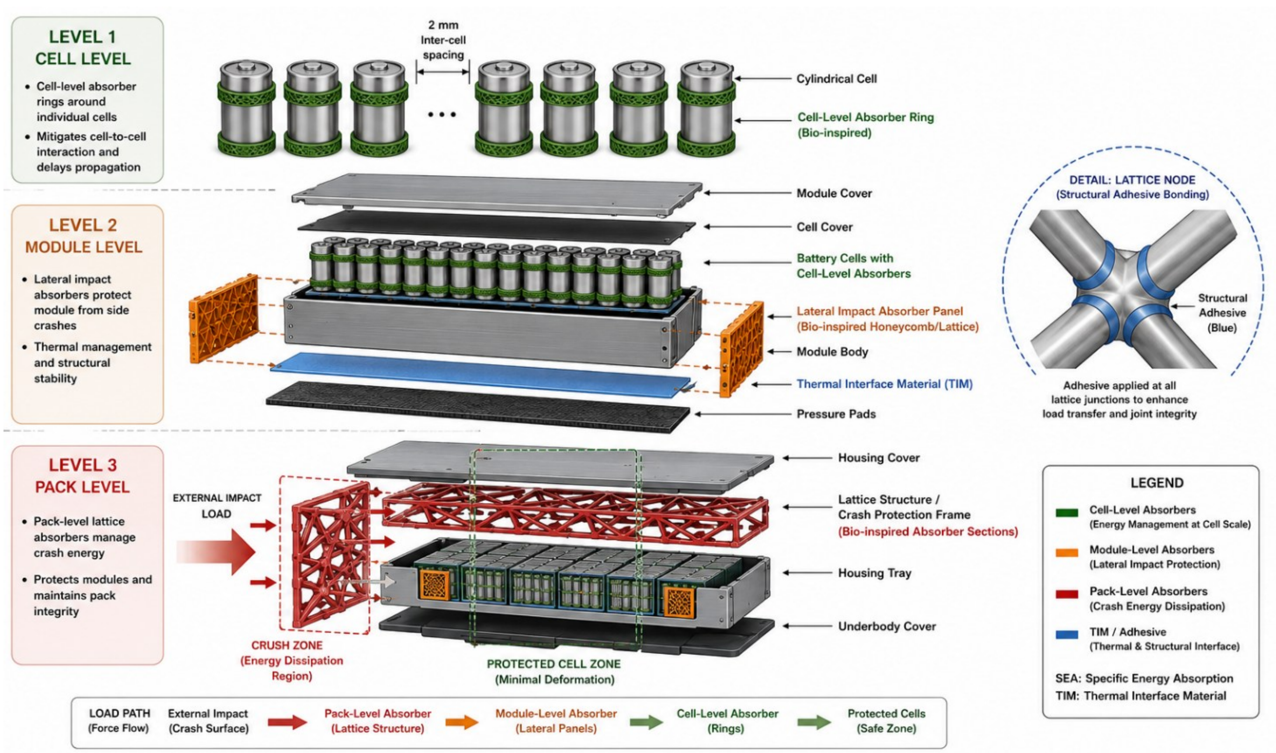

Fig. 6. Hierarchical integration of bio-inspired energy absorbers at cell, module, and pack levels within an EV battery pack assembly.

For cylindrical cell modules, honeycomb or lattice absorbers are integrated around individual cells or cell groups. The absorber walls simultaneously act as thermal conduction paths for the module cooling system. The NASA battery safety requirement specifies a minimum intercell spacing of 2 mm for batteries exceeding 80 Wh/kg. This constrains the available absorber wall thickness and favors materials with high SEA per unit volume rather than per unit mass [14].

Prismatic cell modules are increasingly common in high-energy-density EV applications. Their flat cell surfaces are suitable for sandwich panel absorber configurations. Bio-inspired face sheets with graded density cores are positioned between cell faces. They provide lateral impact protection and accommodate cell volume expansion during charging and discharging via controlled compression pads. This configuration functions as both an absorber and a compression pad. This reduces the component count and packaging complexity.

