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Review Paper

Crashworthiness of Thin-Walled Structures: Influence of Materials, Geometry, Manufacturing Processes and Loading Conditions

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Abstract

Crashworthiness is a critical requirement for lightweight structures in automotive, electric vehicle and aerospace applications, where efficient energy absorption and controlled force transmission are essential. This review looks at more than 100 experimental, numerical, and analytical studies published between 2013 and 2025. It focuses on how materials, geometry, manufacturing processes, and loading conditions work together to affect the crashworthiness of thin-walled structures. Using a PRISMA inspired systematic narrative review combined with bibliometric and thematic analyses, key performance metrics: peak crushing force (PCF), mean crushing force (MCF), energy absorption (EA), specific energy absorption (SEA) and crushing force efficiency (CFE) are evaluated across metals, polymers, composites and hybrid systems, as well as non-tapered, tapered geometries under quasi-static and dynamic loading. The reviewed studies show that crashworthiness is best improved through a good combination of material, geometry, manufacturing quality and loading conditions. Hybrid structures are particularly promising, but their performance depends heavily on the interface quality, shape, and testing conditions.

Keywords: Crashworthiness; Thin-walled structure; Specific energy absorption; Structural optimization; Additive manufacturing

1. Introduction

Crashworthiness is a critical aspect in the design of modern engineering structures, particularly in transportation systems such as automotive vehicles, electric vehicles, aerospace structures and unmanned aerial vehicles (UAVs). It refers to the ability of a structure to absorb impact energy efficiently while controlling peak loads and deformation modes in order to minimize damage to occupants, payloads, or critical components. As demands for lightweight, energy efficient and high performance structures continue to increase, the development of effective energy absorbing systems has become a central research focus in structural engineering [1], [2].

Thin-walled structures, including thin-walled tubes, crash boxes and honeycombs, have been widely investigated as primary energy absorbers due to their high specific energy absorption (SEA) and relatively stable progressive collapse behavior. Early research focused on conventional metal geometries, such as circular and polygonal tubes, which displayed stable folding mechanisms when subjected to axial loads [3], [4], [5]. However, these configurations are often constrained by mass penalties and limited design flexibility.

To improve crashworthiness performance, recent research has increasingly explored advanced geometric concepts such as multi-cell, tapered, graded and hierarchical structures as well as lightweight materials, including fiber reinforced composites, polymers and metal–composite hybrid systems [6], [7], [8], [9], [10], [11]. In parallel, bio-inspired design concepts, copying from natural systems such as bamboo, lotus stems and DNA-like architectures, have demonstrated enhanced deformation stability and energy absorption efficiency through hierarchical folding mechanisms and more effective load redistribution [4], [7], [9], [12], [13]. The total effects of geometric parameters, including cell number, wall thickness and internal architecture, have also been shown to strongly influence key crashworthiness metrics, such as peak force, SEA, mean crushing force (MCF) and crushing force efficiency (CFE) [10], [14].

Advances in additive manufacturing have further expanded the design option for crashworthy structures by enabling the fabrication of complex geometries that are difficult to achieve using conventional manufacturing techniques. 3D printed polymer structures based on PLA, ABS and composite materials have demonstrated competitive SEA to density ratios compared to conventional metals, although challenges related to material anisotropy and performance consistency remain [5], [15].

Despite the swift growth of literature on thin-walled crashworthy structures, most existing studies continue to place emphasis on axial quasi-static loading, which does not fully represent realistic crash scenarios involving dynamic effects and oblique impact conditions [3], [7]. Moreover, systematic investigations that compare the coupled influence of material and geometry on key crashworthiness parameters remain relatively limited [6], [16].

Therefore, this review aims to provide a comprehensive and critical synthesis of the impact resistance performance of thin-walled structures by examining the combined effects of materials, geometries, and manufacturing processes under various loading conditions. More than one hundred experimental, numerical and analytical studies are analyzed to identify dominant research trends, existing gaps and future directions toward the development of lightweight, high performance energy absorbing structures for automotive, aerospace and UAV protection applications.

Besides summarizing previous studies, this review presents a simple framework for designing crashworthy thin-walled structures. This links five interconnected dimensions: material selection, geometry, manufacturing processes, loading conditions, and performance evaluation. Their effects are assessed using essential indicators such as PCF, MCF, EA, SEA, CFE, force–displacement stability, and deformation mode. As shown in **Table 1**, this framework describes how these factors interrelate with each other in energy absorption, force control, progressive failure, and deformation stability in various engineering applications.

Table 1. Proposed design framework for crashworthy thin-walled structures

Design domain	Main influence	Design guideline
Material selection	Controls density, ductility, strength, strain-rate sensitivity, SEA, MCF, and failure behavior.	Identify materials that offer an optimal balance of low weight, adequate ductility, high energy absorption, and stable crushing behavior.
Geometrical configuration	Determines folding mode, plastic hinge formation, deformation path, PCF, EA, SEA, and CFE.	To facilitate progressive folding and prevent global buckling, features such as tailored cross-sections, multi-cell configurations, tapering, functionally graded thickness, or biomimetic structures should be utilized.
Manufacturing process	Affects anisotropy, porosity, dimensional accuracy, interlayer bonding, interface quality, and repeatability.	Manufacturing should be treated as a design variable, since process-induced defects can substantially compromise crashworthiness performance.
Loading condition	Influences collapse mode, strain-rate response, force fluctuation, and deformation stability.	Evaluate structural integrity under realistic axial, lateral, oblique, quasi-static, and dynamic loading scenarios.
Performance evaluation	Integrates PCF, MCF, EA, SEA, CFE, force–displacement stability, and deformation mode.	Rather than relying on a single-metric assessment, priority should be given to maximizing EA and SEA, while simultaneously maintaining a controlled PCF, high CFE, and a stable progressive collapse behavior.

2. Methods

The review adopted a hybrid approach that combines a PRISMA-based systematic narrative review with bibliometric analysis and thematic synthesis. This approach allows for transparent literature selection while also accommodating the diversity of literature found in impact resistance studies, particularly in terms of materials, geometries, manufacturing methods, and loading conditions.

Suitable articles were collected from Scopus, ScienceDirect, SpringerLink, Taylor & Francis Online, and MDPI and were evaluated based on DOI availability, methodological clarity and quantitative crashworthiness data. Since the reviewed studies varied in material system, geometry, dimensions, loading rate, boundary conditions and reported parameters, a direct statistical meta-analysis was not performed. Instead, a quantitative meta-synthesis was applied by comparing SEA, EA, PCF, MCF, CFE, percentage improvements, SEA–density trends and deformation modes to identify performance trends without producing misleading direct rankings across different study conditions.

2.1. *Literature Search and Selection Strategy*

A systematic literature search was conducted using structured Boolean search strings based on combinations of keywords related to crashworthiness, energy absorption, thin-walled structures, materials, geometry, manufacturing processes, and loading conditions. The main search strings included: ("crashworthiness" AND "thin-walled structure"), ("energy absorption" AND "thin-walled tube"), ("specific energy absorption" AND "crash box"), ("mean crushing force" AND "thin-walled structure"), ("bio-inspired" AND "crashworthiness"), ("3D print*" OR "additive manufacturing" AND "crashworthiness"), ("PLA" OR "polymer" AND "thin-walled crashworthiness"), ("composite" OR "hybrid" AND "crashworthiness"), ("tapered tube" AND "energy absorption"), and ("dynamic impact" OR "quasi-static compression" AND "thin-walled tube"). These search strings were applied to Scopus, ScienceDirect, SpringerLink, Taylor & Francis Online, and MDPI, with minor adjustments according to the search syntax of each database.

The selection process of the literature is illustrated through a PRISMA flow diagram in Figure 1. 162 initial data points were identified, 20 of which were removed using database filters because they were non-final publications (n = 4), non-journal sources (n = 15), or non-article documents (n = 1). The titles and abstracts of the remaining 142 records were screened, resulting in the exclusion of 30 studies that were outside the review scope, unrelated to thin-walled crashworthiness, lacked sufficient quantitative data, or had unclear methodologies. The final data collected was 112 studies which were used for thematic synthesis and bibliometric mapping. 9 classical theoretical references were also retained to support the theoretical framework but were excluded from the VOSviewer analysis.

2.2. *Inclusion and Exclusion Criteria*

The inclusion criteria covered experimental, numerical and/or analytical studies that explicitly investigated the crashworthiness of thin-walled structures and reported at least one quantitative performance parameter, namely specific energy absorption, mean crushing force, peak crushing force or crushing force efficiency. In addition, the selected studies were required to specify the material, provide geometric descriptions of the specimens and loading condition. A study is included if it provides sufficient quantitative or visual evidence to support crashworthiness interpretation, including force–displacement response, deformation mode, energy absorption behavior, or numerical validation.

Articles were excluded when they were not directly related to thin-walled crashworthy structures, did not report quantitative crashworthiness parameters, lacked clear material or geometrical information, had unclear methodology, or did not provide sufficient evidence for deformation or energy absorption behavior. Review papers without primary data, microscale studies not representative of macroscopic structural crashworthiness, non-final publications, non-journal sources, and non-article documents were also excluded from the main quantitative synthesis.

2.3. *Article Quality Assessment*

An article quality assessment was conducted before final inclusion using engineering-based cri-

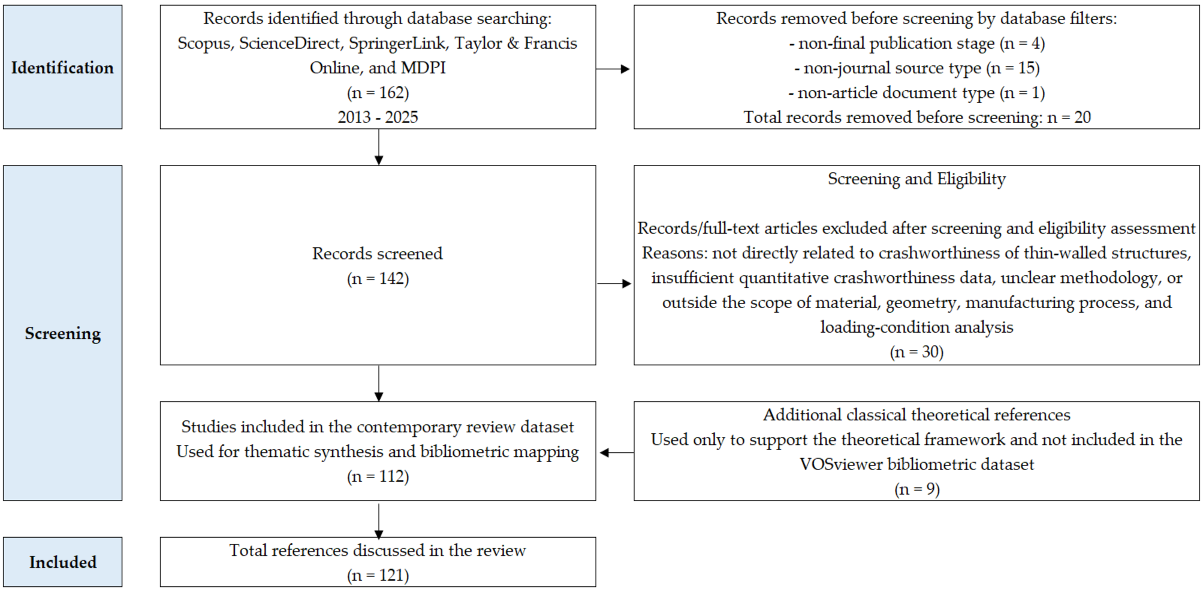

Figure 1. Prisma diagram

teria adapted for experimental, numerical, and analytical crashworthiness studies. Each article was evaluated based on five criteria: clarity of material properties, specimen geometry and dimensions, loading and boundary conditions, availability of quantitative crashworthiness parameters and method reproducibility. Each criterion was rated on a scale of 0–2, resulting in a maximum score of 10. Studies scoring 7–10 were included in the main synthesis, while those scoring 5–6 were used only to support the discussion. Studies scoring below 5 were excluded from the quantitative comparison. This assessment helped ensure that the comparison was based on studies with sufficiently clear methods and reliable crashworthiness data.

