

ENERGY CONVERSION RATE INDEX (ECRI) EVOLUTION OF AUXETIC SANDWICH COMPOSITE CORES UNDER IMPACT FRACTURE

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Abstract - Impact processing is not merely about total target breakage, it reveals how efficiently advanced materials like composites manage, transform and dissipate energy during their fracture. Sandwich composite structures, widely used in aerospace and defence, are valued for their high stiffness to weight ratio and excellent energy absorption. However, existing studies focus only on the total energy absorbed by composites during impact situations and overlook the rate at which the energy is dissipated. Conversion rate of Kinetic energy of the impactor to Internal energy of composite directly influences stress wave propagation, damage initiation and fracture evolution. Novelty of this work lies in introducing a new parameter- the Energy Conversion Rate Index (ECRI), which captures the rate at which Kinetic energy is converted into Internal energy during an impact. Auxetic core geometries such as re-entrant and chiral designs as well as newly proposed conic-auxetic hybrid configurations are systematically studied under equal mass and volume conditions to ensure their fair comparison. Explicit dynamic simulations using LS-DYNA are employed to evaluate both energy absorption and its temporal evolution. The results show that conic profiled auxetic hybrid cores significantly outperform conventional and existing auxetic designs by enhancing energy dissipation rates, promoting more uniform deformation and delaying localized failure. These findings highlight that how energy flow within a structure is as important as how much it absorbs. The outcome of this study offers a new direction for designing fracture resistant sandwich composites.

Keywords: Sandwich Composite Structures, Auxetic Metamaterials, High-Velocity Impact (HVI), Energy Conversion Rate Index (ECRI), Conic - Auxetic Core Geometry.

1. Introduction

Sandwich composite structures have emerged as a cornerstone in modern engineering applications particularly in aerospace and defence industries. They characterize exceptional stiffness to weight ratio and yield superior energy absorption capabilities under impact loadings [1, 2]. The ability of these structures to efficiently dissipate impacting kinetic energy plays a critical role in ensuring structural integrity and occupant safety [3]. Extensive research efforts have been directed toward enhancing the impact resistance of sandwich composites through material selection, structural design and advanced core architectures [2, 4].

Auxetic metamaterial configurations are characterized by their negative Poisson's ratio and are marked by their enhanced indentation resistance, shear stiffness and energy absorption performance [5, 6]. Re-entrant and chiral auxetic

geometries have demonstrated promising improvements over conventional honeycomb structures. This is particularly evident in mitigating localized failure and promoting distributed deformation mechanisms [7, 8]. Along with these developments, geometric tailoring of cellular composite core architectures, which includes graded and conic-inspired designs, has emerged as a promising direction for enhancing progressive deformation and impact energy absorption [9, 10]. Recent advances in architected materials and hybrid auxetic composites demonstrate that core geometry plays a dominant role in governing impact response and energy dissipation efficiency. However, the optimization of energy absorption behaviour with respect to auxetic composite core architectures remains an unexplored subject due to the complex interplay between geometry, material response, and loading conditions, the Figure 12 shows ECRI evolution of auxetic sandwich composite cores structures. [2, 11].

Present state of research in impact studies of composites predominantly evaluates impact performance using energy absorption efficiency which quantifies the amount of energy absorbed in impact events. This approach does not capture the rate at which energy conversion occurs in composites during impacts. In High Velocity Impact (HVI) scenarios, the rate of energy transfer is equally critical, as it governs stress wave propagation, peak force transmission and the initiation of damage mechanisms [12]. A significant gap exists in the literature due to the lack of a robust parameter to characterize the temporal evolution of energy absorption in sandwich composites. Present study addresses this limitation by introducing a novel metric termed the Energy Conversion Rate Index (ECRI). ECRI quantifies the rate of transformation of kinetic energy into internal energy during impact events. ECRI, unlike conventional energy measurement metrics, captures the dissipation and kinetics of energy thereby providing deeper insight into the dynamic impact response of sandwich structures.

In this work, a series of high-performance auxetic sandwich core geometries are systematically designed and analyzed under a mass and volume conserved framework. This ensures a fair and consistent comparison across chosen configurations. Explicit dynamic finite element simulations are carried out using the industry standard solver LS-DYNA to evaluate both energy absorption efficiency and the evolution of ECRI under varying impact energy levels. The results demonstrate that conic-auxetic hybrid geometries significantly outperform conventional and chiral auxetic cores in terms of total energy absorption and in the rate of energy conversion. Optimized conic configurations exhibit near ideal energy conversion behavior, highlighting the critical role of core geometry design in evolving next-generation impact resistant sandwich composites.

2. Geometric Modelling of Sandwich Composite Cores

Five distinct sandwich composite core configurations were designed to systematically investigate the role of geometry on impact performance. The baseline PRIMITIVE core consists of simple vertical walls and serves as a reference for benchmarking. The HEX configuration represents a conventional hexagonal re-entrant auxetic structure with a re-entrant angle of 120 degrees. To further explore geometric tailoring HEX_0.5CON and HEX_0.7CON are developed by introducing conic profiling to the core walls of the hexagonal re-entrant structure at conic parameters of 0.5 and 0.7 respectively.

