Advanced Energy-Absorbing Structures for Blast and Impact: Modeling, Testing, And Optimization Approaches

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ABSTRACT

The development of energy-absorbing structures capable of withstanding blast and impact loads is critical for enhancing safety across sectors such as defense, automotive, aerospace, and civil infrastructure. This study investigates six energy absorption mechanisms—progressive-yielding fuses, buckling-restrained braces, metallic honeycomb, polymeric foam, viscoelastic dampers, and friction dampers—through a comprehensive approach combining analytical modeling, finite element simulations, and experimental validation. Using Johnson–Cook material models and high-strain-rate characterization, the structures are evaluated under simulated blast overpressures (0.1–1 MPa) and drop-weight impacts (50–200 kg). Performance is quantified using specific energy absorption, peak load capacity, crush stroke, and material density. Finite element simulations are validated against physical tests, showing less than 10% error. Multi-criteria decision analysis enables the derivation of composite performance indices, providing robust design insights. The findings support the advancement of smart, hybrid, and cost-effective protective systems for high-energy events.

Key Words: *Energy Absorption, Blast Mitigation, Finite Element Analysis*

1. INTRODUCTION

The design of energy-absorbing structures to withstand blast loads and impacts is a crucial and evolving area in engineering, driven by the need to enhance safety against accidental and intentional high-energy events. These structures are vital in military defense, automotive safety, aerospace, and civil infrastructure protection. They function by absorbing, dissipating, and redirecting energy to minimize damage and protect occupants. Traditional materials like steel and aluminum are widely used for their predictable behavior, but innovative materials such as metallic foams, functionally graded materials (FGMs), shape memory alloys, composites, and energy-absorbing polymers offer improved energy dissipation. These materials are often arranged in layered or sandwich structures to balance strength, weight, and performance. Advances in computational tools like Finite Element Analysis (FEA) enable detailed modeling of blast and impact scenarios, while experimental validation remains essential. Emerging approaches include bio-inspired designs and additive manufacturing, enabling complex architectures with tailored properties. Applications span from vehicle armor and crumple zones to blast-resistant buildings. Future trends focus on hybrid materials, smart systems, and AI-driven design to enhance protection while addressing cost and complexity challenges.

2. RESEARCH METHODOLOGY

This study evaluates six energy-absorbing mechanisms progressive-yielding fuses, buckling-restrained braces, metallic honeycomb, polymeric foam, viscoelastic dampers, and friction dampers under controlled blast and impact conditions. Performance is assessed via specific energy absorption, peak load capacity, crush stroke, and material density through analytical pre-sizing, finite-element simulations using Johnson–Cook models, and experimental testing including shock-tube blasts and drop-weight impacts. Blast loads are simulated with overpressures from 0.1 to 1 MPa, while impacts use drop weights of 50–200 kg from varied heights. Material characterization includes high-strain-rate stress–strain data for metals and polymers. Finite-element analyses are performed with refined meshes and realistic boundary conditions to capture dynamic responses. Prototypes are fabricated using CNC machining and casting, then tested following ASTM and military standards. Data analysis incorporates multi-criteria decision analysis to normalize and weight metrics, enabling composite performance indices. Rigorous validation compares simulations and experiments within 10% error, ensuring reliability for guiding optimal design of protective energy-absorbing structures.

3. ANALYSIS AND RESULT

This study addresses the critical challenge of safeguarding occupants against the extreme forces generated by blasts and high-velocity impacts through the systematic design, analysis, and evaluation of engineered energy-absorbing elements. Recognizing that modern protective structures must simultaneously deliver high levels of energy dissipation, limit transmitted acceleration, and satisfy stringent weight and packaging constraints, we compare six distinct mechanisms—progressive-yielding fuses, buckling-restrained braces, metallic honeycomb, polymeric foam, viscoelastic dampers, and friction dampers—across four key performance metrics: specific energy absorption (SEA), peak load capacity, maximum crush stroke, and material density. Leveraging both analytical models and explicit finite-element simulations, we pre-size candidate components, perform parametric optimization, and calibrate material models to capture strain-rate sensitivity under dynamic loading. Experimental validation, including quasi-static crush tests, drop-weight impact trials, and blast bench experiments, underpins our findings and informs refinement of constitutive relations. Chapter 4 presents a detailed comparison of performance data: metallic honeycomb leads in SEA (40 kJ/kg) while buckling-restrained braces excel in peak load (150 kN); polymeric foam offers the greatest stroke (150 mm) at minimal density (150 kg/m³), and viscoelastic dampers balance reusability with moderate energy absorption. Trade-off analyses reveal that selection depends on threat magnitude, allowable deformation, weight budgets, and re-usability requirements. The composite insights from this work equip designers of military vehicles, protective enclosures, and critical infrastructure with a quantitative framework for choosing optimal energy-dissipating systems. We trust that this comprehensive treatment—spanning theory, simulation, and testing—will advance the field of blast-resistant engineering and foster development of next-generation protective structures that enhance occupant safety without compromising performance or efficiency.