2.4. *Analysis and Bibliometric Mapping*

The selected literature was analyzed using qualitatively and quantitatively synthesis approach. The qualitative analysis was conducted by classifying the reviewed studies according to material system, geometrical configuration, manufacturing route, and loading condition. Based on the type of material, these studies are grouped into metals, polymers, composites, and hybrid structures. Based on geometry, the structures were further classified into non-tapered, tapered, multi-cell, hierarchical, bio-inspired, and additively manufactured configurations. This classification was used to identify recurring deformation mechanisms, collapse stability trends, and performance trade-offs in terms of PCF, MCF, EA, SEA, CFE, and deformation mode.

Bibliometric analysis was carried out using VOSviewer to identify the main research topics and how they changed over time. Research Information Systems (ris) dataset includes 112 selected articles published between 2013 and 2025. Keyword co-occurrence was analyzed using the full counting method, with keyword occurrence used as the weighting criterion. After keyword normalization, 309 unique keywords were identified and a minimum occurrence threshold of three resulted in 25 keywords in the final network. The network consisted of six clusters, 96 links, and a total link strength of 104.50, as summarized in Table 2. Classical theoretical references published before the main review period were excluded from the VOSviewer mapping but retained to support the theoretical framework on progressive folding, mean crushing force prediction, structural impact, and strain-rate correction.

Figure 2 to Figure 4 present the same keyword co-occurrence dataset using network, overlay, and density visualizations. The network map shows that "crashworthiness" is the central theme, closely linked to keywords such as "bio-inspired," "additive manufacturing," "thin-walled structure," "optimization," "quasi-static," and "numerical simulation." The map depicts the development of research topics from period to period. Earlier studies mainly focused on conventional thin-walled structures, axial impact, and numerical simulation, while recent studies focus more on bio-inspired design, hierarchical structures, additive manufacturing, 3D printing, and polymer structures. The density map also shows that crashworthiness, bio-inspired structures, additive manufacturing, numerical simulation, and optimization are topics that are being widely researched. These findings reinforce the primary themes of this review, facilitating the identification of contemporary research trends and existing literature gaps.

3. Factors Influencing Crashworthiness Performance

Crashworthiness isn't just measured by how much energy a structure can absorb. Equally

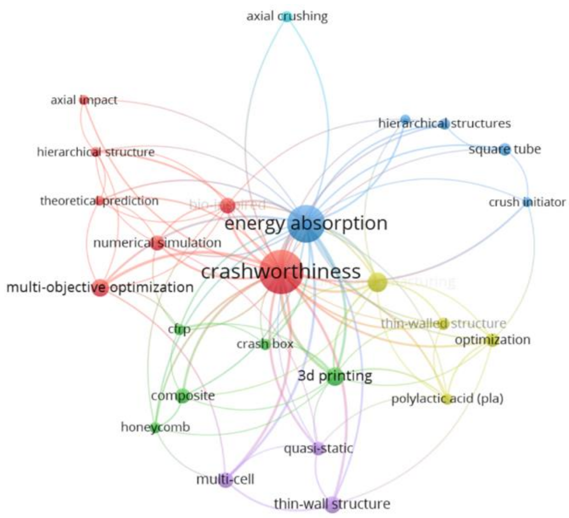

Figure 2. Keyword network visualizations

Table 2. Quantitative summary of the VOSviewer bibliometric analysis

Parameter	Description / result
Bibliometric software	VOSviewer version 1.6.19
Dataset format	RIS bibliographic dataset
Total documents included	112
Publication year range	2013–2025
Type of analysis	Keyword co-occurrence analysis
Unit of analysis	Keywords
Counting method	Full counting
Weight used in visualization	Occurrences
Minimum keyword occurrence threshold	3
Total unique keywords before thresholding	309
Keywords included after thresholding	25
Number of clusters	6
Number of links	96
Total link strength	104.50
Visualization modes	Network, overlay, and density visualization

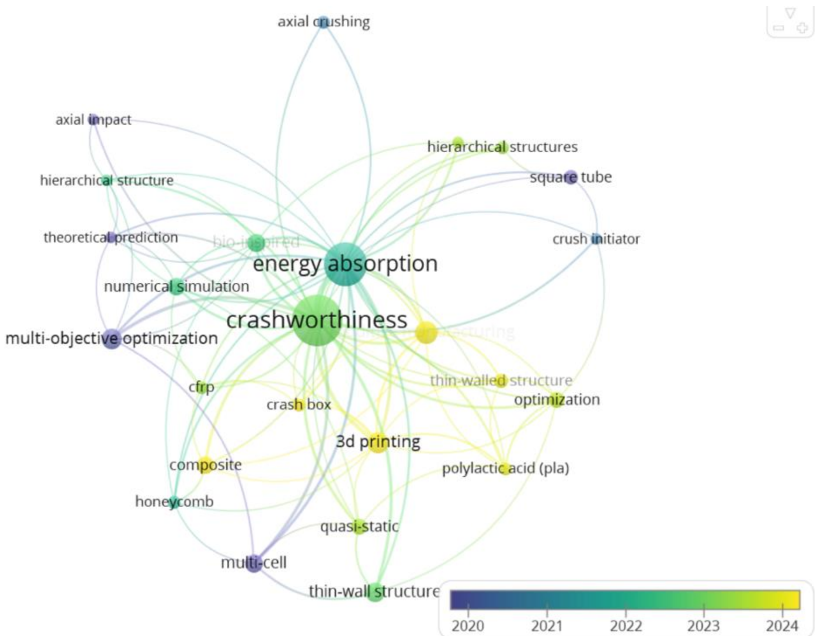

Figure 3. Co-occurrence overlay visualizations

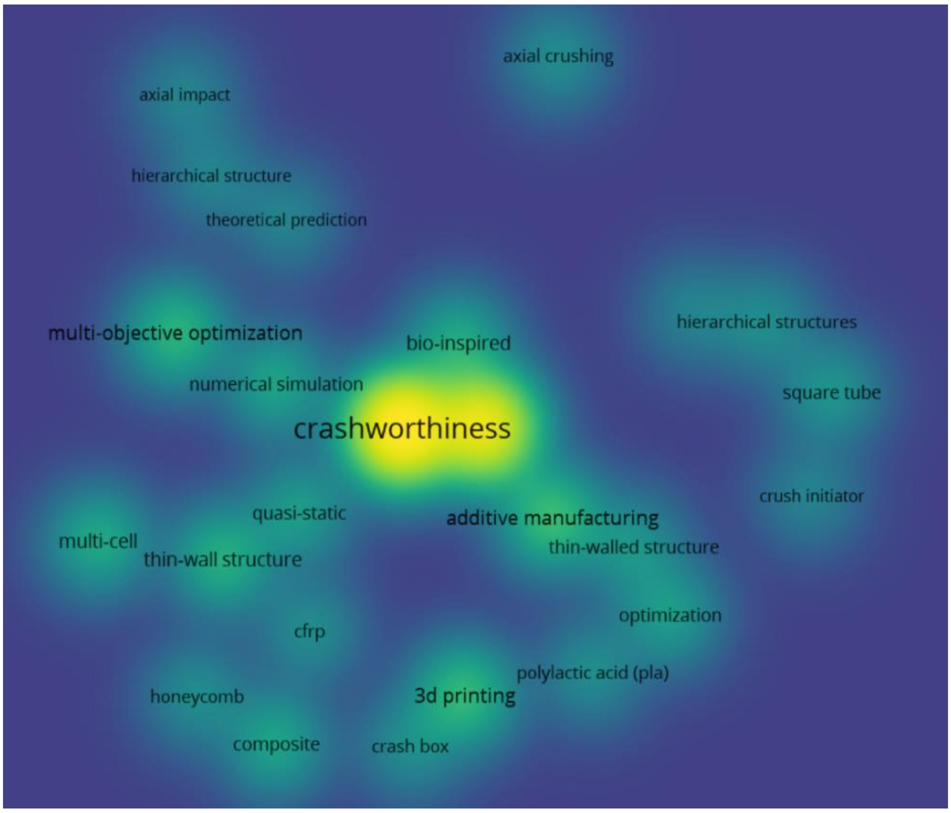

Figure 4. The density map

important is the stability of the deformation process and the ability to control the force level during an impact. For this reason, quantification criteria such as Peak Crushing Force (PCF), Mean Crushing Force (MCF), Specific Energy Absorption (SEA) and Crushing Force Efficiency (CFE) underpin the comprehension of how design changes dictate structural response. Experimental, numerical and analytical studies consistently show that energy absorption performance emerges from the interaction between material behavior, structural geometry, loading conditions and manufacturing quality. Accordingly, this section focuses on the most influential factors: crashworthiness parameters as evaluation metrics, illustrated as in **Figure 5**.

Although materials, geometry, manufacturing, and test conditions are discussed separately, they are closely connected. Material properties influence fold stability and failure modes, while geometry determines load distribution and fold formation. Mistakes in factory making can cause problems. For example, it can make defects, wrong material direction, bad wall thickness and bonding issues. Loading conditions also affect whether the structure shows stable folding, global bending, or early fracture. Therefore, each factor

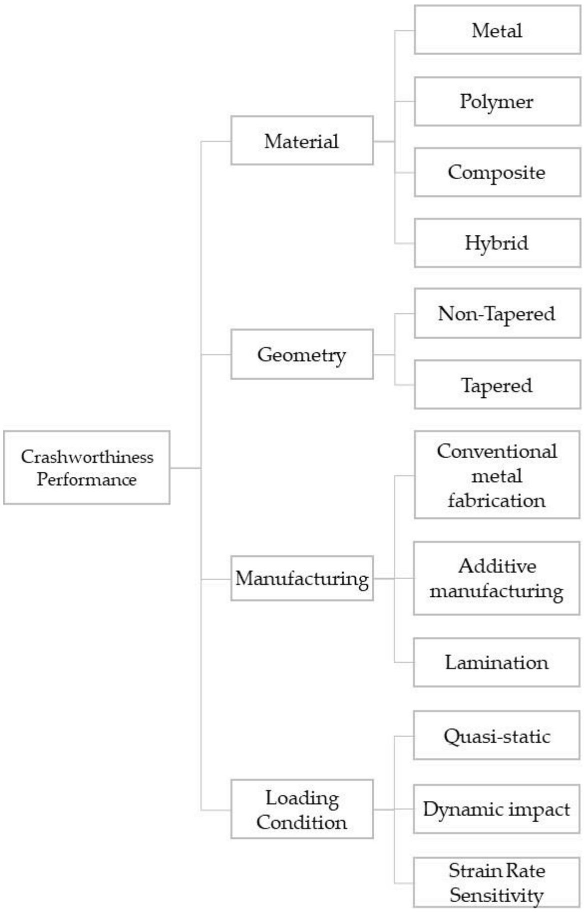

Figure 5. Factor influencing crashworthiness performance

can only be studied separately under controlled conditions. Otherwise, crashworthiness should be considered as the combined effect of all factors on PCF, MCF, EA, SEA, CFE, and deformation stability.

