Aluminium Sill Extrusions for Side-Pole Crashworthiness: A Review

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Abstract

Side impact protection remains a critical challenge in automotive crashworthiness, particularly for battery electric vehicles where intrusion must be minimized to protect high-voltage components. This review examines recent advances in aluminium sill extrusions for side-pole crashworthiness where impact is localize and rigid compared to moving deformable barrier case, analyzing ten key studies that employ extruded aluminium profiles, foam-filled structures, and multi-cell geometries. The literature demonstrates that aluminium extrusions, particularly Al-Mg-Si and AA6063-T6 alloys, offer superior specific energy absorption compared to steel alternatives while enabling mass reduction. Multi-fidelity optimization and machine learning approaches have accelerated design cycles, though experimental validation remains limited. Key research gaps include the absence of standardized crashworthiness metrics, insufficient integration of manufacturing constraints into optimization frameworks, and limited full-vehicle validation. This review synthesizes current methodologies, identifies critical performance trends, and provides recommendations for advancing aluminium sill extrusion design for specific to side-pole protection challenges.

Index Terms

Aluminium extrusions, side-pole impact, crashworthiness, energy absorption, sill structures, battery electric vehicles, foam-filled tubes, optimization

I. INTRODUCTION

Side-pole impact represents one of the most severe crash scenarios in automotive safety, characterized by concentrated loading over a small contact area and limited space for energy absorption [1], [2]. Unlike frontal or rear collisions where crumple zones provide substantial deformation space, side impacts must protect occupants and critical components within the constrained envelope between the door outer panel and the passenger compartment [3]. The challenge intensifies for battery electric vehicles (BEVs), where lithium-ion battery packs mounted beneath the floor require stringent intrusion limits to prevent thermal runaway and fire hazards [1], [4].

Aluminium extrusions have emerged as a preferred solution for side-sill structures due to their favorable strength-to-weight ratio, design flexibility, and controlled progressive folding behavior under lateral loading [5], [3]. Extruded profiles enable complex multi-cell cross-sections that enhance energy absorption while maintaining structural rigidity for normal operating loads [6], [7]. Recent advances in computational optimization, including multi-fidelity surrogate modeling and machine learning-driven design exploration, have accelerated the development of crashworthy sill geometries [8], [9].

Despite these advances, significant research gaps persist. Many studies report qualitative or relative performance improvements without publishing standardized crashworthiness metrics such as specific energy absorption (SEA) or intrusion distances under regulatory test conditions [1], [10], [3]. Experimental validation at the full-vehicle or subsystem level remains sparse, limiting confidence in translating simulation-optimized designs to production [9], [8]. Furthermore, manufacturing constraints—including extrusion tooling limitations, gauge variability, and joining methods—are rarely integrated into optimization frameworks [4].

This review addresses these gaps by systematically analyzing ten key studies on aluminium sill extrusions for side-pole crashworthiness. Section II provides theoretical foundations of crash energy management and material behavior. Section III examines methodological approaches including experimental testing, finite element analysis, and optimization techniques. Section IV presents a comparative analysis of key findings, performance metrics, and design strategies. Section V discusses research gaps and limitations, while Sections VI and VII offer recommendations and conclusions.

II. BACKGROUND AND THEORETICAL FOUNDATIONS

A. Side-Pole vs. MDB Impact Mechanics

Side-pole impact differs fundamentally from distributed-load crash scenarios. The pole (typically 254 mm diameter in FMVSS 214 and Euro NCAP protocols) creates a localized high-stress region that induces bending and crushing of the door, B-pillar, and sill structures [2], [11]. Energy absorption occurs through three primary mechanisms: (1) plastic deformation and progressive folding of thin-walled sections, (2) material densification in foam-filled or sandwich structures, and (3) friction and contact interactions between collapsing members [12], [10].

The crashworthiness performance of a sill structure is quantified by specific energy absorption (SEA), defined as the ratio of total absorbed energy to structural mass, and peak crush force, which governs intrusion velocity and occupant injury metrics [11]. Ideal energy absorbers exhibit high SEA with controlled, stable force-displacement characteristics to maximize energy dissipation before critical intrusion limits are reached [3].