Lastly, the HEX_CHIRAL configuration combines the hexagonal re-entrant geometry (120°) with chiral cross-links that connect each cell to a central circular node of 6 mm diameter. Each composite is designed under a strict mass and volume conservation framework, where the total weight is fixed at 60 grams and the overall dimensions are maintained at 100 × 30 × 20 mm (Fig. 1). This approach ensures a fair comparison by redistributing material within the geometry rather than altering mass or size. Such conservation is essential to evaluate the influence of geometry alone under identical loading conditions. Each composite candidate is constructed with four layers to capture the interaction and coupling of damage mechanisms during impact. Each of the composite core configurations are elaborated in Fig. 2.

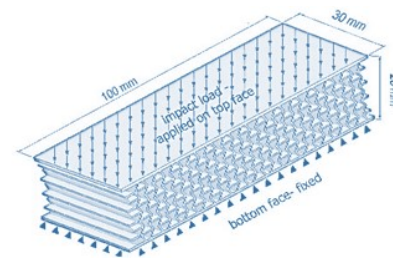


Figure 1: Geometry and boundary conditions of the sandwich composites

Nomenclature and Unit cell configuration	Stacked configuration
HEX 	
HEX_0.5CON 	
HEX_0.7CON 	
PRIMITIVE 	
HEX_CHIRAL 	

Figure 2: Composite configurations

Nomenclature system followed in present research for data sets of Kinetic energy (KE) and Internal energy (IE) for selected composite cores is elaborated in Table 1.

Table 1. Nomenclature system followed in present research

Impact Energy	Kinetic energy	Internal energy
Core	Hexagonal re-entrant sandwich structure with straight core walls	
11.7 J	HEX_11J_KE	HEX_11J_IE
26.49 J	HEX_26J_KE	HEX_26J_IE
46.8 J	HEX_46J_KE	HEX_46J_IE
Core	Hexagonal re-entrant sandwich structure with core walls at 0.5 conic parameter	
11.7 J	HEX_0.5CON_11J_KE	HEX_0.5CON_11J_IE
26.49 J	HEX_0.5CON_26J_KE	HEX_0.5CON_26J_IE
46.8 J	HEX_0.5CON_46J_KE	HEX_0.5CON_46J_IE
Core	Hexagonal re-entrant sandwich structure with core walls at 0.7 conic parameter	
11.7 J	HEX_0.7CON_11J_KE	HEX_0.7CON_11J_IE
26.49 J	HEX_0.7CON_26J_KE	HEX_0.7CON_26J_IE
46.8 J	HEX_0.7CON_46J_KE	HEX_0.7CON_46J_IE
Core	Sandwich structure primitive geometry core	
11.7 J	PRIMITIVE_11J_KE	PRIMITIVE_11J_IE
26.49 J	PRIMITIVE_26J_KE	PRIMITIVE_26J_IE
46.8 J	PRIMITIVE_46J_KE	PRIMITIVE_46J_IE
Core	Hexagonal re-entrant sandwich structure with chiral configuration	
11.7 J	HEX_CHIRAL_11J_KE	HEX_CHIRAL_11J_IE
26.49 J	HEX_CHIRAL_26J_KE	HEX_CHIRAL_26J_IE
46.8 J	HEX_CHIRAL_46J_KE	HEX_CHIRAL_46J_IE

3. Material Modelling of Sandwich Composite Cores

For reliable prediction of High Velocity Impact behaviour of sandwich composite structures with the selected core geometries, an appropriate description of material properties is essential. In the present work, the entire sandwich configuration including both facesheets and the auxetic core is treated as a monolithic system fabricated from Aluminium alloy 2014-T6. This precipitation hardened alloy is widely adopted in aerospace and defence sectors owing to its favourable combination of strength and deformability [13,14]. In its T6 temper, Al 2014 exhibits a density of approximately 2.8 g/cm³, an elastic modulus in the range of 72–73 GPa, a yield strength around 414 MPa and an ultimate tensile strength close to 483 MPa, along with an elongation to failure of nearly 13% [13,15]. Such a balance of mechanical properties makes it well suited for applications involving severe dynamic loading, where both resistance to deformation and retention of structural integrity are critical [14,16].

3.1. Numeric Modelling of Impact Event

Numerical modelling has emerged as a powerful tool for investigating the complex behaviour of sandwich composite structures under high-velocity impact (HVI), where experimental techniques often fail to capture transient internal phenomena such as stress wave propagation, localized deformation, and progressive fracture [17,18]. The need to understand how energy is transferred, dissipated, and localized within advanced composite architectures has driven

the adoption of explicit finite element (FE) methods, which are particularly suited for nonlinear, high strain-rate problems involving large deformations and contact interactions [19,20]. Recent studies have emphasized that not only the magnitude of energy absorption but also the rate and pathway of energy transfer play a decisive role in fracture initiation and propagation in sandwich systems [21, 22]. The present study employs an explicit dynamic finite element framework implemented in LS-DYNA, which is widely recognized for its robustness in simulating impact events. The governing equation of motion is expressed as Eqn (1).

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \quad (1)$$

This equation represents the balance between inertia forces $[M]\{\ddot{u}\}$, damping forces $[C]\{\dot{u}\}$ and internal stiffness forces $[K]\{u\}$ with the externally applied forces $\{F\}$. This forms the foundation of dynamic analysis in explicit finite element simulations, particularly for High-Velocity Impact (HVI) problems.