3.1. Crashworthiness Parameters

The evaluation of structural crashworthiness typically relies on four primary metrics: PCF, SEA, MCF, and CFE (**Figure 6**). All these things are connected, meaning there is often a trade-off between them. Designs that increase SEA and MCF can also result in higher PCF values if the initial folding process is not properly controlled. Therefore, the primary objective of crashworthiness is not only to maximize energy absorption, but also to keep the PCF within acceptable limits and maintain stability.

Although this review only covers studies published from 2013 to 2025, modern crashworthiness analysis is still based on classical impact theories. Fundamental concepts of progressive folding, plastic hinge formation, folding wavelength, mean crushing force, and energy dissipation were established through model developed by Alexander, Abramowicz–Wierzbicki, Jones, and others. These concepts explain why stable progressive collapse is preferred over global bending or catastrophic failure.

Modern crashworthiness designs still follow classical folding principles. Triggers control where folding starts, while advanced geometries distribute the load and improve stability. These geometries can be fabricated via additive manufacturing, while composite or hybrid materials offer expanded design options for energy absorption. However, classical models were mainly developed for metal tubes under axial loading, so their use for modern structures is limited. Therefore, future analytical models should extend classical folding theory by incorporating material-specific behavior, manufacturing imperfections, complex geometry, and loading-direction effects, as summarized in **Table 3**.

3.1.1. Peak Crushing Force (PCF)

Peak Crushing Force (PCF) is the highest load that happens when plastic deformation starts during crushing. It is the most crucial variable in terms of person injury or payload damage. excessive PCF results in unwanted deceleration spikes, therefore minimizing it is the most important thing in crashworthy designs. In the literature, local stiffness, folding initiation, and geometric gradients have a big effect on PCF. Crush initiators, wall thickness reduction, tapering, and internal filling are effective strategies for reducing PCF by promoting earlier and smoother progressive folding, as shown by reported reductions in peak impact force of about 23.69% using crush initiators, 56.75% through wall thickness reduction from 1.0 mm to 0.6 mm, and approximately 16% in tapered-grooved square tubes, while also improving energy absorption by up to 11.83%. Several studies indicate that triggers, geometry gradients, and internal filling can reduce PCF by promoting smoother folding initiation [17], [18], [19].

3.1.2. Energy Absorption (EA)

Energy Absorption (EA), equation (1) represents the total energy dissipated during crushing and corresponds to the area under the force–displacement curve over a defined stroke, expressed as:

$$EA = \int_0^{\delta} F(x)dx \qquad (1)$$

where, F(x): crushing force as a function of displacement; δ: crushing stroke.

In both experimental and numerical studies, EA is mainly controlled by the chosen crushing stroke and the stability of the deformation mode. Stable progressive folding creates a force plateau that stays pretty much the same, which makes it

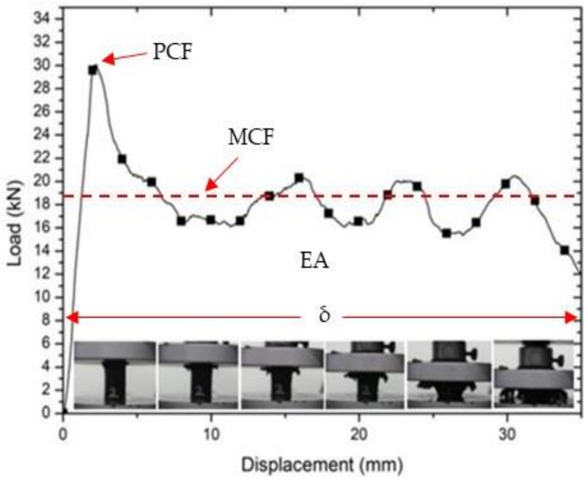

Figure 6. Load – displacement [20]

Table 3. Connection between classical collapse theory and modern crashworthy thin-walled designs

Classical theory or concept	Main theoretical contribution	Connection to modern thin-walled designs	Ref
Alexander collapse model (1960)	Early analytical model for concertina crushing and MCF prediction of circular tubes.	Foundation for circular, elliptical, and near-circular crash absorbers, although later studies show that correction is needed for improved accuracy.	[21]
Abramowicz–Jones models (1984)	Kinematics-based MCF prediction for circular and square tubes under axial crushing.	Provides a reliable basis for conventional metallic crash boxes and validation of numerical models.	[22]
Jones structural impact theory (1989)	Establishes energy balance, plastic work, and dynamic progressive buckling concepts for impact-loaded structures.	Provides the theoretical basis for interpreting EA, SEA, PCF, MCF, CFE, and the difference between quasi-static and dynamic crashworthiness.	[23]
Wierzbicki super-folding theory (1992)	Describes progressive crushing through folding elements and plastic hinge formation.	Supports modern multi-cell, polygonal, origami, hierarchical, and bio-inspired designs that guide or increase controlled folding mechanisms.	[24]
Singace eccentricity correction (1995)	Refines MCF prediction by modifying the eccentricity factor in progressive folding models.	Useful for improving analytical prediction in circular, elliptical, and modified tubular geometries.	[25]
Zhang and Zhang angle-element model (2013)	Represents polygonal crushing using local angle elements and inextensional mechanisms.	Relevant for polygonal, honeycomb, kagome, and multi-corner structures where local angle elements control collapse.	[26]
Tabacu polygonal/ star-shaped model (2019)	Estimates MCF for polygonal and star-shaped sections using bending and membrane energy.	Connects classical energy-based theory to non-conventional cross-sections and architected thin-walled structures.	[27]
Cowper–Symonds strain-rate correction (1957)	Converts quasi-static crushing response into dynamic prediction through strain-rate-dependent flow stress.	Bridges analytical MCF prediction with dynamic impact simulations and crash tests.	[28]
Generalized MCF model (2024)	Combines geometry, number of corners, wall thickness, flow stress, and crushing mode into a simplified equation.	Enables rapid preliminary comparison of circular, square, hexagonal, and octagonal tubes before detailed FE simulation.	[2]
Limitations of classical collapse theories (2024)	Classical models were mainly developed for metallic tubes, simple cross-sections, and axial loading.	Modern designs require extensions for AM defects, anisotropy, composites, hybrids, delamination, oblique loading, and dynamic effects.	[29]

easy to keep energy. On the other hand, global bending, asymmetric buckling, or brittle fracture cause force fluctuations that make energy dissipation less effective. A lot of crashworthiness studies of thin-walled and advanced multi-cell or hierarchical energy absorbers use this definition and evaluation of EA, along with SEA and peak force related indices [30], [31], [32].

3.1.3. Specific Energy Absorption (SEA)

Specific Energy Absorption (SEA), Eq. (2) describes the amount of energy absorbed per unit mass (m).

$$SEA = \frac{EA}{m} \tag{2}$$

A high SEA indicates efficient energy dissipation with minimal mass penalty, which is an important factor in designing lightweight crashworthy products. The literature shows that wall thickness [18], material type, and folding stability are the main factors that affect SEA. Cross-sectional configuration also affects SEA, since a more uniform stress distribution and stable progressive folding lead to more efficient energy absorption [33], [34].

However, SEA values should be interpreted carefully when they are collected from different studies. Although SEA normalizes energy absorption by mass, it does not normalize differences in specimen geometry, crushing stroke, loading rate, boundary condition, material processing, and deformation mode. Therefore, SEA should not be used as a single absolute ranking parameter across unrelated studies, but rather as a comparative indicator when supported by PCF, MCF, CFE, test condition, and deformation behavior.

3.1.4. Mean Crushing Force (MCF)

Mean Crushing Force (MCF), Eq. (3) is defined as the average force developed during progressive plastic crushing. It reflects the stability of the load response over the crushing stroke (δ). Higher thickness-to-diameter ratios and a larger number of folding waves are usually associated with higher MCF values. Simple plastic folding energy models, such as those proposed by Alexander and Abramowicz–Wierzbicki, are able to predict MCF with good accuracy and in close agreement with experimental results [35]. Therefore, MCF is an important indicator in the energy absorption process, especially in impact-resistant structures, where maintaining a relatively constant force level during the compression process is desired.

$$MCF = \frac{EA}{\delta} \tag{3}$$

3.1.5. Crushing Force Efficiency (CFE)

Crushing Force Efficiency (CFE), equation (4) is defined as the ratio between mean crushing force (MCF) and peak crushing force (PCF). This ratio gives a simple indication of how stable the crushing response is. A large CFE indicates that the structure experiences a more progressive collapse and a flatter force response, while a small CFE indicates a large initial force surge. The tapered design of the bio-inspired DNA tube has been shown to increase CFE stability by up to 0.7-0.8, compared to conventional forms [12], [36]. This is why CFE is often used to check whether energy absorption comes with a controlled force level.

$$CFE \frac{MCF}{PCF} \tag{4}$$

3.1.6. Normalizing and reporting and cross-study comparison limitations

There are several various phrases used in the literature about crashworthiness. Like peak crushing force, in some literature there are mentions of 'peak force', 'peak crushing force' and 'maximum force'. Apart from that, some units of mass use grams or kilograms. This diversity of terms and units must be standardized to make it easier to analyze and compare crashworthiness performance between literatures. For consistency of terms, PCF, EA, SEA, MCF and CFE are used, while for units, kJ and Kg are used. Comparing different studies requires more than using the same units. Differences in specimen size, mass, crushing distance, wall thickness, loading rate, and boundary conditions must also be considered. Therefore, SEA values in this review are used to identify general trends, not to directly rank the studies.

3.1.7. Application-oriented interpretation of sea and crashworthiness parameters

Although SEA is commonly used to measure weight efficiency, it should not be used as a single standard value (**Table 4**). The required SEA depends on the application, crushing distance, allowable peak load, intrusion limit, impact direction, and protected system. Front crash boxes, side sills, roof rails, EV battery protection structures and UAV payload protection systems each require different balances between energy absorption, force control, structural integrity, and component survivability. This application-specific view is also consistent with safety regulations such as FMVSS 214 and ECE R94, which evaluate crash performance through occupant protection, force, deformation, acceleration, and structural response rather than prescribing a minimum SEA for individual components. Therefore, SEA in this review is interpreted as a design indicator that must be assessed together with PCF, MCF, CFE, deformation mode, crush stroke, and application-specific safety constraints.

3.2. Material Types

3.2.1. Metals

Metals are the most widely used materials in crashworthiness studies because they offer a practical balance of high strength, stable plastic deformation and efficient energy absorption. Carbon/mild steels [14], [18], [37], [38], stainless steels [39], [40], [41], [42] and aluminium alloy [7], [9], [11], [34], [36], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58] are therefore commonly employed in thin-walled

Table 4. Summarizes the application-oriented interpretation of crashworthiness parameters

Application	Main crashworthiness requirement	Dominant parameters	Interpretation of SEA
Front crash box	Absorb frontal impact energy and control deceleration pulse	EA, SEA, PCF, MCF, CFE	↑ SEA is important, but PCF must remain ↓ & the folding must be stable.
Side sill / side door beam	Limit lateral intrusion and protect occupants or battery pack	PCF, intrusion, MCF, CFE, deformation stability	Evaluating SEA independently is insufficient because the restricted crumple zone makes intrusion resistance and force management highly critical.
Roof rail / upper side structure	Maintain occupant compartment integrity and support side/roof load paths	Stiffness, intrusion resistance, force transmission	Moderate SEA can still be acceptable if the structure remains strong and transfers the load effectively.
EV battery protection	Prevent battery intrusion and reduce risk of cell damage or thermal runaway	Intrusion, PCF, EA, deformation mode	SEA must be harmonized with minimal intrusion and regulated force transmission to safeguard the battery enclosure.
Aerospace / UAV payload protection	Protect sensitive payloads with limited weight and crushing space.	SEA, PCF, acceleration limit, deformation stability	SEA target should be based on the payload, allowable acceleration, impact speed, and available crushing distance.

tubular structures for automotive and aerospace applications.