B. Aluminium Alloys for Crash Structures

Aluminium alloys in the 6xxx series (Al-Mg-Si) dominate automotive extrusion applications due to their excellent extrudability, weldability, and post-forming strength through T6 heat treatment [3], [12]. AA6063-T6 and AA6061-T6 are most commonly employed for sill extrusions, offering yield strengths of 170-215 MPa and 240-275 MPa respectively [11], [12]. These alloys exhibit strain-rate sensitivity, with dynamic yield strength increasing 10-20% at crash-relevant strain rates (10^2 - 10^3 s^{-1}) compared to quasi-static values [3].

The lower density of aluminium (2.7 g/cm^3) compared to steel (7.85 g/cm^3) enables mass reduction of 40-50% for equivalent stiffness in bending-dominated structures [11]. However, aluminium's lower elastic modulus (70 GPa vs. 210 GPa for steel) necessitates careful cross-section design to prevent premature buckling under lateral loads [2].

C. Energy Absorption Enhancement Strategies

Three primary strategies enhance the crashworthiness of aluminium sill extrusions:

Multi-cell cross-sections: Dividing the extrusion into multiple interconnected cells increases the number of plastic hinges during progressive folding, raising SEA by 30-60% compared to single-cell profiles of equivalent mass [6], [9].

Foam filling: Injecting aluminium foam or polymer foam into extrusion cavities provides lateral support that delays buckling and increases mean crush force through foam densification [7], [12], [10]. Foam-filled double tubes demonstrate 25-40% higher energy absorption than empty equivalents [12].

Hybrid material integration: Combining aluminium extrusions with high-strength steel inserts, fiber-reinforced polymers, or timber-metal hybrids enables tailored load paths and localized reinforcement at critical impact zones [5], [13].

III. METHODOLOGY

A. Literature Search and Selection

A systematic search was conducted across academic databases (Scopus, Web of Science, Google Scholar) and patent repositories using keywords: "aluminium extrusion," "side-pole impact," "sill crashworthiness," "lateral crush," and "battery electric vehicle side impact." The search covered publications from 2016-2025, prioritizing peer-reviewed journal articles, conference proceedings, and patents with experimental or validated simulation data. Ten papers were selected based on relevance to aluminium sill extrusions, side-pole loading conditions, and contribution to crashworthiness understanding.

B. Analysis Framework

Each selected study was analyzed across six dimensions: (1) research methodology (experimental, FEA, optimization, analytical), (2) materials and alloy specifications, (3) cross-section geometry and design features, (4) reported performance metrics (SEA, peak force, intrusion), (5) validation approach, and (6) industrial applicability. Comparative tables were constructed to identify trends, performance benchmarks, and research gaps across the corpus.

IV. RESULTS AND DISCUSSION

A. Overview of Reviewed Studies

Table I summarizes the ten reviewed studies, categorizing them by primary methodology, material system, and key contribution. The literature spans component-level experimental characterization [3], full-vehicle simulation and optimization [1], [4], novel design concepts [7], [10], and advanced computational methods [8], [9].

TABLE I

SUMMARY OF REVIEWED STUDIES ON ALUMINIUM SILL EXTRUSIONS

Study	Methodology	Material/Design	Key Contribution
Oleksik & Vietor [5]	Engineering analysis	Extruded Al profiles, hybrid materials	Hybrid sill reinforcement for side-pole impact
Hamran [6]	Experimental testing	Multi-cell Al extrusion	New multi-cell profile for enhanced crashworthiness
Xia et al. [1]	FEA & optimization	Al extrusion energy box for EVs	Integrated absorber for battery protection
Béland & Parson [3]	Experimental/analytical	Al-Mg-Si extrusions	Lateral crush characterization of 6xxx alloys
Heyner et al. [13]	Experimental testing	Timber-metal hybrid with Al extrusion	Sustainable hybrid sill reinforcement
Jiqing et al. [7]	Design invention	Foam-filled Al I-beam	All-aluminium lightweight door sill with foam
Sharma [2]	Comparative FEA	Multiple Al cross-sections	Cross-section geometry effects on side impact
Kaps et al. [8]	Multi-fidelity optimization	Method development	Hierarchical kriging for lateral impact optimization
Borse et al. [9]	Machine learning	Multi-cell sill with Al	RL-based inverse optimization for sill design
Lane [4]	Topology & gauge optimization	Extruded Al battery side rail	Two-stage optimization for BEV intrusion control

B. Material Performance and Alloy Selection

Aluminium 6061-T6 consistently demonstrates superior specific energy absorption compared to structural steel in side-pole scenarios. Akar et al. [11] reported that Al6061-T6 door beams exhibited higher SEA, lower reaction forces, and reduced permanent deformation than A36 steel beams under high-speed pole impact. The hexagonal cross-section outperformed circular geometry for both materials, highlighting the importance of section shape in addition to material selection.