6.2 Pack-Level Integration and Lattice Structure

At the battery pack level, the internal lattice structure positions and protects the battery modules and absorbs crash forces. Load paths through the lattice differ for frontal, side, and rear impacts. The absorber geometry must perform adequately in all three principal directions simultaneously [1].

Bio-inspired lattice absorbers integrated into the pack-level crash protection frame must transmit forces along the designated load paths to the vehicle body structure. They must also limit the penetration into the cell zone. The lattice structure is connected to the housing tray via conventional fasteners combined with a structural adhesive. This connection maintains the stiffness, damping, and sealing integrity to prevent electrolyte vapor leakage during crash energy absorption [1].

Pack Body Integration is a growing design approach in which the battery pack carries a portion of the vehicle body stiffness. This adds to the requirements for the internal lattice absorber. In addition to its crash energy absorption function, the absorber must provide adequate stiffness and load transmission under normal operating loads, including NVH, static, and dynamic forces. The Porsche Taycan and Audi e-Tron illustrate this approach, wherein their battery packs contribute 10% and 27% of the vehicle stiffness, respectively [1].

6.3 Compatibility with CTP and CTC Architectures

Cell-to-pack (CTP) and cell-to-chassis (CTC) battery architectures eliminate the intermediate module structure to increase the volumetric energy density. This changes the role and integration strategy of energy absorbers. In CTP designs, cells are embedded directly in the pack structure without module enclosures. The packaging density increases, but one layer of mechanical protection disappears. In CTC architectures, the pack becomes a structural element of the vehicle's chassis. This compresses the available protection layers between the external crash surface and cells.

These architectures impose stricter demands on the energy absorber performance. The absorber must compensate for the absence of module-level protection and simultaneously contribute to the vehicle's structural stiffness at the same time. Bio-inspired absorbers offer multidirectional performance and structural efficiency. Integrating them into CTP and CTC designs requires resolving a repairability conflict: the same structural integration that improves crash performance makes post-collision inspection, cell replacement, and end-of-life disassembly substantially more difficult [3].

Tesla and BYD have demonstrated production-viable CTP and CTC implementation. The energy-absorber designs in these systems remain proprietary. The open

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research problem is the development of reversible structural bonding techniques. The candidates include mechanically detachable adhesive joints, thermally reversible polymers, and modular lattice connection systems. These must maintain crash performance while allowing disassembly as required by circular economy mandates.