Where, the mass, damping and stiffness matrices govern the structural response under dynamic loading. Unlike implicit methods, explicit solvers advance the solution in small time increments without requiring global equilibrium iterations, making them computationally efficient for highly transient problems [18, 23]. This formulation is particularly effective in capturing high-frequency stress waves and rapid contact interactions typical of impact events [24].

The deformation behaviour is described using strain decomposition into elastic and plastic components as in eqn. (2).

$$\varepsilon = \varepsilon_e + \varepsilon_p \quad (2)$$

For high-velocity impacts involving large strains and rotations, a finite deformation framework is adopted using multiplicative decomposition as in eqn. (3).

$$F = F_e F_p \quad (3)$$

Where, F is the deformation gradient, and F_e , F_p represent elastic and plastic contributions respectively. This approach enables accurate tracking of large distortions and is essential for modelling progressive collapse and fracture in sandwich cores [20, 25].

3.2. Elastic Behaviour

The initial response of the material is governed by linear elasticity eqn. as in (4).

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} \quad (4)$$

Where,

σ_{ij} - Cauchy stress tensor representing internal forces per unit area acting within the material

C_{ijkl} - Fourth-order elasticity (stiffness) tensor, defining material stiffness properties

ε_{kl} - Strain tensor, representing deformation of the material

i, j, k, l - Tensor indices corresponding to spatial directions (x, y, z)

For isotropic materials eqn. (5) holds.

$$\sigma_{ij} = 2G \varepsilon_{ij} + \lambda \varepsilon_{kk} \delta_{ij} \quad (5)$$

Where,

G - Shear modulus of the material

λ - First Lamé constant

ε_{ij} - Strain tensor components

ε - Volumetric strain

δ_{ij} - Kronecker delta

ε_{kk} - First invariant (trace) of the strain tensor, representing volumetric strain

This elastic framework provides the foundation for more advanced nonlinear constitutive models and is critical in capturing the initial stress wave propagation during impact [17].

3.3. Elastic-Plastic Behaviour

To accurately capture the nonlinear response under high strain rates, the Ramberg-Osgood relation combined with Power Law Plasticity is adopted as in eqn. (6).

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K} \right)^n \quad (6)$$

where

ε - Total strain

σ - Applied stress

E - Young's modulus (elastic response component)

K - Strength coefficient (material constant defining stress level for plastic flow)

n - Strain hardening exponent (controls curvature of plastic region)

This formulation ensures a smooth transition between elastic and plastic regimes and allows representation of strain hardening effects. Such models are widely used in impact simulations of metallic and composite systems due to their numerical stability and physical accuracy [25, 26].

Element stiffness matrix is formulated as eqn. (7):

$$[K] = \int_V [B]^T [D] [B] dV \quad (7)$$

Where $[B]$ is the strain-displacement matrix and $[D]$ is the constitutive matrix. The numerical solution follows an incremental stress update algorithm, which evaluates stress evolution at each time step based on strain increments. This approach enables accurate tracking of nonlinear material behaviour and large deformation kinematics [18, 23].

In this study, penalty-based contact algorithms are employed to simulate the interaction between the impactor and the sandwich composite. Boundary conditions are defined such that the bottom face of the structure is fixed, while the impact load or velocity is applied on the top face. Proper contact definitions ensure realistic force transfer and prevent numerical instabilities such as interpenetration [24, 27].

3.4. Energy Formulations in an Impact Event

The impact process is fundamentally governed by conservation of energy in eqns. (8) and (9).

$$E_{\text{input}} = E_{\text{absorbed}} + E_{\text{transmitted}} + E_{\text{lost}} \quad (8)$$

In physical terms:

$$KE_{\text{impactor}} = IE_{\text{structure}} + KE_{\text{residual}} + E_{\text{dissipation}} \quad (9)$$

Energy-based approaches provide a deeper understanding of structural performance by linking deformation mechanisms to energy flow within the system [21, 28].

Energy absorption in sandwich composites occurs through multiple interacting mechanisms, including elastic deformation of facesheets, core crushing, shear deformation, and progressive buckling of cellular structures. Additionally, fracture processes such as crack initiation, propagation, and interfacial debonding contribute significantly to energy dissipation. Recent research has shown that auxetic and architected core geometries enhance energy absorption by promoting distributed deformation and delaying localized failure [22, 30, 31].

The evolution of kinetic and internal energy provides critical insight into impact performance. Efficient energy-absorbing structures exhibit a rapid decrease in kinetic energy accompanied by a smooth and continuous increase in internal energy, indicating controlled deformation and minimal

rebound. In contrast, poor designs show high residual kinetic energy and abrupt energy transitions, indicating inefficient energy dissipation and potential catastrophic failure [21, 29].

The stability of explicit simulations is governed by the Courant condition, given in eqn. (10).

$$\Delta t \leq \frac{L}{c} \quad (10)$$

Where c , is the wave speed in the material. Adhering to this condition ensures accurate stress wave propagation and prevents numerical divergence during simulation [23].