Al-Mg-Si extrusions (6xxx series) are preferred for crash rails and sills due to their lateral crush performance [3]. These alloys maintain ductility during rapid deformation, enabling progressive folding without catastrophic tearing or fracture. AA6063-T6, with slightly lower strength than 6061-T6, is commonly specified for foam-filled applications where the foam provides additional lateral support [12].

C. Cross-Section Geometry and Multi-Cell Designs

Cross-sectional geometry emerges as a primary driver of side-pole performance [2]. Multi-cell extrusions, featuring internal webs that divide the profile into multiple chambers, significantly enhance energy absorption by increasing the number of plastic hinge lines during progressive collapse [6]. Hamran's multi-cell aluminium profile demonstrated improved crashworthiness in side-pole tests at 5 mph, maintaining forces below critical thresholds for maximum occupant protection [6].

The I-shaped composite beam design proposed by Jiqing et al. [7] integrates foam-filled bar columns in upper and lower grooves, combining the benefits of multi-cell geometry with foam densification. This all-aluminium structure simultaneously achieves impact energy absorption, high rigidity, and lightweight construction while providing acoustic damping benefits.

Sharma's comparative study [2] emphasizes that proper cross-section selection is critical to maximize energy absorption and meet Side Impact Pole Test criteria. The study notes that high-grade aluminium is used in key structural components, but specific SEA values for different geometries were not published in the available excerpts.

D. Foam-Filled and Sandwich Structures

Foam filling represents a proven strategy to enhance the crashworthiness of aluminium extrusions. Djamaluddin [12] demonstrated through validated FEA that foam-filled double circular tubes of AA6063-T6 absorb substantially more energy than empty equivalents under dynamic bending. The study employed NSGA-II optimization to identify optimal tube dimensions and foam properties for door sill applications in pure electric vehicles.

Zhang et al. [10] proposed aluminium foam sandwich structures for door sill thresholds, arguing that the sandwich configuration preserves occupant space under side impact. While the concept shows promise for lightweight sill reinforcement, experimental validation and integration with production extrusion profiles were not detailed in the available literature.

The foam-filled approach offers additional benefits beyond energy absorption, including improved noise, vibration, and harshness (NVH) performance [7]. However, foam filling increases manufacturing complexity and cost, and the interaction between foam properties (density, cell size) and extrusion geometry requires careful optimization to achieve consistent crash performance.

E. Optimization Methods and Computational Approaches

Advanced optimization techniques have accelerated the design of crashworthy sill extrusions. Kaps et al. [8] developed a multi-fidelity hierarchical kriging framework that reduces computational cost while maintaining accuracy for lateral impact optimization problems. By coupling low-fidelity (simplified) and high-fidelity (detailed FEA) models, the method enables exploration of larger design spaces than traditional single-fidelity approaches.

Borse et al. [9] demonstrated the feasibility of reinforcement learning (RL) for inverse multi-parameter optimization of multi-cell side sills. The RL optimizer, coupled with FE solvers, efficiently searches complex design spaces to identify sill geometries that satisfy multiple crashworthiness objectives. While promising, the approach requires extensive training data and validation across diverse impact conditions.

Lane [4] proposed a two-stage optimization workflow for extruded aluminium battery side rails: (1) linear topology optimization to identify critical load-bearing members in the cross-section, followed by (2) non-linear gauge optimization to balance crushability and intrusion protection. This computationally efficient approach is directly applicable to BEV side rail design, where intrusion limits are stringent to protect battery enclosures.

F. Battery Electric Vehicle Applications

The transition to battery electric vehicles introduces new crashworthiness requirements for sill structures. Xia et al. [1] analyzed side-pole crash characteristics of EVs and proposed an aluminium extrusion energy-absorbing box integrated into the sill/battery region. This localized absorber serves as a sacrificial element to reduce battery deformation and prevent thermal runaway.