In general, performance improvements in the literature are largely driven by geometric and internal design strategies. Simple local features, such as elliptical crush initiators, can already reduce PCF by about 10% and increase CFE by roughly 14% in carbon-steel tubes [14]. Graded all thickness in segmented circular crash boxes hasbeen shown to raise SEA by around 22.5% compared with uniform tubes, with little mass penalty [57]. For polygonal multi-cell tubes, increasing the number of sides generally enhances energy absorption and folding stability, with certain configurations providing the most stable response [44]. Multi-cell hexagonal designs with triangular sub-cells likewise outperform single-cell hexagons in both MCF and SEA [37].

More recent studies extend metallic performance through biomimetic and metamaterial concepts. Asymmetric gradient hierarchical bi-hexagonal aluminum tubes achieved up to 1.82 times higher SEA and 1.47 times higher CFE than conventional designs [43], while tapered hierarchical aluminum structures reached SEA values of about 40.87 kJ/kg without significant mass increase [51]. Auxetic aluminum tubular metamaterials further improved SEA by approximately 30–40% [41] and antiprism patterns in additively manufactured stainless steel enhanced both SEA and CFE compared with standard tubes [42].

Metals are frequently used as baseline materials because many reviewed studies report stable plastic collapse, repeatable folding, and SEA improvements when combined with multi-cell hierarchical, or auxetic geometries. Most gains come from controlling fold initiation, using multi-cell or hierarchical layouts, introducing taper or adopting metamaterial architectures, although the achievable improvement remains closely tied to geometry, loading conditions and buckling control.

3.2.2. *Polymers*

FDM based thermoplastics such as PLA and its variants (PLA+, PLA-CF, PLA-GF) are attractive for crashworthy structures because of their low weight and design freedom, particularly for multi-cell and bio-inspired layouts. In FDM multi-cell tubes, both the number of sides and the way internal walls are connected matter: wall to wall configurations have been shown to absorb 19–80% more energy than corner to corner designs [5]. Infill strategy is equally influential. Square infill produced the highest SEA, about 26.52 kJ/kg, while a zig-zag pattern delivered the best crushing efficiency (CFE ≈ 0.91) under the same test conditions [15]. Targeted geometric tailoring can also lower force peaks without losing the ability to absorb energy. For example, optimized cut-outs decreased PCF by about 30.48% and increased absorbed energy by about 17.21% [59].

Biomimetic polymer designs have been reported to improve SEA and CFE compared with regular designs, although the magnitude of improvement depends on cell configuration, printing parameters, and loading condition. FDM multi-cell structures with DNA-like helical ribs improved SEA by up to 166.62% and CFE by up to 169.70% compared with regular single-tube designs [12]. Polymer response can also change with temperature and loading rate. Some studies have found that under certain conditions, the polymer goes from ductile folding to more brittle fracture [60]. FDM polymers offer good potential as lightweight, low-cost energy absorbers, although their performance is strongly influenced by internal structure, process parameters, and failure control.

3.2.3. *Composites*

Fiber-reinforced composite structures are well known for their high specific energy absorption, mainly because their damage processes—such as progressive crushing, controlled delamination, and fiber fracture—can be carefully tuned through lay-up and architectural design. According to Zhang *et al.* [61], CNTF/epoxy origami thin-walled tubes exhibited better crashworthiness than conventional square and circular tubes, particularly at 15–20 wt% epoxy content, with even the lowest-performing CNTF/EP tube showing more than five times higher SEA than pure CNTF tubes; after manual recovery and cyclic compression, the origami tubes also maintained improved PF, SEA, and MCF, indicating good potential for reuse after deformation. Similarly, Ciampaglia *et al.* [62] showed that CFRP origami crash boxes could absorb up to 7400 J while maintaining an average deceleration of 7.9 g and a peak deceleration of 32 g, with a 14% reduction in mass and a 21% improvement in mean deceleration compared with the previous aluminum honeycomb design. Through multi-objective optimization, Sun *et al.* [63] showed that hybrid 2D triaxially braided composite tubes increased SEA from 23.23 to 28.52 J/g, or about 22.9%, while reducing peak crushing force from 36.64 to 30.58 kN, or about 16.45%, by decreasing the total fiber volume fraction from 0.52 to 0.43 and the carbon-fiber fraction from 0.75 to 0.32, with an optimum braid angle of about 43.89°. Other studies further show that stacking sequence, trigger design and fiber configuration including natural fibers strongly influence whether deformation remains progressive or shifts toward brittle failure [64], [65], [66].

In short, composites offer an effective route to improved crashworthiness through careful control of lay-up, triggers, origami or architected geometries and fiber hybridization. However, their performance strongly depends on manufacturing quality because delamination and bonding differences can change the collapse behavior.

3.2.4. *Hybrids*

Hybrid structures show promising crashworthiness trends in several studies because they combine plastic deformation, progressive crushing, and interface-based energy dissipation. However, their performance is highly dependent on bonding quality, layer configuration, and failure mode. Zhu *et al.* [6] showed that aluminum–CFRP tubes can develop a coupled mechanism external inversion in the aluminum and progressive crushing in the CFRP that improves SEA while maintaining stable collapse. In foam-filled ellipse and double-ellipse tubes, Gao *et al.* [67], [68] reported high SEA and controlled PCF under oblique loading, where optimized FET increased SEAα by 26.7–45.1% while reducing PCF0 by 1.75–2.3%, and optimized F-DET achieved SEAα of 13.021 J/g at PCF0 of 79.589 kN, which was 11.77% higher than F-ET and 10.51% higher than F-DCT under the same 80 kN PCF constraint. Altın [69] found that augmenting the taper angle up to 10° in aluminum/E-glass FRP hybrid tubes enhanced both SEA and CFE, with circular sections showing the most stable response in their study. Recent manufacturing techniques indicate promising hybrid pathways: the integration of FDM with filament winding has yielded positive outcomes in PLA/GFRP tubes [70], and fiber–metal laminate (FML) configurations in C-channels have significantly surpassed monolithic CFRP in energy absorption [71].

Collectively, hybrid structures [72], [73], [74], [75] show promising crashworthiness trends because they combine several energy absorption mechanisms. Reported examples include aluminum/CFRP hybrid tubes with about 3.0 times higher specific energy and 2.5 times higher specific bending load capacity, CFRP/3D-printed cellular crash boxes with SEA up to 15 J/g, CFRP/steel fractal nested structures with 122.97% higher SEA and 25.53% higher CFE, and 3D-printed PLA–Al multi-cell hybrid tubes with EA of 504 J and SEA of 18.61 J/g. However, their performance is highly sensitive to interface bonding, strain-rate effects, fiber orientation, and layer configuration, while debonding, delamination, and dynamic collapse may reduce SEA and CFE. In addition, manufacturing complexity, joining quality, repairability, recyclability, cost, and scalability remain practical challenges. Therefore, hybrid structures should be viewed as promising candidates only when their mechanical benefits can be balanced with practical implementation requirements.

Although hybrid structures can achieve high SEA, their performance should be interpreted cautiously because energy absorption depends strongly on the interaction and bonding stability between constituent materials. In metal-composite hybrids, the metal layer absorbs energy through folding, inversion, or buckling. The composite layer absorbs energy through matrix cracking, fiber breakage, delamination, layer bending, brittle fracture, and friction. These mechanisms are consistent with composite crushing behavior described by Farley and Jones [76] and Bisagni *et al*. [77], who emphasized that absorbed energy must be evaluated together with failure mode and crushing morphology. However, early separation at the interface can disturb load transfer, reduce the composite contribution, and change stable crushing into unstable local failure. This issue becomes more critical under dynamic loading, oblique impact, thermal variation, moisture exposure, or service degradation, where strain-rate sensitivity, thermal mismatch, adhesive softening, voids, and manufacturing defects may accelerate delamination or debonding. Therefore, hybrid crashworthiness should be assessed not only using SEA, PCF, MCF, and CFE, but also through interface integrity, failure mode, post-crushing damage morphology, and environmental durability. Hybrid structures should therefore be regarded as promising but interface-sensitive energy absorbers rather than universally superior solutions.

3.2.5. Material performance synthesis based on sea and density

The literature does not indicate a single dominant material trend for crashworthy thin-walled structures. Metals provide stable plastic folding and good repeatability but are limited by higher density, while polymers offer low density and manufacturing flexibility but are sensitive to printing parameters, anisotropy, layer bonding and failure transition. Composites and hybrids can achieve higher SEA, although their performance may be affected by delamination, interface debonding, manufacturing defects and repeatability issues. Therefore, material performance should not be judged by SEA alone, but also by PCF, CFE, deformation mode, manufacturability, repairability, recyclability and loading condition.

Figure 7 summarizes the reported SEA distribution for different material classes in thin-walled crashworthy structures. Metals show a wide SEA range of about 10–80 kJ/kg due to stable plastic deformation and progressive folding, although their higher density may limit lightweight efficiency. Polymers generally show lower SEA, around 5–35 kJ/kg, but offer advantages in lightweight and flexible designs, especially when combined with multi-cell or bio-inspired geometries. Composites often exceed 40 kJ/kg because of progressive fiber fracture, matrix cracking, and delamination, while hybrid structures can combine multiple deformation mechanisms. The SEA values in **Figure 7** show general performance trends, not a direct material ranking. This is because each study used different geometries, sizes, wall thicknesses, crushing distances, loading rates, manufacturing methods, and boundary conditions. **Table 5** summarizes the SEA values and test conditions for a more careful comparison.

Composites and hybrids can provide high SEA, but their performance depends on layer design, bonding quality, defects, and manufacturing consistency. Metals usually have lower SEA but provide more stable and repeatable deformation. Polymers are lightweight and easy to form into complex shapes, but their behavior is affected by printing quality, loading rate, and