4. Results and Discussions

The presented simulations map the Von Mises effective stress fields in sandwich composite configurations subjected to impact energies of 11.7 J, 26.49 J, and 46.8 J, enabling a direct comparison of structural response across different core geometries. The stress contours are examined at a representative time instant of 0.5 seconds, capturing the peak stress state along with the progression of both localized and distributed deformation within the structure. This visualization highlights how variations in core architecture influence stress distribution and load transfer under increasing impact severity. Detailed examination of these stress patterns helps identify regions of stress concentration and likely initiation sites for damage, providing critical insight into the overall dynamic performance and impact resistance of each composite configuration.

At an impact energy of 11.7 J, the interaction between kinetic energy (KE) and internal energy (IE) reveals the baseline energy conversion behaviour of all five core configurations (see Fig. 3). The PRIMITIVE core shows minimal growth in internal energy and retains a significant portion of kinetic energy throughout the event, reflecting its poor energy absorption capability. In comparison, the HEX and HEX_CHIRAL configurations exhibit a more rapid decline in kinetic energy along with a corresponding increase in internal energy, indicating early activation of auxetic re-entrant deformation and rotational responses. The conic-based cores, HEX_0.5CON and HEX_0.7CON, demonstrate the most effective performance, with a steep rise in internal energy and near-total dissipation of kinetic energy within a shorter time span. This response is attributed to efficient progressive crushing enabled by the conic wall geometry. Collectively, the results at 11.7 J establish a clear performance order - PRIMITIVE < HEX < HEX_CHIRAL < HEX_0.5CON < HEX_0.7CON - based on their energy absorption and conversion efficiency.

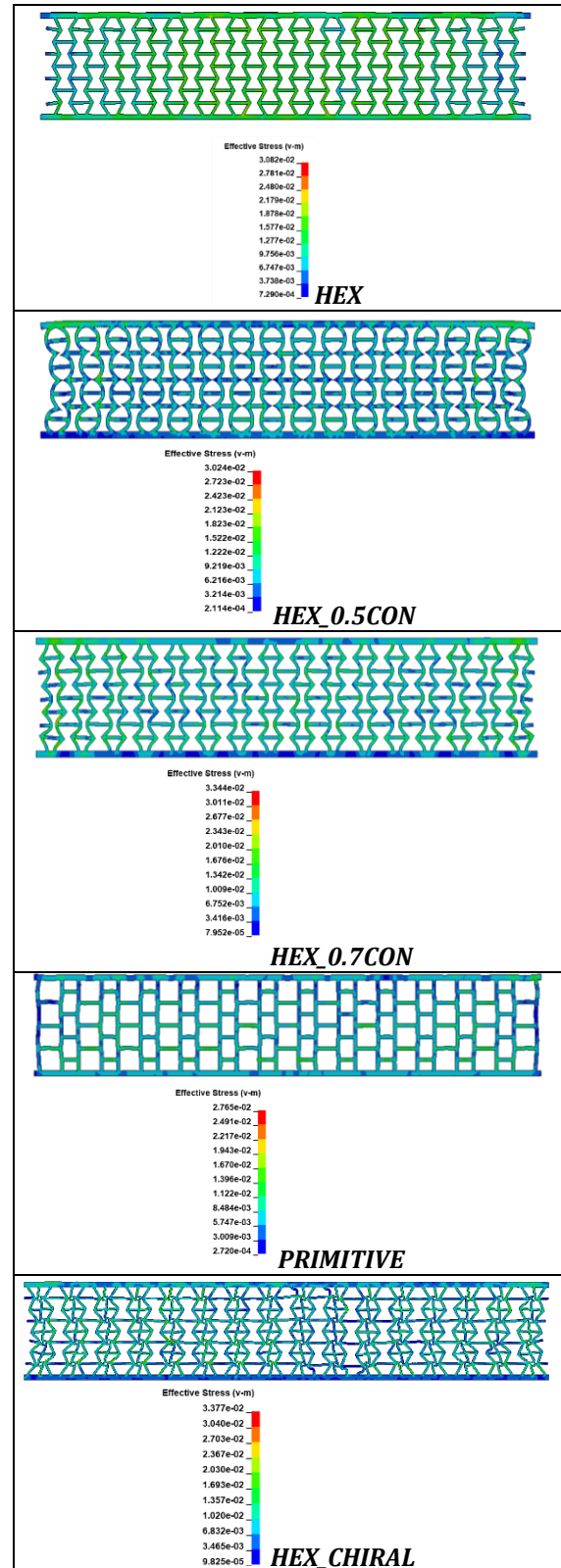


Figure 3: Von Mises effective stress for 11.7 J impact response at 0.5 seconds

The combined KE-IE evolution illustrating this behaviour is presented in Fig. 4.