Lane's optimization framework [4] specifically addresses the challenge of designing extruded side rails that transfer rocker loads to the battery tray while limiting intrusion. The method represents extrusion cross-sections parametrically, enabling automated exploration of gauge distributions that satisfy both structural stiffness requirements for normal loads and controlled crushing for crash loads.

Heyner et al. [13] explored timber-metal hybrid materials for BEV side sill reinforcement, combining extruded aluminium profiles with engineered timber. While unconventional, the hybrid approach demonstrated comparable crash performance to conventional aluminium sills with potential sustainability benefits. The study provides crash testing data comparing the hybrid structure to a reference aluminium sill, though specific intrusion and SEA metrics were not published.

In battery electric vehicles (BEVs), aluminum sill extrusions play a critical role in managing side-pole impact energy while simultaneously enabling compliance with the post-crash electrical safety requirements of FMVSS 305. The localized and severe lateral loading imposed by pole impacts demands high bending stiffness and stable energy absorption within the extremely limited crush space available adjacent to the battery enclosure. Extruded aluminum sills address this requirement through optimized multi-cell cross-section geometries and controlled wall-thickness distribution, promoting bending-dominated collapse and effective energy absorption with a significantly reduced rocker section compared to conventional bulky steel rocker designs. This geometric efficiency allows the sill to function as a primary lateral load path, limiting intrusion into the occupant compartment and preventing deformation of the high-voltage battery enclosure, which is essential for maintaining electrical isolation and avoiding electrolyte spillage in accordance with FMVSS 305 isolation resistance and leakage criteria. By controlling deformation and load transfer, the extruded sill reduces the risk of damage to battery mounting interfaces and high-voltage components, thereby mitigating post-impact electrical hazards such as isolation loss, short circuits, and thermal runaway initiation [14]. In addition to its crash performance benefits, the ability to achieve required structural capability with a slimmer rocker section improves everyday occupant ingress and egress by reducing step-over height and sill width, an important ergonomic advantage in flat-floor BEV architectures, while ensuring predictable structural behavior during accident mitigation.

V. RESEARCH GAPS AND LIMITATIONS

Despite methodological advances, several critical gaps limit the translation of research findings to production applications:

Lack of standardized metrics: Many studies report qualitative improvements (e.g., "foam-filled outperforms empty") or relative comparisons without publishing absolute SEA values, peak forces, or intrusion distances under standardized test conditions [1], [10], [3]. This absence of quantitative benchmarks hinders cross-study comparisons and validation of simulation models.

Limited experimental validation: Optimization and machine learning studies [8], [9] demonstrate computational efficiency but provide limited experimental validation at the component or subsystem level. Full-vehicle pole tests with instrumented sill structures are notably absent from the reviewed literature.

Manufacturing constraints not integrated: Extrusion tooling imposes constraints on minimum wall thickness, corner radii, and web connectivity that are rarely incorporated into optimization frameworks [4]. Similarly, joining methods (adhesive bonding, self-piercing rivets, laser welding) and their influence on crash performance are under-explored.

Multi-load scenario assessment: Most studies focus on a single impact configuration (e.g., perpendicular pole impact at vehicle centerline). Real-world crashes involve oblique angles, varying impact heights, and combined loading modes that may alter the effectiveness of optimized designs [6].

Material variability and aging: The influence of manufacturing variability (e.g., extrusion die wear, heat treatment uniformity) and in-service aging (e.g., corrosion, fatigue) on crash performance is not addressed in the reviewed studies.

A. Comparative Performance Analysis

Table II synthesizes reported performance characteristics across studies where quantitative or semi-quantitative data were available. Akar et al. [11] provide the most detailed comparative data, showing Al6061-T6 hexagonal beams achieve higher SEA than both Al6061-T6 circular and A36 steel beams. Djamaluddin [12] confirms that foam-filled AA6063-T6 double tubes absorb more energy than empty tubes, with validated FEA models showing good agreement with experiments.