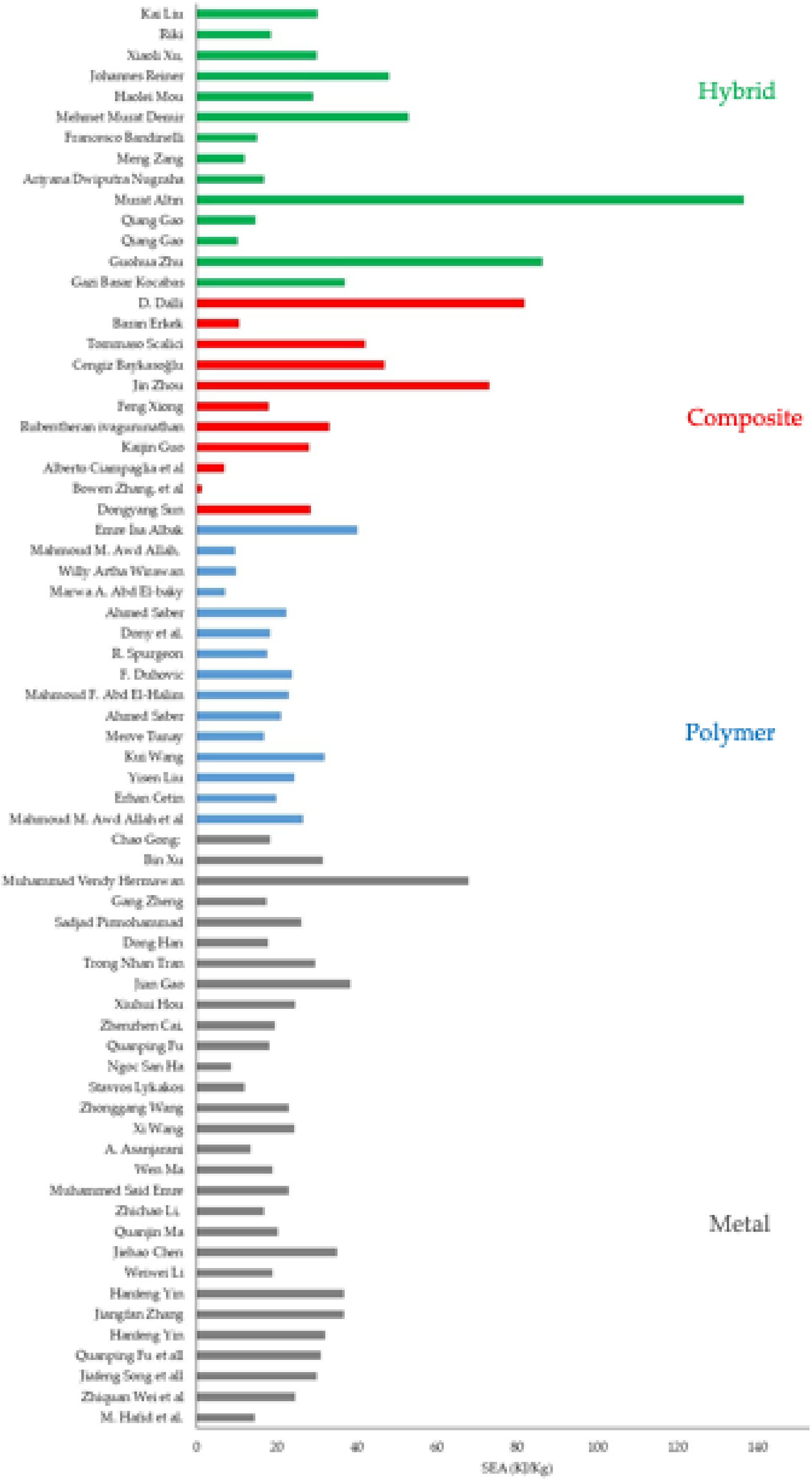

Figure 7. Literature-based SEA distribution by material type [The values are compiled from different studies and are intended for trend-level comparison rather than direct one-to-one ranking, due to differences in specimen geometry, dimensions, loading rate, crushing stroke, and testing conditions]

Table 5. Data extraction basis for the representative highest SEA value in **Figure 7**

Category	Material	Geometry	Loading Type	Loading rate	Test Method	SEA	PCF	CFE	Note
Hybrid Altın [69]	Steel / E-glass-PET199	Circular tapered hybrid tube, CSCA10, taper angle 10°, wall thickness 2 mm, length 200 mm	Axial impact	15 m/s; 750 kg impactor	Numerical FE, LS-DYNA	136.47 KJ/Kg	348.98 kN	0.70	Highest SEA and CFE among circular, square, and hexagonal hybrid tubes in the study
Composite Dalli *et al.* [78]	5HS woven CFRP composite	F1 Side Impact Structure, 8-ply crushing region, nominal thickness 2.4 mm, crushed mass 0.203 kg	Axial quasi-static crushing	25 mm/min	Experimental test	81.75 Kj/Kg	NR	NR	The same structure showed lower SEA under dynamic loading, 60.07 kJ/kg
Polymer / AM Albak [79]	FDM-printed PLA	Bamboo-inspired circular tube, GYROID_T20F30D18, wall thickness 2.0 mm, gyroid infill, 30% infill density, 18 mm inner diameter	Axial quasi-static compression	5 mm/min	Experimental test, UTM 200 kN	40.07 KJ/Kg	41.18 kN	NR	Average of two repetitions; original SEA reported in J/g
Metal Hermawan *et al.* [57]	Al 6063	Two-segment circular crash box, CDM-t2-t1 configuration, t1 = 1 mm	Axial impact	13 m/s	Numerical FE, Abaqus/ Explicit	67.93 Kj/Kg	205.88 kN	0.69	Selected as the best balanced metal configuration because it combines high SEA with lower PCF and higher CFE

temperature. Therefore, materials should be selected based on the application needs, not only on SEA.

Figure 8 shows general SEA and density trends from the reviewed studies. When density data were unavailable, nominal material values were used. Since the studies used different designs, manufacturing methods, and test conditions, the figure should not be treated as a direct material ranking. No material is always the best because each has different advantages and limitations. Composites and hybrids show a good SEA-density balance, but their cost, manufacturing complexity, interface quality, repair, recycling, and large-scale production must also be considered. Therefore, material selection should be based on integrated evaluation of material behavior, structural geometry, manufacturing quality, loading condition, and practical implementation requirements.

The SEA–density distribution in **Figure 8** groups the reviewed materials into metal, polymer, composite, and hybrid clusters. The dashed yellow region indicates an indicative optimal design zone, representing relatively high SEA with low-to-moderate density. This zone is intended as application-oriented design guidance rather than a universal regulatory threshold.

In addition, practical crashworthiness design should also consider production cost and manufacturing feasibility. Since most reviewed studies do not provide standardized cost data, a direct SEA-per-cost meta-analysis is not feasible. Therefore, this review provides a relative cost-effectiveness interpretation based on SEA level, material cost, manufacturing complexity, production scalability, and industrial feasibility, as summarized in **Table 6**.

This comparison shows that the most crashworthy structure is not always the most cost-effective solution. Hybrid, composite, and complex bio-inspired structures may offer high SEA, but their practical adoption depends on whether the performance gain can compensate for higher material cost, longer production time, more difficult inspection and lower mass-production feasibility. Conversely, metallic tubes with simple triggers, tapered profiles, or machined initiators may provide a more favorable

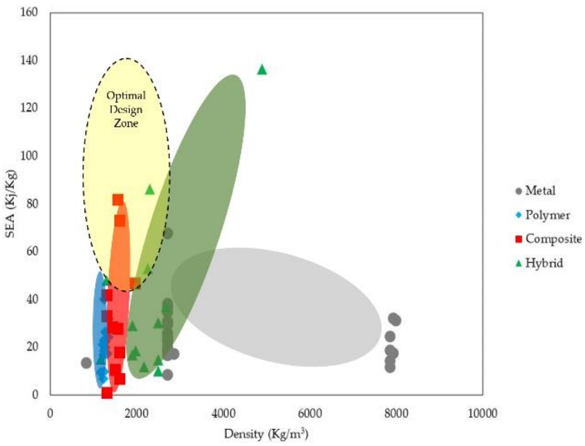

Figure 8. Diagram of material mapping based on SEA and density

Table 6. Relative cost-effectiveness interpretation of material and design classes

Material / design class	Typical SEA tendency	Manufacturing cost tendency	Mass-production feasibility	Relative cost-effectiveness interpretation
Conventional steel / aluminum tubes	Moderate to high	Low to moderate	High	High for mass production because of mature forming, welding, and machining processes
Metallic tubes with simple triggers, holes, or grooves	Moderate to high	Low incremental cost	High	Very practical because PCF can be reduced with limited additional manufacturing cost
FDM polymer thin-walled structures	Low to moderate	Low material cost but slow production	Low to moderate	Suitable for prototypes, lightweight components, and low-volume applications
Bio-inspired / multi-cell polymer AM structures	Moderate	Moderate to high	Low to moderate	Promising when geometric complexity provides clear SEA or CFE gains
CFRP / composite tubes	High	High	Moderate	Attractive for weight-critical applications, but limited by material cost, lay-up time, curing, and inspection
Metal–composite hybrid structures	High to very high	High to very high	Low to moderate	Mechanically promising but cost-effective only when SEA gain justifies bonding, inspection, and repair complexity
Metal AM lattice / auxetic / origami structures	Moderate to high	Very high	Low	Suitable for specialized or low-volume applications, but less attractive for automotive mass production
Simple tapered metallic structures	Moderate to high	Low to moderate	High	Cost-effective when tapering improves PCF, SEA, or CFE without complex tooling

balance between crashworthiness improvement and production feasibility for automotive mass-production applications.

3.3. Geometry

3.3.1. Non-Tapered

Non-tapered structures can be grouped into basic cross-sectional shapes such as closed-curve, polygonal and open sections and advanced architected structures, including lattice, auxetic, origami and bio-inspired designs, as illustrated in **Figure 9**.

For closed-curve sections, circular tubes are often used as the baseline. Real performance gains tend to come from internal design strategies such as multi-cell layouts [3], [7], [12], [13], filling [80], biomimetic features [13], [47], [79], [81], cut-out [59] rather than from changing the outer shape alone. Elliptical tubes, by contrast, tend to show more stable folding under certain conditions, especially when loading is misaligned or eccentric [35], [67], [68], [82], [83]. In polygonal sections, performance generally improves as the number of panels increases [54], [84], [85], [86] and when multi-cell concepts or triggers are introduced [43], [87], [88], as these features increase the number of plastic hinges and help stabilize folding paths. Open section designs [64], [71], [89], [90], face greater challenges, mainly local instability and interface failure; here, material hybridization and bonding control often determine whether the response shifts from unstable buckling or fracture to progressive deformation.

Literature consistently shows that performance gains in basic cross-sectional shapes almost always arise from combining the outer geometry with internal engineering (multi-cell designs, initiators, or fillers) that promotes more progressive and stable deformation. In advanced architected structures, as shown in **Figure 10**, a clear trend emerges: lattice designs [48], [91], [92], [93], auxetic (re-entrant) geometries, origami and bio-inspired concepts can raise SEA and/or reduce PCF by controlling folding topology and redistributing stresses. Re-entrant auxetic structures can improve deformation stability because their negative Poisson's ratio behavior promotes lateral expansion control and more distributed deformation during crushing [94], [95], [96], [97], [98]. Origami tubes can reduce peak force and produce stable folding [61], [62]. Bio-inspired designs based on pine cones, spirals,

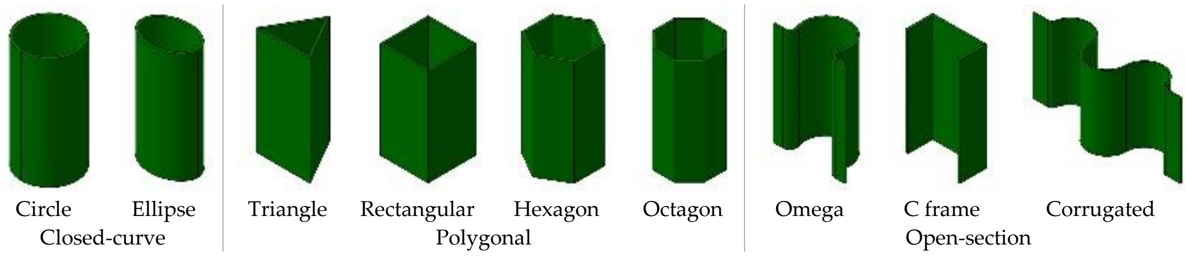

Figure 9. Basic cross-section shapes [9], [15], [17], [49], [54], [64], [71], [89]

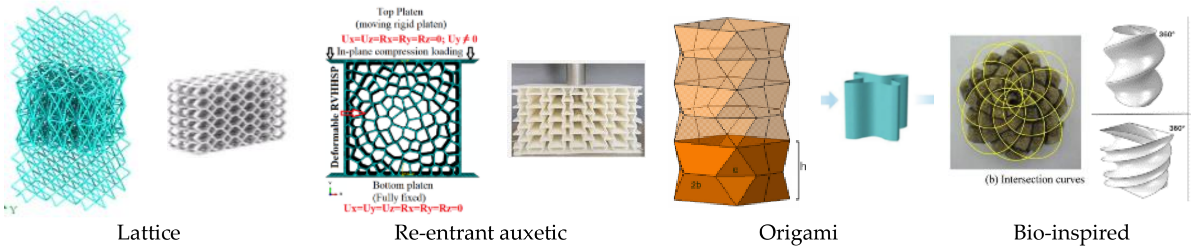

Figure 10. Advanced architected structures [11], [48], [61], [62], [92], [95], [98], [99]

DNA helices, bamboo nodes, and lotus stems also improve collapse control by creating more load paths and controlled folding areas [11], [34], [50], [99], [100], [101]. These features can create more plastic hinges, delay global bending, reduce force changes, and support stable folding. Therefore, bio-inspired geometries should be evaluated not only by SEA, but also by their collapse stability and force-displacement response.