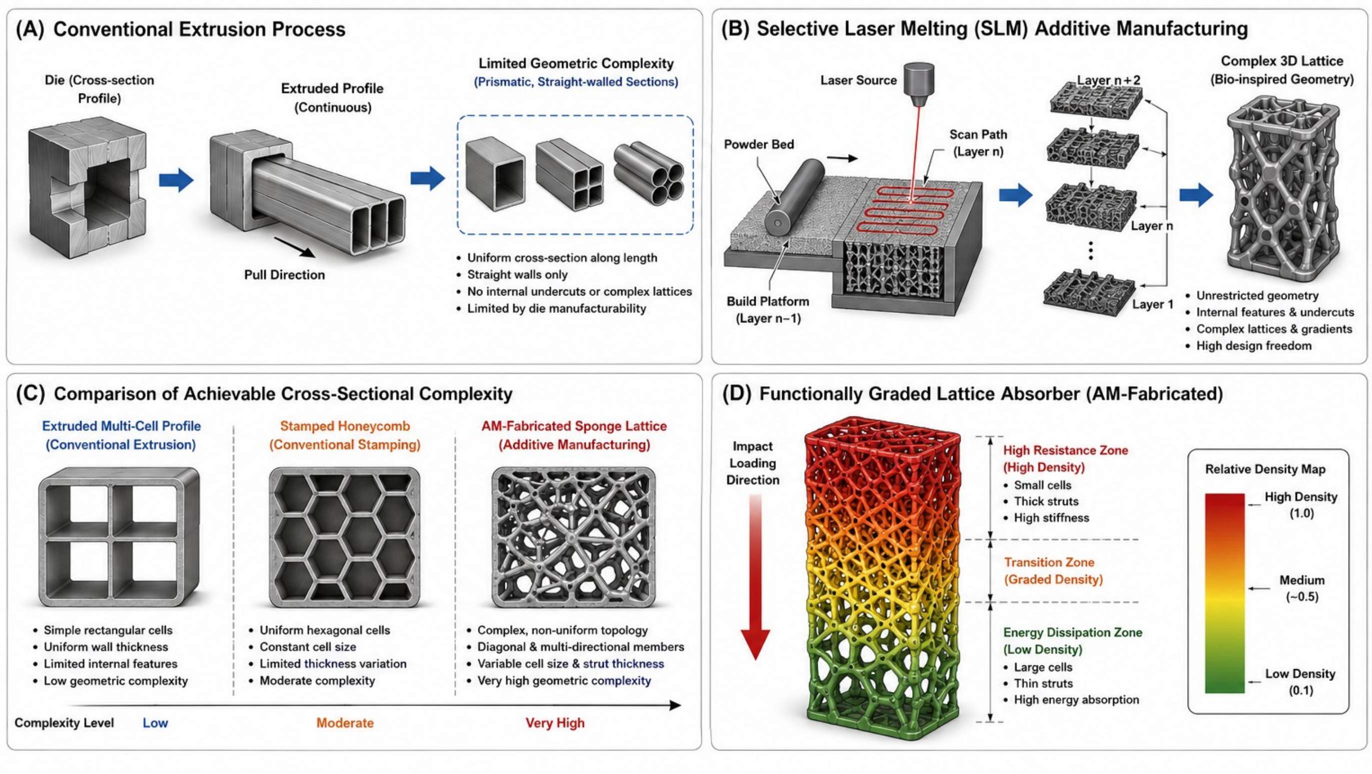

Fig. 7. Role of additive manufacturing in enabling bio-inspired energy absorber complexity

7. Compliance with International Safety Standards

7.1 Overview of Applicable Standards

Bio-inspired energy absorbers for EV battery packs require validation against international mechanical-abuse test standards. These standards define the minimum requirements for structural integrity, containment, and safety under crash and abuse conditions. The scope, test methodology, and acceptance criteria differ across regional regulatory frameworks. Therefore, products intended for global markets require a multi-standard validation approach [15].

The distinction between North American, European, and Asian standards is most consequential for the crush test methodology, which is the test most directly relevant to energy absorber performance. The SAE J2464 and USABC standards calculate the crush force as 1000 times the specimen weight. This can underload lightweight bio-inspired absorbers and may not reproduce the crushing forces of a real vehicle collision. UN ECE R100 and ISO 12405 apply a fixed static crush force of 100–105 kN to the battery pack. This reflects the fact that the vehicle structure, not the battery mass alone, determines the maximum transmitted force. Therefore, the European approach is more representative of pack-level absorber validation [15].

7.2 Critical Test Requirements and Absorber Design Implications

The most directly relevant test categories for bio-inspired energy absorbers are the crush/crash, mechanical shock, and vibration tests.

Crush/Crash Test: This test simulates collision-induced battery deformation. The SAE J2464 procedure runs in two stages: first crushing to 15% of the initial dimensions, then to 50% or until the crush force reaches 1000× the specimen weight. This places explicit demands on the stability of progressive crushing. A bio-inspired absorber with a CFE approaching 90% maintained a near-constant force throughout both stages. It protects the battery cells by preventing force spikes and dissipating the maximum energy within the available crush stroke.

Mechanical Shock Test: This test evaluates the absorber and structural integrity under dynamic impact accelerations. These events represent vehicle braking, acceleration, and crash events. SAE J2464 mandates peak accelerations of 150 g for cells and 25 g for packs over a duration of 6–15 ms. These are among the most stringent dynamic requirements worldwide. Bio-inspired absorbers must maintain progressive deformation under dynamic loading rates. Many materials and geometries behave differently under dynamic loading than they do under quasi-static crush test conditions.