TABLE II

COMPARATIVE PERFORMANCE CHARACTERISTICS

Study	Performance Insight
Akar et al. [11]	Al6061-T6 higher SEA, lower reaction force vs. A36 steel; hexagonal > circular
Djamaluddin [12]	Foam-filled AA6063-T6 tubes absorb more energy than empty; FEA validated
Hamran [6]	Multi-cell profile maintains forces below threshold in 5 mph side-pole test
Béland & Parson [3]	Al-Mg-Si extrusions suitable for lateral crush in side rails/sills
Xia et al. [1]	Al extrusion box effective for EV battery protection (qualitative)

The literature consistently supports multi-cell and foam-filled aluminium extrusions as effective strategies for side-pole crashworthiness. However, the absence of standardized test protocols and published absolute metrics prevents definitive ranking of design approaches or establishment of performance targets for new designs.

VI. RECOMMENDATIONS

Based on the identified research gaps and industrial needs, the following recommendations are proposed:

A. For Researchers

Standardize reporting: Adopt consistent metrics (SEA in kJ/kg, peak force in kN, intrusion in mm) and reference test conditions (pole diameter, impact velocity, vehicle mass) to enable cross-study comparisons and meta-analyses.

Prioritize experimental validation: Complement simulation and optimization studies with component-level crush tests and subsystem pole impact tests using instrumented sill assemblies. Publish force-displacement curves and failure mode photographs.

Integrate manufacturing constraints: Collaborate with extrusion manufacturers to incorporate tooling limitations (minimum wall thickness 1.5-2.0 mm, maximum web aspect ratio 10:1, corner radii ≥1.5 mm) into optimization problem formulations.

Assess multi-load robustness: Evaluate optimized designs across oblique impact angles (±30°), varying impact heights (sill centerline ±100 mm), and combined loading modes to ensure robust performance.

B. For Industry Practitioners

Adopt foam-filled multi-cell extrusions for BEVs: Implement foam-filled or multi-cell extruded sill designs using AA6063-T6 or AA6061-T6 to increase absorbed energy and limit intrusion to battery enclosures [12], [1], [4].

Employ topology and gauge optimization: Use two-stage optimization workflows (topology followed by gauge optimization) for extruded battery side rails to balance manufacturability and crashworthiness [4].

Benchmark against high-strength steel: Conduct component and subsystem pole tests comparing aluminium extrusion options against high-strength steel and hybrid inserts to quantify SEA, peak force, and intrusion under regulatory conditions [11], [3].

Explore localized energy absorbers: Investigate adhesive-bonded or mechanically fastened inserts that provide tunable local crush behavior and facilitate repair or replacement after minor damage [5].

Validate with physical testing: Require physical validation of simulation-optimized designs before production commitment, particularly for novel multi-cell geometries or foam-filled configurations where model fidelity may be uncertain [8], [9].

C. For Standards Bodies

Develop BEV-specific test protocols: Establish side-pole impact test procedures tailored to battery electric vehicles, including intrusion limits relative to battery enclosure and assessment of battery pack integrity post-impact.

Publish performance benchmarks: Create publicly available databases of crashworthiness metrics for common extrusion profiles and materials to guide design decisions and enable performance comparisons.

VII. CONCLUSION

This review synthesizes current knowledge on aluminium sill extrusions for side-pole crashworthiness, analyzing ten key studies spanning experimental characterization, computational optimization, and novel design concepts. Aluminium 6xxx series alloys, particularly AA6061-T6 and AA6063-T6, demonstrate superior specific energy absorption compared to steel alternatives while enabling significant mass reduction. Multi-cell cross-sections and foam-filled configurations enhance energy absorption by 25-60% compared to simple single-cell profiles.

Advanced optimization methods, including multi-fidelity surrogate modeling and machine learning-driven design exploration, have accelerated the development of crashworthy sill geometries. However, critical research gaps persist: standardized crashworthiness metrics are rarely reported, experimental validation at the subsystem and vehicle level remains limited, and manufacturing constraints are insufficiently integrated into optimization frameworks.

For battery electric vehicles, aluminium sill extrusions play a dual role: protecting occupants and preventing battery intrusion. Localized energy-absorbing boxes and topology-optimized side rails represent promising approaches, though full-vehicle validation is needed to confirm their effectiveness across diverse crash scenarios.

The field would benefit from: (1) establishment of standardized reporting protocols for SEA, peak force, and intrusion metrics; (2) coordinated experimental programs validating optimized designs at component, subsystem, and vehicle scales; (3) integration of manufacturing constraints and joining methods into optimization workflows; and (4) assessment of design robustness across multi-load scenarios and material variability.

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