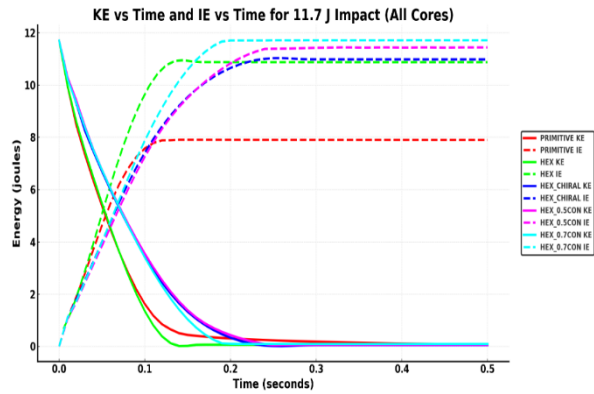


Figure 4: Internal energy and Kinetic energy combined plots for 11.7 Joule impact

At an impact energy of 26.49 J, the KE-IE relationship provides a clearer distinction in the energy handling capability of the different core geometries (see Fig. 5).

The PRIMITIVE configuration continues to show poor performance, with slow kinetic energy reduction and only a modest increase in internal energy, indicating inefficient energy absorption. In contrast, both HEX and HEX_CHIRAL cores exhibit a quicker drop in kinetic energy along with a more uniform and sustained buildup of internal energy, suggesting improved deformation behaviour and better stress redistribution compared to the primitive structure.

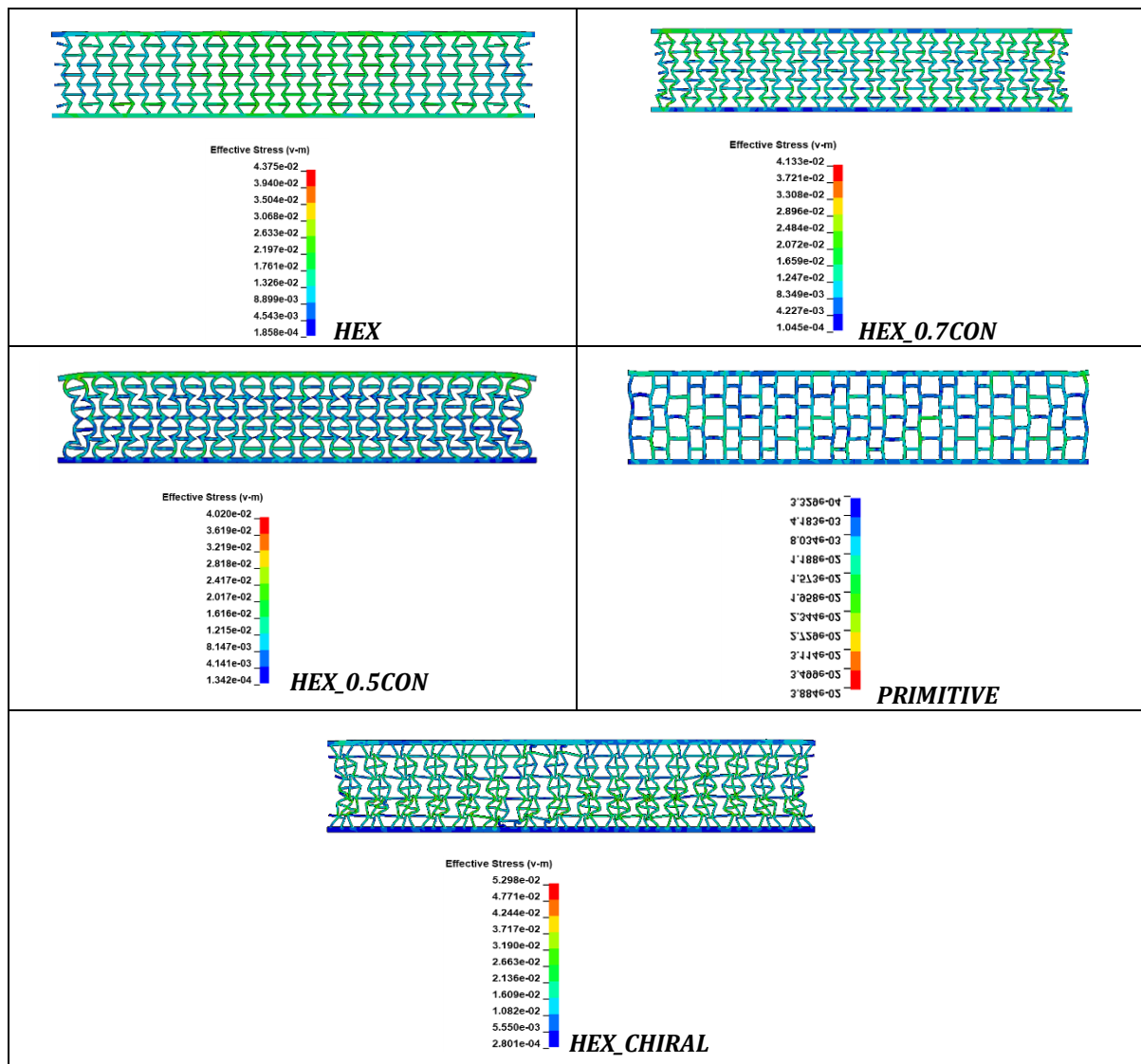


Figure 5: Von Mises effective stress for 26.49 J impact response at 0.5 seconds

The conic-based configurations, HEX_0.5CON and HEX_0.7CON, demonstrate the most pronounced internal energy growth, highlighting their superior ability to convert impact energy at early stages.

Overall, the response at 26.49 J confirms that

conic-profiled cores are more effective in handling impact loads, marked by rapid initial energy conversion followed by a stable plateau.