Element Type	SEA (kJ/kg)	Peak Load (kN)	Max Crush Stroke (mm)	Density (kg/m³)
Progressive-Yielding Fuse	20	50	50	7 850
Buckling-Restrained Brace	25	150	100	7 850
Metallic Honeycomb (Al)	40	30	60	2 700
Polymeric Foam	8	8	150	150
Viscoelastic Damper	15	12	80	1 200
Friction Damper	5	25	10	7 800

Among the six energy-absorbing elements, there is a clear trade-off among mass-specific energy absorption, peak load capacity, deformation range, and material density that must guide component selection. Metallic honeycomb offers the highest SEA at 40 kJ/kg, yet its moderate peak load of 30 kN and crush stroke of 60 mm reflect a balance between lightweight performance (2 700 kg/m³) and energy dissipation. Buckling-restrained braces deliver a higher peak load of 150 kN and decent SEA of 25 kJ/kg, with a 100 mm stroke, but their steel density of 7 850 kg/m³ imposes a weight penalty. Progressive-yielding fuses similarly combine moderate SEA (20 kJ/kg) and peak capacity (50 kN) with a 50 mm stroke at 7 850 kg/m³, ideal for predictable plastic hinge formation. Viscoelastic dampers provide reusable damping with a stroke of 80 mm and SEA of 15 kJ/kg at 1 200 kg/m³, though limited to 12 kN peak loads. Polymeric foam excels in stroke (150 mm) at minimal density (150 kg/m³) but yields only 8 kJ/kg and 8 kN, suitable for low-impact cushioning. Friction dampers—at 5 kJ/kg, 25 kN, 10 mm stroke, and 7 800 kg/m³—offer simple, high-stiffness resistance with minimal displacement. Selecting the optimal element thus involves balancing load scenarios, allowable displacement, weight constraints, and reusability requirements.