For comparison, **Table 7** summarizes the main findings from studies on non-tapered geometries using different materials and configurations. The results indicate that geometry plays a major role in crashworthiness because it governs folding stability, deformation mode, and load distribution during crushing. In multi-cell aluminum hybrids, the circular–square design (CS2) boosted SEA by up to 70.13% compared with the baseline [102]. For CFRP/aluminum hybrid tubes, hexagonal and octagonal shapes absorbed about 6% and 33% more energy than square tubes [52], [103]. A similar trend was found in FDM polymers, where multi-cell designs performed better than simpler tubes. In 3D-printed PLA tubes, MCPC increased EA by 166.6% and SEA by 163.3% compared with MCS, while MCC increased EA by 14.6% and SEA by 15.6%. In FDM crash boxes, the PLA-CF MCC configuration achieved an SEA of 22.378 ± 0.570 J/g and CFE of 0.732 ± 0.016, representing increases of approximately 70.6% and 77.2% over the SCC tube, respectively [104], [105].

However, the benefit of complex polygonal and multi-cell geometries is not universal. Some studies report that increasing the number of polygonal sides improves SEA and folding stability, while others show that the benefit decreases beyond an optimum number of sides [2], [44]. Under oblique loading, polygonal designs may also lose their advantage due to asymmetric collapse or global bending [18], [46]. For example, Li *et al*. reported that polygonal double tubes began to show global bending at 20°, and all configurations bent globally at 30°, causing energy absorption to decrease by 42.51–64.88% and SEA to become up to 22.34% lower than that of single tubes [46]. These different findings show that the best geometry depends on the application, not only on the cross-sectional shape. Crashworthiness is also affected by wall thickness, material ductility, internal cells, trigger design, geometric size, and loading direction [18], [46], [79].

Despite their mechanical advantages, complex bio-inspired and architected geometries also introduce manufacturability and cost challenges. Designs such as DNA-like helical tubes, lotus-stem-inspired multi-cell tubes, auxetic lattices, and origami absorbers often require additive manufacturing, precision forming, multi-step machining, or complex composite lay-up, which may increase production time, dimensional variability, inspection difficulty, and cost. In mass-production applications, a simpler geometry with slightly lower SEA may be more practical than a highly optimized design that is expensive or difficult to reproduce. Therefore, bio-

Table 7. Comparison of crashworthiness performance across non-tapered geometries

Ref	Material	Geometries Compared	Best Performance Ranking
[102]	Aluminium alloy (hybrid multi-cell)	CS1, CS2, SC1, SC2	CS2 best: SEA 21.36–21.74 kJ/kg, PCF 104–108 kN (+70.13% vs baseline)
[103]	CFRP + Aluminium	Rectangle, Square, Hexagon, Octagon, Circle	Octagon > Hexagon > Square > Rectangle > Circle
[52]	Aluminium alloy	Triangle → Decagon (B3–B10)	Nonagon (B9) best; Octagon second
[104]	PLA (FDM)	MCS, MCP, MCC, MCPC	MCPC > MCP > MCC > MCS
[105]	PLA+, PLA-ST, PLA-LW, PLA-CF, PETG	SCC, MCC, SCS, MCS	PLA-CF + MCC best (SEA ≈ 22.38 kJ/kg, CFE 0.73)
[53]	Aluminium (HMC)	CH1, CH2, HC1, HC2	HC2 best (SEA +21.53%, PCF −3.41%)
[18]	Mild steel	Circle, Ellipse, Square, Rectangle, Hexagon, Octagon	Hexagon > Octagon > Circle > Rectangle > Square > Ellipse
[44]	Aluminium alloy AA6060	n = 4 to 24 side	Performance increases up to a peak at **n ≈ 18,** then declines

inspired geometries should be evaluated not only by SEA, PCF, MCF, and CFE, but also by manufacturability, scalability, tolerance control, quality assurance, repairability, and cost efficiency.

3.3.2. *Taper*

Previous studies have shown that tapering can improve crashworthiness under certain design and loading conditions, particularly by reducing PCF and promoting more progressive folding. This is especially true because it allows for progressive folding and lowers the chance of global bending when loading isn't ideal. As reported by Altın *et al*., in aluminum-composite hybrid structures, increasing the taper angle resulted in raised SEA and CFE, while decreasing PCF in comparison to straight configurations [69]. Lykakos *et al*. also discovered that tapered hybrid tubes with circular-square transitions absorbed more energy and showed more stable folding modes [38]. The advantages of taper become more evident when integrated with hierarchical or biomimetic concepts. Xiang *et al*. demonstrated that hierarchical tapered tubes achieved significantly superior SEA compared to traditional tapered designs [51]. Xiong *et al*. found that conical and functionally graded square composite tubes increased SEA and reduced PCF compared with the basic designs. This shows that non-linear tapering works to reduce bending effects when loading is performed at angles [106]. Additional research on multi-cell conical and double-conical configurations indicates that a well-designed taper can diminish performance sensitivity to oblique impact angles in comparison to straight tubes [107]. **Table 8** summarizes the quantitative comparisons of crashworthiness performance between non-tapered and tapered structures reported in various studies, encompassing a diverse array of materials, geometries, and design methodologies.

Adding a taper does not always improve crashworthiness. It can reduce PCF and support progressive folding, but **Table 8** shows that CFE may decrease in some mild steel tubes. This can occur when gradual reduction causes local buckling instead of stable folding. Its performance depends on the taper angle, wall thickness, cross-sectional shape, material, loading direction, and trigger design. Therefore, tapered structures should be evaluated using PCF, MCF, SEA, CFE, and deformation mode.

3.4. *Influence of Manufacturing Processes on Crashworthiness Performance*

3.4.1. *Metalworking and machining processes*

The quality of the manufacturing process is very important for the crashworthiness of thin-walled tubular structures because it directly affects how accurate the geometry is, how easily it buckles, how stable it folds, and how much energy it can absorb. Extrusion, rolling, forming and stamping are all common metalworking processes which produce structures with edges that are the same thickness and stable mechanical properties. However, forming- and joining-induced imperfections may significantly alter the force–

Table 8. Crashworthiness performance of non-tapered versus tapered

Material	Geometry	Straight Tube (SEA – PCF – CFE)	Tapered Tube (SEA – PCF – CFE)	Ref
Steel–Composite–Aluminium Hybrid	Circular (CSCA)	SEA = 98.19 kJ/kg, PCF = 615.98 kN, CFE = 0.45	SEA = 136.47 kJ/kg, PCF = 348.98 kN, CFE = 0.70 (at 10°)	[69]
3D-printed polymer (PLA/ Resin)	CTT, HTT, HCTT	Lower SEA; higher peak force	SEA +85.8%; lower PCF	[51]
Mild Steel	Circle	11.77 – 744.01 – 0.39	12.27 – 709.21 – 0.38	[18]
	Ellipse	11.21 – 744.44 – 0.38	12.46 – 713.72 – 0.40	
	Hexagon	12.05 – 731.89 – 0.65	13.40 – 653.30 – 0.62	
	Octagon	11.21 – 740.06 – 0.38	13.48 – 659.59 – 0.42	
	Rectangle	9.43 – 712.67 – 0.29	9.92 – 657.42 – 0.28	
	Square	11.75 – 731.78 – 0.40	12.36 – 688.09 – 0.39	
Aluminium 2024-T3	7 Bio-inspired geometries	SEA 15-17 kJ/kg; PCF 35-38, CFE 0.7-0.75	SEA 16-18 kJ/kg; PCF 34-37 kN; CFE 0.75-0.8	[108]
PLA+, PLA–CF	Cylindrical & Tapered	SEA 1.112 kJ/kg, PCF = 12.155 kN, CFE = 0.028	SEA = 23.5 kJ/kg, PCF = 3.934–4.084 kN, CFE = 0.704	[36]

displacement response, peak force, and collapse mode. Therefore, manufacturing quality should not be considered only as a fabrication issue, but also as a factor that controls crashworthiness performance.

Machining, especially drilling, grooving, indentation, and cut-out formation, is widely used to introduce crush initiators and control the first fold during axial crushing. Drilled hole configurations facilitate the transition from global buckling to progressive folding and significantly affect peak force and energy absorption [84]. Moreover, optimizing hole diameter and orientation can enhance CFE by up to 23% and SEA by 17% [85]. Through-hole crush initiators can also reduce PCF by approximately 3–10% in circular tubes and 5–16% in square tubes compared with tubes without initiators [109]. Similarly, modification by creating grooves can control the crushing mode, absorbed energy, and initial crushing load by adjusting the spacing between the grooves [110]. These findings show that machining-based features are not merely geometric modifications, but active design tools for controlling fold initiation, force response, and overall crashworthiness.

The performance of machined triggers depends on the balance between reducing peak force and keeping the structure strong. If holes, grooves, or cuts are too large, they can weaken the wall, reduce MCF and CFE, and cause unstable folding. Therefore, these triggers must reduce PCF while maintaining enough crushing resistance and stable deformation. Precision machining processes such as CNC machining, EDM, and WEDM can improve wall thickness control, cutting accuracy, and specimen repeatability, leading to more stable crushing behavior and better agreement between experimental and numerical results. Previous studies found that WEDM-made hybrid tubes had errors mostly below 5%. For EDM wire-cut tubes with variable thickness, the differences were only 0.9–1.8% for PCF and 3.3–4.2% for MCF [9], [53], [56], [57], [102].

Besides machining-based features, conventional forming and joining processes also strongly influence crashworthiness. Bending, stamping, hydroforming, and welding can introduce residual stresses, local thickness variation, heat-affected zones, local softening or hardening, and geometric distortion around joints. Manufacturing defects result in changes in the local stiffness distribution and can disrupt the planned folding sequence. In some cases, small imperfections from bending or welding can make numerical simulations more realistic, but excessive defects may shift the deformation mode from stable progressive folding to asymmetric collapse, local instability, or global buckling [38], [86]. These changes can reduce the crushing distance and lower EA, SEA, MCF, and CFE.

Therefore, weld location, heat-affected zones, residual stress, dimensional accuracy, and wall thickness variation should be considered when studying or modelling metallic thin-walled structures [38], [86], [111].

Overall, metalworking and machining processes affect crashworthiness through two different mechanisms. First, manufacturing affects the basic quality of the structure, including dimensional accuracy, wall thickness, defects, and material consistency. Second, it can create holes, grooves, or cut-outs to control folding and reduce PCF. However, these features must be designed carefully because excessive weakening can reduce MCF and CFE or cause unstable collapse.Thus, in metallic thin-walled structures, manufacturing should be treated as an active design parameter that interacts with material properties, geometry, and loading condition.