The combined KE-IE trends illustrating this behaviour are presented in Fig. 6.

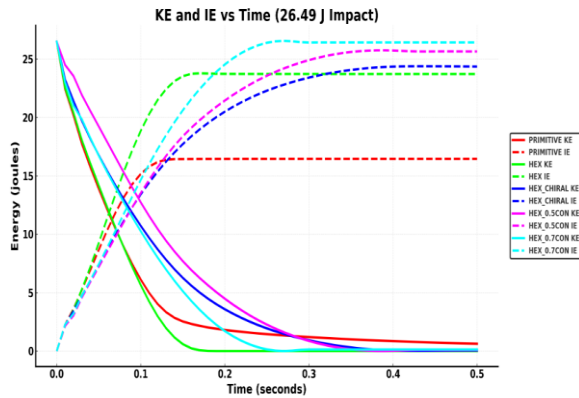


Figure 6: Internal energy and Kinetic energy combined plots for 26.49 Joule impact

At the highest impact energy of 46.8 J, the differences in energy conversion behaviour among the core configurations become distinctly evident (see Fig. 7 and Fig. 8). The PRIMITIVE core shows the poorest performance, with a slow decline in kinetic energy and only a limited rise in internal energy, indicating insufficient core deformation and a tendency to transmit rather than absorb impact loads. A large fraction of the input energy persists as residual kinetic energy, passing through the structure without effective dissipation. In comparison, the HEX and HEX_CHIRAL cores demonstrate a more pronounced reduction in kinetic energy coupled with a consistent increase in internal energy, reflecting improved plastic deformation due to their geometric design.

The conic-profiled cores, HEX_0.5CON and HEX_0.7CON, exhibit the most efficient behaviour, with rapid conversion of kinetic energy into internal energy and the highest levels of energy absorption. Among them, HEX_0.7CON achieves nearly complete energy conversion, approaching 100% efficiency. Notably, a major portion of the energy transfer occurs within the initial 0.1 seconds across all configurations, indicating strong strain-rate sensitivity in the deformation response.

Overall, the results confirm that conic-based core architectures offer superior performance in progressive impact mitigation, with the ranking established as PRIMITIVE < HEX < HEX_CHIRAL < HEX_0.5CON < HEX_0.7CON.