Vibration Test: This test assesses the long-term integrity of absorber-to-structure connections under road-induced vibration profiles. Bond line fatigue is the primary concern for adhesively bonded bio-inspired absorbers. The SAE J2380 random vibration profile was derived from over 100,000 miles of real-world EV driving data. Absorbers must endure this profile without bond-line fatigue cracking or adhesive degradation.

7.3 Standards Summary Table

The EUCAR hazard criterion (levels 0–7) classifies the test outcomes across standardized abuse tests. Energy absorbers must limit outcomes to Level 3 or below, corresponding to electrolyte leakage below 50% by weight under all standardized test conditions. Bio-inspired designs that achieve higher SEA and CFE than conventional absorbers reduce cell deformation and prevent internal short-circuit initiation. This keeps the test outcomes at lower EUCAR hazard levels [15].

Table 4. Summary of international safety standards applicable to bio-inspired energy absorbers in EV battery packs.

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Standard	Key Test Requirements	Acceptance Criteria	Relevance to Absorbers
SAE J2464	Crush to 50% dim., 1000× weight force; Penetration 8 cm/s	EUCAR ≤ Level 3; No fire/explosion	Defines crush force absorber must withstand
SAE J2929	Mechanical shock 150 g (cells); Drop >1m; Rollover 360°	No rupture, no leakage	Validates shock absorption at pack level
UN ECE R100	100 kN static crush; Vibration; Thermal cycling	No fire, explosion, leakage	Primary EU homologation; fixed crush load
ISO 12405-3/4	100–105 kN crush; Vibration at −40°C to 75°C	No rupture, no leakage	Environmental endurance benchmark
IEC 62660	Cell-level crush (1000× weight); Vibration 10–2000 Hz	No fire or explosion	Cell-level absorber performance
USABC/FreedomCAR	Crush 1000× weight; Drop 10m; Penetration 20mm dia.	No fire, rupture, leakage	Most comprehensive; multi-level testing
UL 2580	Drop 1m (3×); Crush 100–1000 kN; Immersion	No fire, no explosion	Consumer product safety baseline

8. Research Gaps and Future Directions

Bio-inspired energy-absorber designs have advanced substantially in the areas reviewed above. However, several research gaps remain before these designs can be widely deployed in production EV battery systems. These gaps span manufacturing scalability, multiphysics simulation, next-generation battery compatibility, circular economy compliance, and digital design tools.

8.1 Manufacturing Scalability of Bio-Inspired Designs

The most immediate barrier to the commercial deployment of bio-inspired absorbers, particularly AM-fabricated lattice structures, is manufacturing scalability. Current metallic AM processes, including SLM and electron beam melting, have high per-part costs, limited build volumes, and throughput rates that are incompatible with automotive production volumes of 100,000–500,000 vehicles per year. Closing this gap requires advances in three areas. First, large-format metal AM systems must increase the build volume and reduce the cycle time. Second, hybrid manufacturing approaches must combine AM for complex bio-inspired features with conventional machining or forming for simple structural elements. Third, bio-inspired geometries must be adapted for fabrication using conventional processes, such as tailored stamping or multi-axis roll forming, while retaining their multi-directional performance advantages.