3.4.2. *Additive manufacturing*

Additive manufacturing (AM), especially fused deposition modeling (FDM) and metal-based methods like selective laser melting (SLM) and laser powder bed fusion (LPBF), makes it possible to make thin-walled structures with complex shapes, such as multi-cell, lattice, hierarchical, and bio-inspired designs. These designs are hard to make with traditional metalworking. This geometric freedom provides significant opportunities to improve SEA, reduce PCF, and tailor progressive folding mechanisms through controlled internal architecture.

However the crashworthiness of structures made with AM is very much affected by how they are developed. In FDM polymer structures, wall thickness, layer height, nozzle diameter, nozzle temperature, printing speed, infill pattern, raster direction, and filament type can significantly influence energy absorption, force response, and deformation stability. Wall thickness is often reported as one of the dominant parameters affecting SEA, while improved dimensional accuracy of internal walls can enhance the stability of progressive folding [33], [36], [60]. The configuration of the infill is also very important, square infill maximizes SEA and zigzag infill improves CFE [15]. Recent multi-parameter studies on 3D-printed PLA multi-cell tubes further confirm that nozzle diameter, layer height, nozzle temperature, printing speed, wall thickness, and material type affect crashworthiness performance, with optimized parameter combinations improving CFE and reducing manufacturing time [112]. Similarly, studies on FDM-printed PLA+ and ABS multi-cell tubes show that different polymer types and wall-connection patterns produce different energy absorption capacities and deformation responses under quasi-static axial compression [5].

A key limitation of polymer AM is process-induced anisotropy. Layer-by-layer deposition creates direction-dependent properties, making the structure sensitive to build orientation, raster direction, and interlayer bonding quality. Reducing layer thickness, improving toolpath strategy, and selecting suitable cross-sectional geometry can promote more stable folding, particularly in continuous fiber-reinforced or multi-cell printed structures [113]. Nevertheless, weak interlayer bonding, voids, poor raster orientation, uneven cooling, and dimensional deviations may reduce through-thickness strength and shift the collapse mode from progressive folding to premature cracking, localized fracture, asymmetric buckling, or global bending. Therefore, an optimized AM geometry does not automatically guarantee high crashworthiness unless printing parameters, interlayer quality, dimensional accuracy, residual stress, and defect sensitivity are also controlled [33], [113], [114].

More progress is made by fine-tuning the printing settings and adding triggers, cutouts, or bio-inspired wall-thickening techniques [91], [114], [115], [116]. Bio-inspired FDM designs can substantially improve crashworthiness; DNA-inspired helical tubes increased SEA and CFE by 166.62% and 169.70%, respectively, while foam-filled auxetic structures improved SEA by 40–50% and optimized auxetic geometry increased absorber efficiency by 34%. Bamboo-inspired tubes also showed optimum performance using grid/honeycomb infill at 20–30% infill ratio [12], [79], [94]. There are also reports of high precision and repeatability for SLS/FS3300PA processes. For example, bio-inspired honeycomb structures have been shown to improve SEA by as much as 121.45% [92].

In metal AM, SLM/LPBF processes allow it control the thickness of the walls and the quality of the folds very precisely. Optimized process parameters and post-processing heat treatments enhance ductility and SEA in AlSi10Mg and stainless steel structures [40], [42], [48]. Architected origami, antiprism, auxetic, and hybrid-reinforced metal tubes consistently improve crashworthiness, with reported SEA gains of about 30–40% in auxetic tubes, 12.19% higher energy absorption and 12.24% lower peak force in optimized graded polygonal tubes, and up to 191.6% SEA improvement in metal honeycomb-reinforced systems [41], [97], [117]. When comparing manufacturing routes, polymer and metal AM follow the same basic pattern crashworthiness depends mainly on build quality and internal design. Polymers are attractive for their low cost and geometric freedom, while metals stand out for their strength, accuracy and folding stability.

Overall, polymer and metal AM show the same pattern: crashworthiness depends on both geometry and printing quality. AM polymers are inexpensive, lightweight and easy to shape, but are sensitive to printing direction, interlayer bonding, and process parameters. Metal AM provides higher strength and accuracy, but porosity, residual stress, surface quality, and post-processing must be controlled. Therefore, material, geometry, printing parameters, and loading conditions should be optimized together.

3.4.3. *Lamination and composite processing*

In composite thin-walled structures, the way the laminate is produced really matters for crash performance because energy absorption is governed by progressive fiber fracture, matrix cracking, delamination, friction, and interlaminar damage. This mechanism depends heavily on the quality of the laminate, grain direction, resin distribution, voids, drying conditions, and the bond between the layers.

Hand lay-up laminates tend to vary more because resin is not always evenly distributed and voids can easily form [64]. But when combined with compression bladder molding or trigger designs, they can still perform well in terms of stable crushing and SEA [65]. The autoclave and hot-press curing process results in more consistent lamination results and creates a better bond, which makes the fold stable and keeps the peak forces low in the CFRP crash box [62]. Hot curing after resin immersion improves folding repeatability [61], and prepreg wrapping in bio-inspired tubes almost doubles SEA [81]. In addition, hand lay-up laminates may show better tolerance to marine exposure than prepreg systems due to their porosity, although this advantage depends strongly on resin system, fiber architecture, and environmental condition [118]. Autoclave co-curing further boosts energy absorption through combined deformation effects [71].

Vacuum methods, such as vacuum infusion and VARTM, facilitate resin flow and laminate quality, resulting in more stable crush resistance. Erkek *et al*. found that carbon/epoxy crash boxes had the highest EA and SEA at 257.28 J and 10.66 J/g. Glass/epoxy tubes also showed stable crushing, with an EA of 211.88 J and an SEA of 9.33 J/g [119]. Good fiber-matrix bonding and trigger design help vacuum-infused structures absorb more energy. For VARTM sandwich structures, the core geometry and bonding between the core and outer layers also play an important role [96].

Filament winding, braiding and wrapping are useful for crashworthy tubes because they control fiber direction and tube stiffness. Their performance depends on winding angle, material ratio, wall thickness, curing, temperature, and crushing speed. A good design can improve SEA, CFE, and folding stability while reducing early delamination [63], [66], [70], [120], [121].

Each manufacturing method has different benefits and limitations. Autoclave and hot-press methods produce consistent laminates, while vacuum methods offer a good balance between quality and cost. Winding methods provide better control of fiber direction and tube stiffness. Therefore, the manufacturing method should be selected based on the material, geometry, and loading condition.

3.5. *Influence of Loading Conditions on Crashworthiness*

3.5.1. *Quasi-static loading*

Quasi-static axial compression is a frequently used method for crashworthiness testing because it is simple, repeatable, low cost and useful for separating and analyzing material and geometric influences. Because inertia and strain-rate effects are small, this test can clearly demonstrate progressive folding and stable energy absorption behavior.

When thin-walled metal tubes are gently compressed in the axial direction, they typically fold in a stable concertina or diamond pattern, which helps absorb energy through plastic deformation. In composites, quasi-static testing makes it clear to see how damage develops, including matrix cracking, fiber fracture, and delamination. Conventional CFRP tubes often fail in a brittle and unstable manner. However, optimized stacking sequences and deformation-controlling layers encourage stable progressive crushing and improve SEA by more than 50% [120]. Hybrid CFRP/aluminum structures make crashworthiness even better by combining stable plastic deformation in aluminum with energy dissipation through composite damage. This leads to higher SEA and CFE and less deformation instability [103], [121].

Environmental exposure also affects quasi-static crashworthiness behavior. Seawater aged CFRP tubes exhibit reduced peak force and energy absorption capacity due to matrix and interfacial degradation, while fundamental deformation mechanisms remain identifiable, confirming the suitability of quasi-static testing for assessing performance degradation during service life [118].

A consistent finding across the literature is that quasi-static testing provides a useful baseline for identifying deformation mechanisms, but it cannot fully represent inertia, strain-rate effects, and instability under dynamic or oblique impact [41], [86], [89], [96], [103], [105], [114], [120]. Structures with stable folding under quasi-static axial loading may show uneven collapse, global bending, or early fracture under real impact conditions. Therefore, quasi-static results cannot be directly applied to dynamic or oblique loading. Since most studies use quasi-static tests, dynamic results should be interpreted carefully. More standard dynamic and oblique impact studies are needed, especially for polymer, composite, hybrid, and 3D-printed structures.

3.5.2. Dynamic impact loading

Dynamic impact loading introduces inertia effects, strain-rate sensitivity, and stress-wave propagation, which greatly change how crashworthiness works compared to quasi-static conditions. When thin-walled structures are crushed by a dynamic axial impact, it usually show a higher peak crushing force and different modes of collapse. This is especially true for high-strength metals and rate-sensitive polymers. At high strain rates, composite and hybrid structures typically accumulate damage much more rapidly, driving the failure mode toward brittle fracture or delamination. Dalli *et al*. showed that CFRP components in Formula 1 lose stability under dynamic loading, which can be concluded that how sensitive carbon fiber composites are to strain rate [78].

The effect of strain rate is significantly influenced by structural design. Foam-filled bamboo tubes showed better performance improvement under dynamic loading conditions, from 22.1–28.2 kJ/kg in quasi-static to 26.3–31.9 kJ/kg [19]. On the other hand, the metal–CFRP hybrid tube absorbs less energy upon impact because the CFRP matrix fails earlier at high strain rates, although the overall folded shape appears stable [6]. Polyamide structures produced by the additive method exhibited similar problems with a decrease in SEA and CFE of up to 59% and 39%, respectively, as well as a clear shift towards brittle behavior under dynamic impact [33].

Oblique impact further increases the complexity of crash response because real crash events rarely occur under perfectly axial loading. In practical conditions, thin-walled structures may experience combined axial compression, bending, shear, eccentricity, and impact-angle effects caused by vehicle misalignment, side impact, rollover, or non-uniform contact. These conditions can change the failure pattern from stable progressive folding to asymmetric deformation, global bending, or local failure, resulting in a decrease in SEA and CFE values. [9], [46], [58], [107]. Under these conditions, bio-inspired and hierarchical geometries exhibited improved deformation stability [81], [93]. While the layered hybrid metamaterial made from LPBF maintained stable deformation across a wide range of strain rates and achieved a 25–84% increase in SEA [48]. These studies show that quasi-static tests are useful for understanding basic deformation behavior. However, they cannot directly predict real crash performance without dynamic and oblique validation, especially for rate-sensitive polymers, composites, hybrids, and 3D-printed structures.

3.5.3. *Strain rate sensitivity across material classes*

Strain-rate sensitivity explains why quasi-static crashworthiness results cannot be directly generalized to dynamic impact. Under dynamic loading, inertia, stress-wave propagation, and rate-dependent material behavior can change PCF, MCF, SEA, CFE, and collapse mode [29]. For metals, this effect is commonly described using the Cowper–Symonds correction, where dynamic flow stress increases with plastic strain rate, although the constants must be calibrated for each material and loading condition [28].

For polymers and additively manufactured thermoplastics, strain-rate sensitivity is governed by viscoelasticity, viscoplasticity, temperature dependence, and process-induced anisotropy [33], [60]. At higher loading rates, polymers may show higher apparent stiffness but lower ductility, causing a transition from stable folding to brittle fracture or unstable collapse. In FDM structures, this response is further affected by raster orientation, interlayer bonding, voids, and build [112], [113], [114]. The reviewed studies show that polymer structures can experience SEA reductions of up to 59% and CFE reductions of up to 39% under dynamic impact compared with quasi-static loading [33].