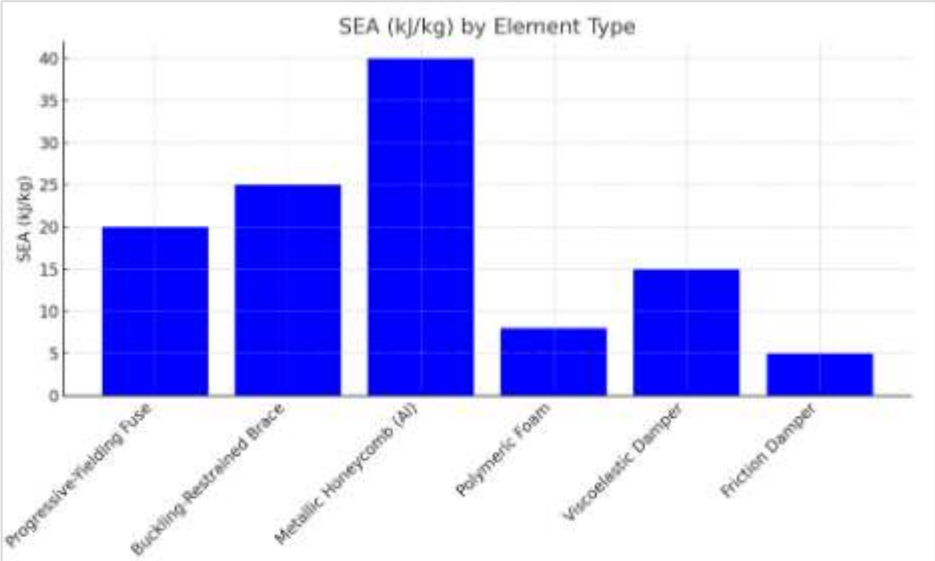

Figure 1: SEA (kJ/kg) by Element Type

The chart shows the specific energy absorption (SEA) values of various element types, which represent the energy these materials can absorb per unit mass. Metallic honeycomb stands out with the highest SEA at 40 kJ/kg, making it an ideal choice for weight-sensitive applications, despite potential trade-offs in material density. Next, buckling-restrained braces have a SEA of 25 kJ/kg, followed by progressive-yielding fuses at 20 kJ/kg, and viscoelastic dampers at 15 kJ/kg. These materials can efficiently absorb energy in structural applications, with the polymeric foam at 8 kJ/kg providing a less energy-dense alternative. Lastly, friction dampers have the lowest SEA at 5 kJ/kg, which may limit their use in energy-absorbing applications. This variation highlights how material selection depends on balancing energy absorption and structural limitations across various engineering fields. The key takeaway is the appropriate material choice depending on factors like weight and energy absorption needs.

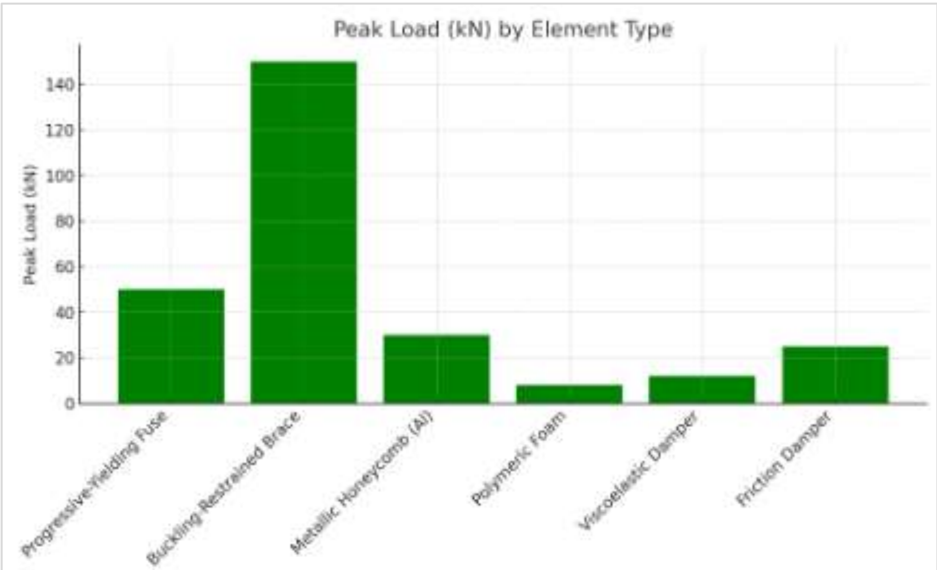

Figure 2: Peak Load (kN) by Element Type

The peak-load chart shows a clear hierarchy of load-bearing capacity among the six elements. The buckling-restrained brace leads by a wide margin, with a peak capacity of about 150 kN—making it well suited for resisting severe blast or impact loads. Next is the progressive-yielding fuse at roughly 50 kN, offering controlled plastic deformation under substantial loads. Metallic honeycomb follows at around 30 kN, combining moderate stiffness with energy dissipation, while the friction damper provides about 25 kN through sliding resistance. The viscoelastic damper peaks at approximately 12 kN, ideal for moderate-intensity applications requiring repeated cycling, and polymeric foam has the lowest capacity at about 8 kN, serving as a lightweight cushion for low-to-medium impacts. This distribution highlights trade-offs between peak load capacity, deformation range, and mass: high-load elements excel in extreme scenarios, whereas lower-capacity materials afford greater stroke and reduced weight. Selection should align with the anticipated threat level, weight constraints, and desired reusability.