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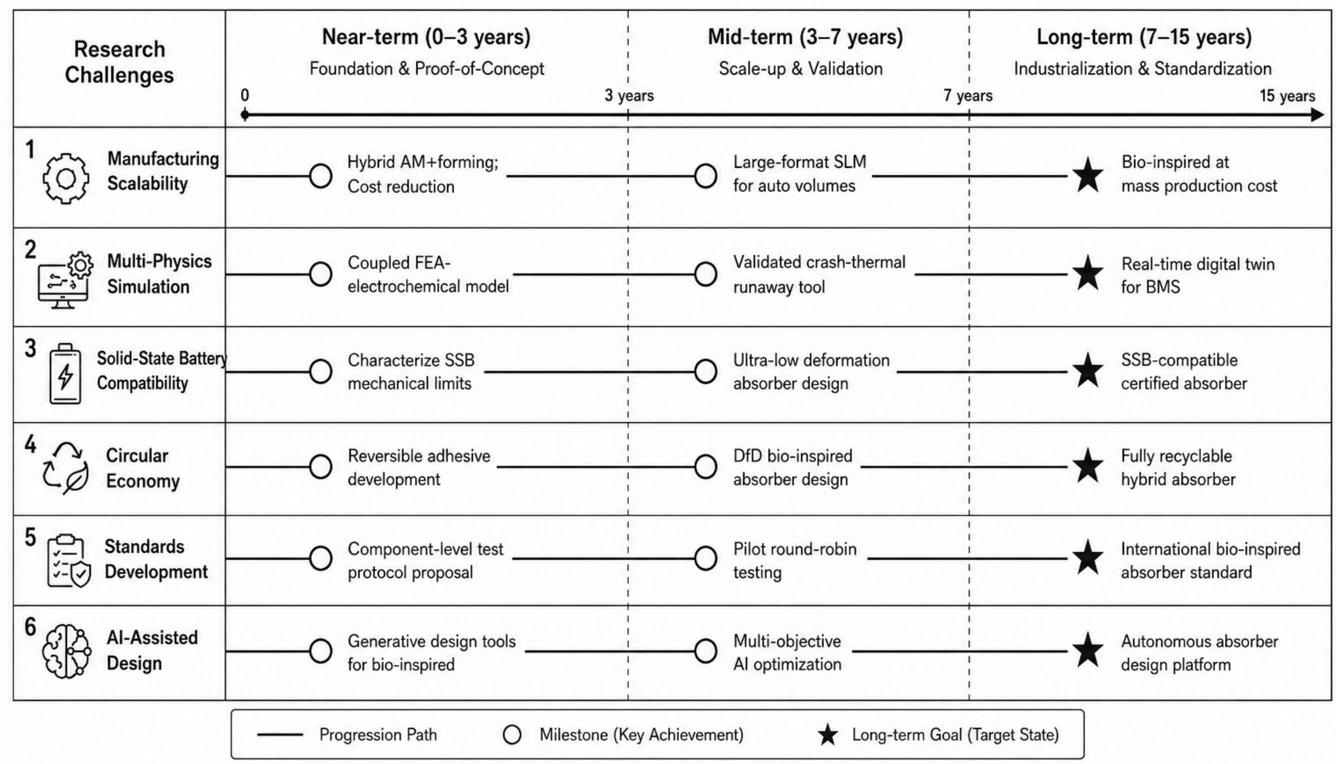

Fig. 8. Research and development roadmap for bio-inspired energy absorbers in EV battery pack protection across six challenge domains.

8.2 Multi-Physics Crash-Electrochemical Simulation Coupling

Current simulation practices treat structural crash analysis and electrochemical cell behavior as independent problems. The FEA models predicted the absorber deformation and force transmission to the battery cells. Electrochemical models simulate cell degradation and thermal runaway separately. This separation was inadequate. The mechanical deformation of cells during a crash directly affects the electrochemical state. The separator compression changes the ionic transport resistance. Electrode cracking alters the lithiation kinetics. Thermal gradients from mechanical deformation affect both the degradation rate and the thermal runaway onset.

A fully coupled multiphysics simulation framework integrates structural FEA with electrochemical pseudo-two-dimensional (P2D) models and thermal simulations. This would allow the prediction of whether a given absorber design prevents thermal runaway initiation under a specific crash event. However, such a capability does not currently exist. Building and validating this framework requires computational advances and experimental data from instrumented crash tests conducted on vehicles. These tests must simultaneously measure the absorber

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deformation, cell deformation, internal cell temperature, and electrochemical response.

8.3 Solid-State Battery Compatibility

The anticipated transition from liquid-electrolyte lithium-ion cells to solid-state batteries (SSBs) introduces different structural requirements for energy-absorbers. SSB cells incorporating ceramic solid electrolytes, including sulfide-based $Li_{10}GeP_2S_{12}$ and oxide-based LLZO, are brittle compared to polymer-separator liquid electrolyte cells. Liquid electrolyte cells tolerate some deformation before an internal short circuit occurs. The SSB cells fractured at much lower deformation levels. Separator compression and cell deformation, which are acceptable for liquid electrolyte cells, can cause catastrophic electrolyte fractures in SSB cells.