For composites and hybrid structures, the strain-rate response is controlled by matrix cracking, fiber fracture, delamination, frictional crushing, and interfacial debonding [76], [78]. These mechanisms may develop more rapidly under impact, reducing progressive crushing stability, especially when different hybrid components respond differently to strain rate. Therefore, future studies should combine quasi-static tests with calibrated dynamic material models and standardized dynamic, oblique, and high-strain-rate testing to improve quasi-static-to-dynamic crashworthiness prediction [60], [73], [76].

3.6. *Integrated Design and Optimization Framework*

Crashworthiness performance is controlled by the interaction of material, geometry, manufacturing quality, and loading condition. Because these factors jointly affect folding initiation, deformation stability, force response, and energy absorption, thin-walled structures should be evaluated using an integrated design approach. This section discusses the main design trade-offs and the role of machine learning-based optimization.

3.6.1. *Coupled interaction and trade-offs*

Although material, shape, manufacturing, and loading conditions are often studied separately, the safety of thin-walled structures actually depends on how these factors work together. Research clearly shows that a design made for only one condition can fail if all other factors are not considered at the same time.

The material–geometry interaction controls collapse mechanisms: multi-cell and hierarchical geometries are highly effective in metals due to ductile plastic hinge formation, but can induce stress concentration and premature brittle fracture or delamination in certain polymers and composites if material ductility or interlaminar strength is insufficient. The geometry–loading interaction further influences robustness, as polygonal and multi-cell sections generally perform well under axial loading but become susceptible to asymmetric collapse and global bending under oblique impacts; tapered or graded geometries mitigate this sensitivity by introducing stiffness gradients. Manufacturing-material coupling also has an equally significant influence on the control of how a component experiences failure. Anisotropy in additive manufacturing, voids in composites, and defects in welding or forming can change deformation from stable folding to brittle fracture or unstable collapse. Finally, the interaction between manufacturing-geometry determines how sensitive imperfections are. For example, complex multi-cell or bio-inspired architectures need very precise fabrication to keep folding stable.

In the end, these interactions show that optimizing crashworthiness is a multi-parameter problem that needs to take into account how materials behave, how they are shaped, how well they are made, and how realistic the loading conditions are in order to get strong and transferable performance. Based on these consideration, **Table 9** provides a overview of the key interrelated in crashworthiness design highlighting the associated failure risks and practical strategies to reduce it.

Table 9. Coupled interactions in crashworthy thin-walled structures: failure risks and mitigation strategies

Coupled Factors	Typical Failure Risk	Mitigation Strategy
Material × Geometry	Brittle fracture in polymers/composites with complex multi-cell layouts	Match geometry to material ductility; introduce triggers or compliant zones
Geometry × Loading	Asymmetric collapse and global bending under oblique impact	Use tapering, graded stiffness, or elliptical sections
Manufacturing × Material	AM anisotropy, CFRP voids, weld induced defects	Process optimization, post-treatment, quality control
Manufacturing × Geometry	Imperfection sensitivity in hierarchical/multi-cell designs	High precision fabrication (EDM/WEDM, optimized AM), tolerance control

3.6.2. Machine learning and surrogate-based optimization in multi-parameter crashworthiness design

Machine learning and surrogate-based optimization are increasingly used in crashworthy thin-walled structure design to reduce the computational cost of repeated finite element simulations. Methods such as Response Surface Methodology (RSM), Artificial Neural Networks (ANN), Kriging, and other metamodels can predict crashworthiness outputs, including PCF, MCF, EA, SEA, CFE, mass, and deformation stability, from design variables such as material, geometry, manufacturing parameters, and loading condition [14], [16], [88].

These approaches are useful for multi-objective optimization because crashworthy design must maximize EA or SEA while controlling PCF, improving CFE, and maintaining stable progressive collapse. RSM is effective for identifying dominant parameters, while ANN, Kriging, and machine learning models are better suited for nonlinear and complex design spaces [16], [67], [102]. However, these models should be supported by validated finite element simulations, experimental data, deformation-mode assessment, and uncertainty analysis to avoid purely data-driven predictions without physical reliability.

4. Application of Crashworthy Thin-Walled Structures

Different engineering applications have very different crashworthiness requirements because safety goals, loading conditions, and mass limits are all different. In automotive thin-walled structures such as crash boxes and side sills are designed to control the peak crushing force and make sure that energy is absorbed steadily to protect passengers within. For electric vehicles (EVs), battery packs add more safety issues related to structural intrusion and thermal runaway. Moghaddam *et al*. demonstrated how applying energy absorbers to the side sills of vehicles can significantly decrease intrusion and improve absorbed energy when a pole crashes into the side of the vehicle, without even adding significant weight [1]. Bio-inspired multi-cell tubes optimized with machine learning show better energy absorption and more stable force response, making them suitable for automotive crash protection components [16]. Similar ideas are used in rail vehicles, where multi-cell structures with windows are used as front-end energy absorbers in high-speed trains to make them safer in crashes [45].

In aerospace and UAV applications, crashworthiness design is limited by strict weight limits, sensitive payload security, and the possibility of non-axial impacts. Hybrid structures combination of composites and metals are an effective solution because the combination of the two creates different deformation mechanisms and makes energy absorption more efficient than single material systems [6], [64]. Geometric concepts such as origami structures and functionally graded structures further improve impact performance by lowering PCF and maintaining stable crush response under multi-directional loading that reflects real impact scenarios [62], [78], [106].

In transportation, crashworthiness concepts have been extended to civil engineering and safety infrastructure. Multi-cell and bio-inspired thin-walled structures used in civil engineering applications show more stable deformation, higher specific energy absorption (SEA), and lower initial peak force under dynamic and oblique loading [108]. Architected and auxetic designs, such as multi-layer origami energy absorbers and re-entrant honeycomb composite guardrails, further demonstrate how crashworthy thin-walled concepts can be scaled across different engineering fields [86], [117].

In practical, crashworthiness performance cannot be viewed separately from its operating conditions. To make lightweight, reliable, and high-performance energy-absorbing structures, it requires integrated design frameworks that take into account material selection, geometric design, manufacturing constraints, and realistic loading conditions all at the same time.

Therefore, SEA values are just references for specific cases, rather than strict, unchanging limits for every design. For front car safety boxes, a high energy absorption is good if the shape folds safely and the impact force is not too high. However, for side parts and electric car battery protection, stopping the impact and pushing the force away are more important than just absorbing energy. For airplanes and drones, the safe energy and force levels depend on the cargo weight, the available space to crush, and the allowed speed changes. Thus, practical crashworthy design should begin from the target application and regulatory context, then translate vehicle-level safety requirements into component-level targets such as allowable PCF, required EA, target SEA, minimum CFE, and stable deformation mode.

5. Conclusion

The main finding of this review is that no single material or geometry is best for everything. Instead crashworthiness performance depends on the specific design needs. In other words, the most effective safe design comes from a combination of material behavior, geometry, manufacturing quality, crash conditions and final goals. This framework helps in choosing the perfect structure based on the project goals, such as reducing weight, improving safety, or increasing stability.

The following key findings and research directions summarize the most robust insights derived from the literature.

a. Effective crashworthiness is only reached when high energy absorption is combined with a controlled peak force and high efficiency. Increasing energy absorption alone can be a mistake if the collapse is unstable or causes too much initial force.
b. Material choice decides how a structure handles a crash. Metals provide predictable progressive folding, additively manufactured polymers offer mass efficiency and design freedom but are sensitive to anisotropy, composites deliver high specific performance through damage based crushing and hybrid systems often provide the most balanced performance but are highly interface dependent.
c. Geometric modification rarely improves crashworthiness through cross-sectional shape alone; the most consistent performance gains arise from coupling external geometry with internal engineering strategies such as multi-cell layouts, triggers, fillers and hierarchical or bio-inspired architectures. Within this framework, tapering provides an effective stiffness gradient that promotes progressive crushing and reduces sensitivity to misalignment, but if it is too aggressive, it can cause local instability or lower efficiency.
d. Manufacturing quality is the most important factor for crashworthiness. This is because defects caused by the process, anisotropy and bonding integrity all have a directly affect how a structure folds, stay stable and handles force. Within this context, FDM enables highly complex, low-density, whereas metal AM processes such as SLM/LPBF provide higher strength, precision, and folding stability. Both routes therefore require manufacturing aware design to fully exploit their respective advantages.
e. Loading conditions are very important for interpreting performance. Quasi-static testing provides us with important mechanical information, is easy to perform and low cost but dynamic and oblique impacts can significantly alter PCF, failure modes and CFE significantly, especially in rate-sensitive material.

Although the reviewed studies demonstrate substantial progress in thin-walled crashworthiness design, several scientific and technical problems remain unresolved. These include the need for normalized performance comparison, more dynamic and oblique impact data, clearer isolation of coupled material–geometry–manufacturing–loading effects, improved numerical validation, better understanding of manufacturing defects and interface degradation, and more application-oriented design guidelines. The main research gaps and recommended future directions are summarized in **Table 10**.

Table 10. Research gap

No.	Research gap	Current limitation	Recommended future direction
1	Standardized performance comparison	SEA values are often compared across studies with different specimen dimensions, mass, crushing stroke, loading rate, material system, and testing conditions.	Develop normalized crashworthiness indices that consider density, volume, wall thickness, crushing stroke, loading rate, PCF, CFE, and deformation mode.
2	Dynamic and oblique impact data	Most available studies are still dominated by quasi-static axial compression, limiting the transferability of results to realistic crash scenarios.	Conduct more standardized dynamic, lateral, and oblique impact tests, particularly for polymers, composites, hybrids, and additively manufactured structures.
3	Coupled design variables	Material, geometry, manufacturing process, and loading condition are often varied simultaneously, making it difficult to isolate individual effects.	Use controlled experimental and numerical designs to separate dominant material, geometry, manufacturing, and loading contributions.
4	Numerical model validation	Many numerical studies are not fully validated against experimental force–displacement curves, deformation modes, and failure mechanisms.	Improve validation using PCF, MCF, EA, SEA, CFE, deformation pattern, and failure mode comparison.
5	Additive manufacturing defects	AM structures are affected by anisotropy, interlayer bonding, porosity, raster direction, and dimensional deviations, but these effects are not always quantified.	Investigate the relationship between AM process parameters, defect formation, interlayer strength, and crashworthiness response.
6	Composite and hybrid interface reliability	Composite and hybrid structures can show high SEA, but their performance is sensitive to delamination, debonding, voids, and interface degradation.	Develop damage-tolerant hybrid designs and validated failure models for delamination, debonding, and progressive crushing.
7	Aging and environmental durability	Long-term effects such as moisture absorption, thermal aging, UV exposure, seawater exposure, and service-life degradation are rarely included.	Evaluate crashworthiness after controlled aging and environmental exposure to assess long-term performance stability.
8	Practical feasibility of hybrid structures	Manufacturing complexity, cost, repairability, recyclability, and industrial scalability are often not discussed.	Include manufacturability, cost, repairability, recyclability, and end-of-life assessment in crashworthiness optimization.
9	Classical theory and modern architectures	Classical folding theories are not always connected to modern bio-inspired, auxetic, origami, AM, and hybrid structures.	Extend analytical models to include complex geometry, graded thickness, anisotropic materials, AM defects, and hybrid interfaces.
10	Application-specific design guidelines	Many studies remain at laboratory scale and are not directly linked to automotive, aerospace, UAV, or EV design requirements.	Develop application-oriented design frameworks based on allowable PCF, target SEA, available crush distance, mass limit, and expected loading scenario.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Additional information

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