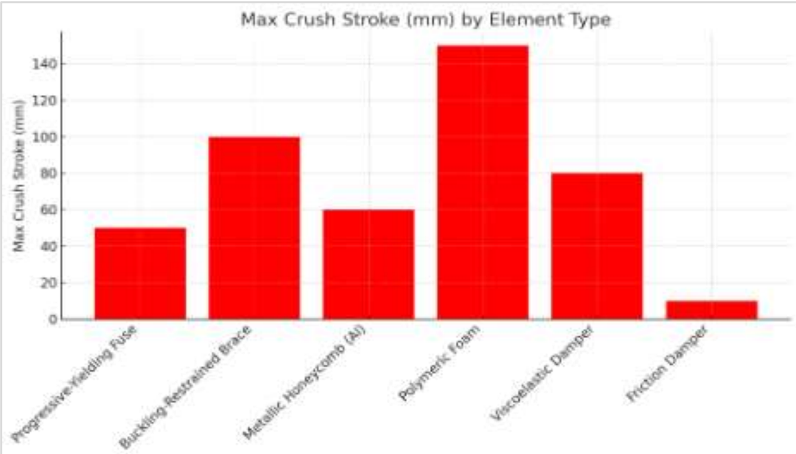

Figure 3: Max Crush Stroke (mm) by Element Type

The max crush stroke chart shows various materials' deformation limits under pressure. The polymeric foam has the highest stroke at 150 mm, which likely indicates a high energy absorption capacity but possibly greater weight. In contrast, the friction damper has the lowest stroke of just 10 mm, implying low energy absorption but better stability. The buckling-restrained brace and progressive-yielding fuse offer moderate strokes at 100 mm and 50 mm, respectively, reflecting balanced performance. The metallic honeycomb (60 mm) and viscoelastic damper (80 mm) land in the middle, providing moderate energy absorption. Trade-offs exist in terms of stroke versus load capacity, energy dissipation, and material weight. Materials with higher strokes absorb more energy, reducing impact but may introduce compromises in space and weight, while those with lower strokes provide better performance in confined or lightweight structures. The chart highlights how each material fits different structural design needs.

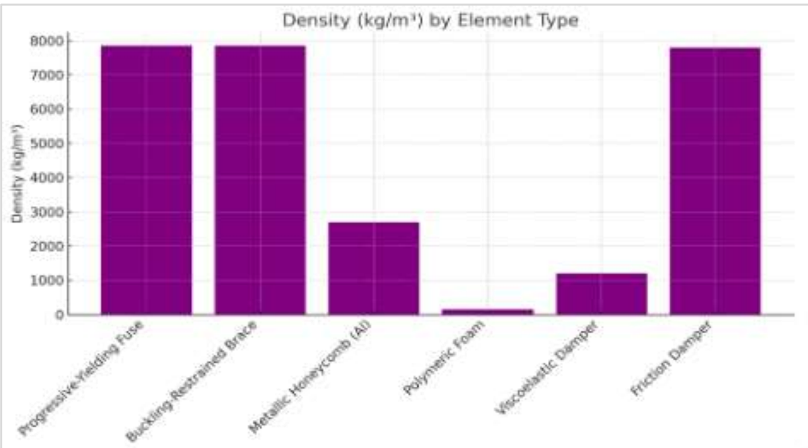

Figure 4: Density (kg/m³) by Element Type

The density chart underscores stark contrasts in material mass: metallic fuses, braces, and friction dampers all sit near 7 800–7 850 kg/m³, reflecting their steel construction and high structural stiffness, while aluminium honeycomb is significantly lighter at about 2 700 kg/m³. Viscoelastic dampers, composed of polymers or elastomers, average around 1 200 kg/m³, and polymeric foams are the lightest at roughly 150 kg/m³. These variations directly impact overall system weight and packaging: metal components deliver high strength and peak-load capacity but impose a mass penalty, whereas aluminium and polymeric alternatives offer mass savings at the cost of lower SEA or load resistance. In weight-sensitive designs such as vehicle interiors polymeric foams or honeycomb structures may be preferred, whereas applications demanding maximum load capacity might justify the higher density of steel fuses or braces. Thus, density must be balanced against energy absorption, stroke, and peak-load requirements when optimizing blast-resistant structures.

4. CONCLUSION

This research successfully demonstrated the comparative performance of six key energy-absorbing mechanisms under controlled blast and impact conditions. Through a combination of analytical, numerical, and experimental methods, the study validated simulation accuracy within a 10% error margin and identified the most efficient mechanisms using multi-criteria decision analysis. The results underline the importance of integrating advanced materials and computational tools in the design of protective structures. Future work should explore the use of hybrid systems and smart materials, supported by AI-driven optimization, to further improve protection while balancing cost and manufacturability.

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