Therefore, energy absorber designs for SSB packs must achieve much lower cell deformation limits than the current standards. This demands either a substantially higher SEA, so that the absorber dissipates more energy before the force reaches the cell, or a reduced absorber stroke using very stiff, short-stroke absorbers. SSB cells also require a uniform stack pressure to maintain electrolyte-electrode contact. The absorbers must protect the cells from external impact forces and maintain a controlled internal stack pressure throughout a crash event. These two requirements conflict with the progressive stroke-dependent deformation behavior of bio-inspired absorbers. This conflict is a fundamental design problem for the next generation of battery-pack protection systems.

8.4 Circular Economy and Repairability Requirements

European and international circular economy regulations increasingly require battery packs to be designed for disassembly, repairability, and recyclability at the end of life. Bonded hybrid Al/CFRP absorbers offer the best crash performance but are among the most difficult structures to disassemble in the recycling process. Structural adhesives designed for long-term durability under thermal cycling and vibration resist the mechanical and chemical methods used in recycling facilities.

Resolving the conflict between repairability and structural integration requires reversible bonding technologies. Three candidate approaches are available. Thermally reversible adhesives liquefy at elevated temperatures, allowing nondestructive disassembly. The mechanically activated release mechanisms are embedded in the bond line and triggered on demand. Solvent-reversible adhesive formulations must also be compatible with the electrolyte environment of battery packs. Design for disassembly (DfD) principles must be incorporated into bio-inspired absorber geometry at the earliest design stage. Practical measures include accessible bond line edges and the elimination of geometric lock-in features that prevent absorber removal after bonding.

8.5 Digital Design Tools and AI-Assisted Bio-Inspired Optimization

The complexity of bio-inspired absorber geometry, material system selection, and multidirectional loading optimization exceeds the capacity of manual design iteration. AI-

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assisted generative design tools can automatically explore the design space of bio-inspired geometries subjected to specified loading conditions, mass constraints, and manufacturing limitations. This provides a route for identifying optimized absorbers for specific battery pack applications.

Digital twin platforms that integrate the bio-inspired absorber model with the full battery pack structural model, thermal management system, and vehicle-level crash simulation environment would allow the concurrent optimization of the absorber geometry, material selection, and integration strategy. Reinforcement learning algorithms are suitable for this multi-objective optimization problem. They can navigate the large, non-convex design space of bio-inspired geometries while simultaneously satisfying crashworthiness, mass, cost, and manufacturing constraints at the same time.

8.6 Standardization of Bio-Inspired Absorber Testing

Currently, no dedicated international standard exists for the characterization and qualification of bio-inspired energy absorbers in EV battery applications. Existing standards, including SAE J2464, UN ECE R100, and ISO 12405, test battery packs as systems. They do not provide component-level pass/fail criteria for individual absorbers. As a result, bio-inspired absorber developers cannot obtain component-level certification. Each design iteration requires full pack-level testing, which increases the cost and slows development.

A component-level standard addressing the multi-directional SEA and CFE characterization of battery pack energy absorbers would shorten the technology development cycle. Such a standard would cover bio-inspired and hybrid material construction. It specifies the test procedures for axial, lateral, oblique, and three-point bending loading conditions at both quasi-static and dynamic loading rates. The acceptance criteria are linked to the EUCAR hazard levels used for pack-level certification.

9. Conclusion

This review traced the evolution of energy absorber designs for EV battery pack protection. It covered conventional multi-cell aluminum extrusions, three biological inspiration pillars (plant-, animal-, and microstructure-inspired geometries), hybrid Al/CFRP bonded constructions, and AM-fabricated bio-inspired lattices. Beyond summarizing this literature, two concepts stand out as the most industrially promising in different time horizons: hybrid Al/CFRP bonded constructions for near-term production, and AM-fabricated sponge-lattice designs for longer-term, high-performance applications once manufacturing scalability improves. The following conclusions were drawn:

- Hybrid aluminum/CFRP bonded structures appear to be the most promising bio-inspired design for near-term industrial implementation. They offer a favorable combination of high specific energy absorption (65–100 kJ/kg), high crash force efficiency (75–92%), competitive cost, and compatibility with existing manufacturing processes. These advantages make them more practical

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for large-scale production than many other bio-inspired concepts reviewed in this study. However, their widespread adoption depends on overcoming challenges related to adhesive bond durability and structural repairability. Future research should focus on developing adhesive systems capable of withstanding the thermal and vibration conditions encountered in service, while also addressing disassembly and recycling requirements. Resolving these issues will be essential for accelerating the transition of hybrid aluminum/CFRP bonded structures from research to commercial applications.

- Bio-inspired energy absorbers outperform conventional designs under all loading conditions reviewed. The largest improvement is observed under lateral loading (up to 98.96% SEA increase), a critical condition in side-impact and pole-side crash scenarios for battery packs, followed by three-point bending (up to 62.86%) and axial loading (up to 43.73%). But, comparisons among plant-, animal-, and microstructure-inspired designs should be made cautiously, as many of the best-performing structures were fabricated using additive manufacturing. Future work should focus on separating the effects of biological design and manufacturing methods to better assess the true benefits of bio-inspired architectures.
- Additive manufacturing is the dominant fabrication method for complex bio-inspired structures, particularly sponge-lattice and functionally graded designs. But, its high cost, typically 5–20 times greater than extrusion, limits its use to low-volume applications. Consequently, scaling these designs to automotive production volumes remains a major challenge and represents the key barrier to their widespread industrial adoption, unlike hybrid Al/CFRP structures, which are already compatible with existing manufacturing processes.
- Bio-inspired absorbers into Cell-to-Pack (CTP) and Cell-to-Chassis (CTC) battery architectures requires not only high crashworthiness but also adequate structural stiffness, thermal compatibility, and repairability. A key challenge is meeting circular economy and recycling requirements, which often conflict with highly integrated structural designs. Therefore, the development of reversible bonding and disassembly-friendly solutions may be more critical to the adoption of bio-inspired absorbers in CTP/CTC platforms than further improvements in crash performance.

References

[1] GhasemiPourMasoule, S. H., Keshavarzi, A., & Saeidi Googarchin, H. (2026). A review on structural and mechanical insights into electric vehicle battery packs: Subsystems, standards, and design innovations. Journal of Energy Storage, 158, 121657. https://doi.org/10.1016/j.est.2026.121657

[2] Arora, S., Shen, W., & Kapoor, A. (2016). Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles. Renewable and Sustainable Energy Reviews, 60, 1319–1331. https://doi.org/10.1016/j.rser.2016.03.013.

[3] Belingardi, G., & Scattina, A. (2023). Battery Pack and Underbody: Integration in the Structure Design for Battery Electric Vehicles—Challenges and Solutions. Vehicles, 5(2), 498–514. https://doi.org/10.3390/vehicles5020028

[4] Arora, S., Kapoor, A., & Shen, W. (2018). Application of Robust Design Methodology to Battery Packs for Electric Vehicles: Identification of Critical Technical Requirements for Modular Architecture. Batteries, 4(3), 30. https://doi.org/10.3390/batteries4030030

[5] Ruiz, V., Pfrang, A., Kriston, A., Omar, N., Van den Bossche, P., & Boon-Brett, L. (2018). A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles. Renewable and Sustainable Energy Reviews, 81, 1427–1452. https://doi.org/10.1016/j.rser.2017.05.195

[6] Baratian Sani Devin, A., Keshavarzi, A., Hemami, A. A., Feyz Bashipour, A., & Saeidi Googarchin, H. (2025). From Nature to Engineering: The Evolutionary Journey of Bio-Inspired Energy Absorbers Across Diverse Loading Conditions. Thin-Walled Structures, 216, 113684. https://doi.org/10.1016/j.tws.2025.113684

[7] Baratian Sani Devin, A., Keshavarzi, A., Hemami, A. A., Feyz Bashipoor, A., & Googarchin, H. S. (2025). Bio-inspired energy absorbers: Evolutionary designs and mechanical performance under various loading conditions. Mechanics Based Design of Structures and Machines, 54(1). https://doi.org/10.1080/15397734.2025.2532740