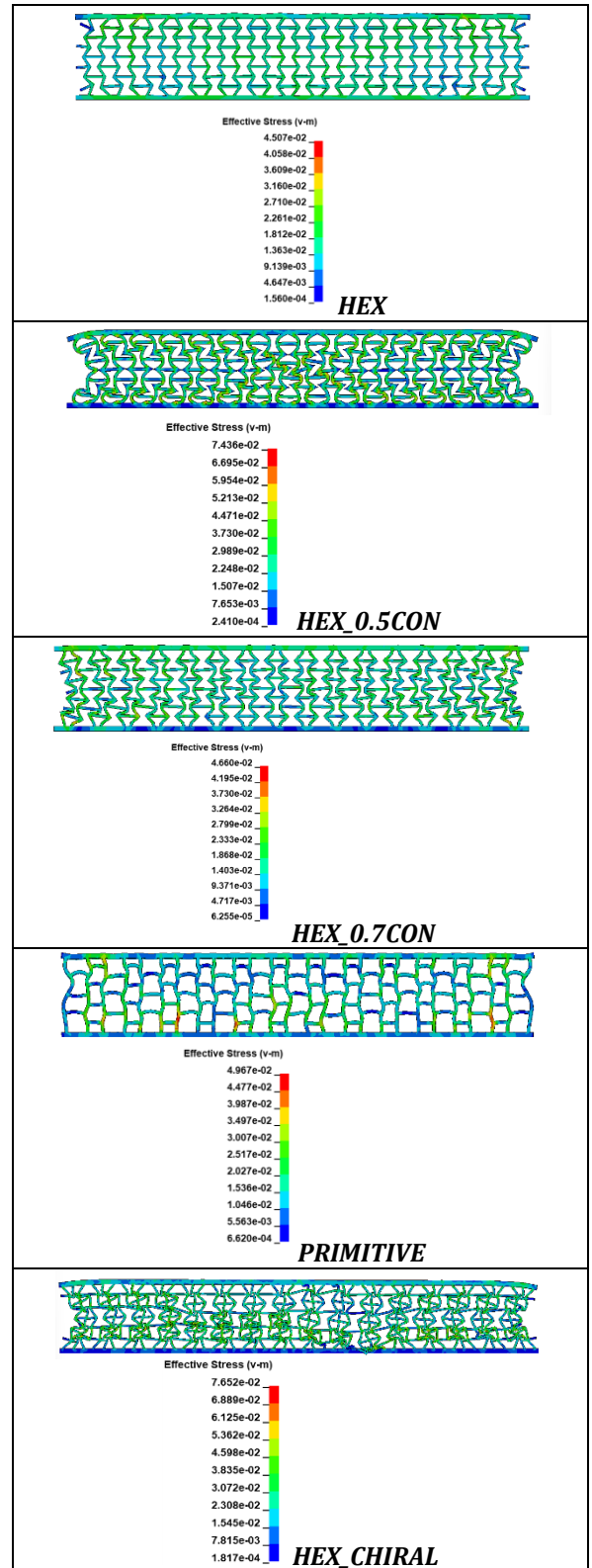


Figure 7: Von Mises effective stress for 46.8J impact response at 0.5 seconds

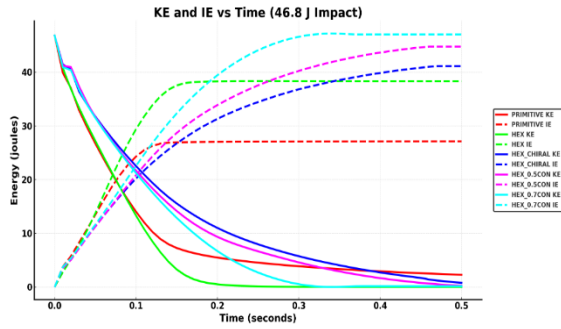


Figure 8: Internal energy and Kinetic energy combined plots for 46.8 Joule impact

Internal energy at stabilization and Energy absorption efficiency at stabilization is summarized in Table 2(a) and 2(b) respectively.

Table 2.a. Internal energy stabilization values and energy absorption efficiency values

CORE TYPE	Internal energy at stabilization (Joules)		
	at 11.7 J impact	at 26.49 J impact	at 46.8 J impact
HEX	10.95	23.78	38.34
HEX_0.5CON	11.45	25.75	44.77
HEX_0.7CON	11.72	26.56	47.20
PRIMITIVE	7.91	16.46	27.11
HEX_CHIRAL	11.03	24.39	41.14

Table 2.b. Internal energy stabilization values and energy absorption efficiency values

CORE TYPE	Energy absorption efficiency at stabilization (Unity)		
	at 11.7 J impact	at 26.49 J impact	at 46.8 J impact
HEX	0.94	0.90	0.82
HEX_0.5CON	0.98	0.97	0.96
HEX_0.7CON	1.00	1.00	1.00
PRIMITIVE	0.68	0.62	0.58
HEX_CHIRAL	0.94	0.92	0.88

5. Experimental Validation

A full-scale sandwich panel incorporating a HEX_CHIRAL architecture was manufactured from Al 2014-T6 using a wire-cut fabrication process. The fabricated specimen was then tested under a drop-weight impact corresponding to an impact energy of 11.7 J, delivered using a drop tower with a height of 1 meter.

The experimental setup of Drop weight impact test rig was designed with Load cell and data acquisition system to record the data (Fig. 9). sandwich panel made of Al 2014-T6 is tested in the rig (Fig 10(a)). For validation purposes, an overlapping digital image correlation analysis was carried out. The experimentally obtained

deformation patterns (Fig. 10(b)) were systematically compared with those predicted through finite element simulations. The resulting deformation contours from both methods showed a high degree of match (Fig. 10(c)). This is established through error mapping between respective images and quantified by Normalized Cross Correlation (NCC) value at 0.92.

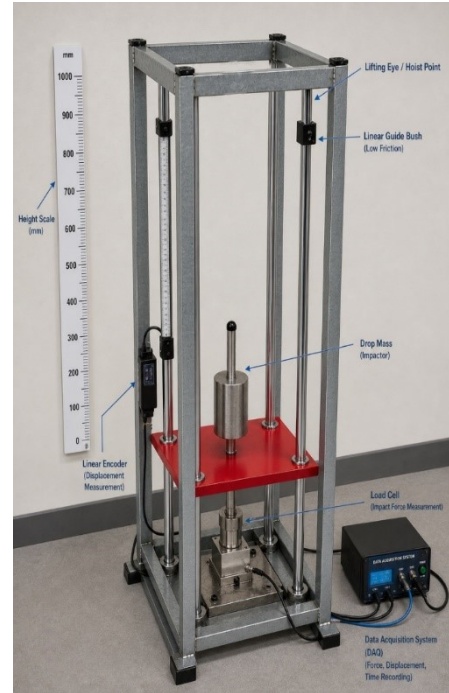


Figure 9: Experimental setup for drop-weight impact test

The strong visual agreement between experimental and numerical results provides compelling evidence for the validity of the finite element model, demonstrating its robustness and effectiveness in accurately capturing the dynamic impact behaviour of comparable structural configurations investigated in this work.

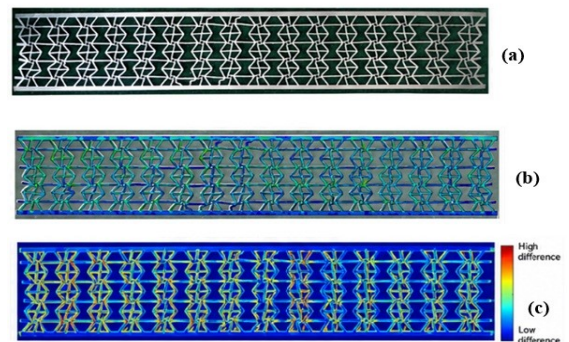


Figure 10: (a) Experimental result of HEX CHIRAL after impact of 11.7 Joules, (b) Simulation result of HEX CHIRAL after impact of 11.7 Joules, (c) Error mapping of experimental and simulation results