[8] Mudassir, M., Tarlochan, F., & Mansour, M. A. (2020). Nature-Inspired Cellular Structure Design for Electric Vehicle Battery Compartment: Application to Crashworthiness. Applied Sciences, 10(13), 4532. https://doi.org/10.3390/app10134532

[9] Zhang, J., Lu, G., & You, Z. (2020). Large deformation and energy absorption of additively manufactured auxetic materials and structures: A review. Composites Part B: Engineering, 201, 108340. https://doi.org/10.1016/j.compositesb.2020.108340

[10] Setiawan, R., & Salim, M. R. (2017). Crashworthiness Design for an Electric City Car against Side Pole Impact. Journal of Engineering and Technological Sciences, 49(5), 587–603. https://doi.org/10.5614/j.eng.technol.sci.2017.49.5.3

[11] Keshavarzi, A., & Saeidi Googarchin, H. (2024). Local reinforcement of adhesively bonded square shape aluminum energy absorber with CFRP under quasi-static axial loading: An experimental and numerical study. International Journal of Adhesion and Adhesives, 135, 103835. https://doi.org/10.1016/j.ijadhadh.2024.103835

[12] Golivari, H., Saeidi Googarchin, H., Zaeri, A., & Keshavarzi, A. (2024). Experimental and numerical investigation of the energy absorption in hybrid double-hat thin-walled structures reinforced by adhesive bonding under three-point bending. International Journal of Adhesion and Adhesives, 128, 103543. https://doi.org/10.1016/j.ijadhadh.2023.103543

[13] Baratian Sani Devin, A., Keshavarzi, A., & Saeidi Googarchin, H. (2026). Harnessing predictable failure: a bio-inspired adhesively bonded Al/CFRP hybrid structure with guided crushing for enhanced crashworthiness under oblique loading. Materials &Amp; Design, 262, 115461. https://doi.org/10.1016/j.matdes.2026.115461

[14] Jeevarajan, J. A. (2015). Revisions to the Crewed Space Vehicle Battery Safety Requirements JSC 20793. Space Safety Is No Accident, 127–129. https://doi.org/10.1007/978-3-319-15982-9_14

[15] Haghbin, S., Rezaei Larijani, M., Zolghadri, M., & Hedayati Kia, S. (2025). Automotive battery pack standards and design characteristics: a review. Discover Applied Sciences, 7(7). https://doi.org/10.1007/s42452-025-07339-w

[16] Latifzadeh, F., Keshavarzi, A., & Saeidi Googarchin, H. (2025). Crashworthiness of adhesively bonded bio-inspired AL/CFRP hybrid tubes under lateral loading. Mechanics of

[DOI: 10.22068/ase.2026.749]

Advanced Materials and Structures, 33(1). https://doi.org/10.1080/15376494.2025.2472399

[17] Rahmani, R., Keshavarzi, A., & Googarchin, H. S. (2024). On the role of local reinforcement in an adhesively bonded <scp>AL</scp>/<scp>CFRP</scp> energy absorber under axial loading: A theoretical investigation and optimization. Polymer Composites, 46(4), 3439–3460. Portico. https://doi.org/10.1002/pc.29184

[18] Saeidi Googarchin, H., Sadeghi, S., & Keshavarzi, A. (2025). Numerical analysis of bio-inspired foam-filled multi-cell tapered tubes for energy absorption. Mechanics Based Design of Structures and Machines, 53(7), 5360–5387. https://doi.org/10.1080/15397734.2025.2464760

[19] Czerwinski, F. (2021). Current Trends in Automotive Lightweighting Strategies and Materials. Materials, 14(21), 6631. https://doi.org/10.3390/ma14216631

[20] Doughty, D., & Crafts, C. (2006). FreedomCAR :electrical energy storage system abuse test manual for electric and hybrid electric vehicle applications. (, Ed.). Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/889934

[DOI: 10.22068/ase.2026.749]