6. Energy Conversion Rate Index (ECRI)

The Energy Conversion Rate Index (ECRI) is introduced as a metric to describe how quickly impact energy is converted into internal energy within a sandwich composite after loading. In this work, ECRI is determined by taking the initial rate of increase of the internal energy–time response and normalizing it with the corresponding impact energy, ensuring comparability across different configurations. This measure is critical in impact studies because it captures the speed of energy absorption and dissipation, offering deeper insight into the dynamic response of the structure. The value of ECRI is strongly governed by the core geometry, making it an effective parameter for evaluating and comparing different sandwich core designs. Mathematically the expression for ECRI is given as in Eqn. (11).

$$ECRI = \frac{\frac{d(IE)}{dt} \big|_{0 \rightarrow t}}{KE_{initial}} \quad (11)$$

Table 3. ECRI evolution during impact events

COMPOSITE CORE	CORE STRUCTURE	INITIAL IMPACT ENERGY (J)	ECRI EVOLUTION		
			ECRI (0–0.1 s)	ECRI (0–0.2 s)	ECRI (0–0.3 s)
HEX		11.7	7.80	4.21	3.01
		26.49	6.95	4.10	2.98
		46.8	6.28	3.99	2.73
PRIMITIVE		11.7	6.48	3.38	2.25
		26.49	5.73	3.11	2.07
		46.8	5.19	2.89	1.93
HEX_CHIRAL		11.7	6.34	4.55	3.13
		26.49	5.07	3.87	2.95
		46.8	4.32	3.35	2.62
HEX_0.5CON		11.7	6.20	4.63	3.05
		26.49	5.11	4.05	3.13
		46.8	4.45	3.62	2.87
HEX_0.7CON		11.7	6.73	5.01	3.52
		26.49	5.54	4.63	3.43
		46.8	4.82	4.21	3.35

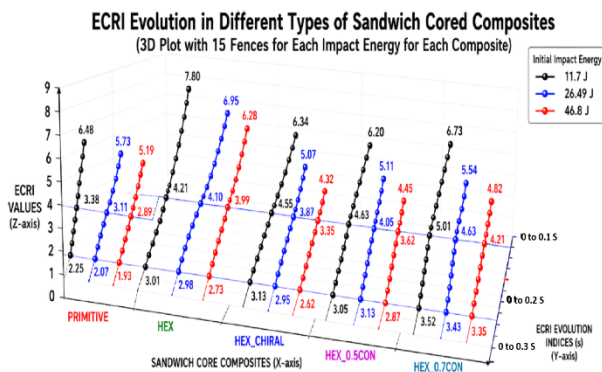


Figure 11: Comparative ECRI evolution fence plots during impact events.

In this study, the first 0.3 seconds of the Impact response are used to evaluate the rate of internal energy development. This range is fixed considering the highest level of energy interaction as is evident from the L S Dyna simulation figures.

Most of the composite damage, and hence energy absorption, is seen happening at this time interval. For a more comprehensive interpretation, the ECRI evolution was further examined over three-time intervals: 0 - 0.1 s, 0 - 0.2 s, and 0 - 0.3 s. The slope is determined by applying a linear fit to the internal energy–time curve within this initial time interval. ECRI evolution in present study are enumerated in Table. 3. A fence graph is plotted for comparative study of the ECRI evolution in different impact events in Fig. 11.

A higher ECRI signifies a rapid increase in internal energy, indicating quicker absorption of impact energy. The HEX configuration shows strong ECRI values at the early stage, but this advantage diminishes as the interaction progresses. In contrast, HEX_0.7CON maintains high ECRI levels consistently over time, demonstrating superior and sustained energy absorption due to its conic geometry, making it the most efficient configuration. HEX_0.5CON also exhibits stable behaviour throughout the impact duration, reinforcing the effectiveness of conic-based designs. The HEX_CHIRAL core displays moderate ECRI values but fails to retain this performance at later stages. Meanwhile, the PRIMITIVE core shows an initial increase in ECRI followed by a sharp decline, underscoring its inability to sustain energy absorption over time.

6. Conclusions

In this research, both analytical and numerical examinations have been conducted on different hybrid sandwich core structures. The most important outcomes of the study are as follows:

The PRIMITIVE configuration continues to show poor performance, with slow kinetic energy reduction and only a modest increase in internal energy, indicating inefficient energy absorption.

In comparison, the HEX and HEX_CHIRAL cores demonstrate a more pronounced reduction in kinetic energy coupled with a consistent increase in internal energy, reflecting improved plastic deformation due to their geometric design.

Overall, the results confirm that conic-based core architectures offer superior performance in progressive impact mitigation, with the ranking established as PRIMITIVE < HEX < HEX_CHIRAL < HEX_0.5CON < HEX_0.7CON.

The HEX configuration shows strong ECRI values at the early stage, but this advantage diminishes as the interaction progresses. In contrast, HEX_0.7CON maintains high ECRI levels consistently over time, Figure 12 show the ECRI evolution of Auxetic sandwich cores. the study demonstrates superior and sustained energy absorption due to its conic geometry, making it the most efficient configuration. Insights of the present study could be used as interim design for future development of composite structures for varied applications involving impact loads.

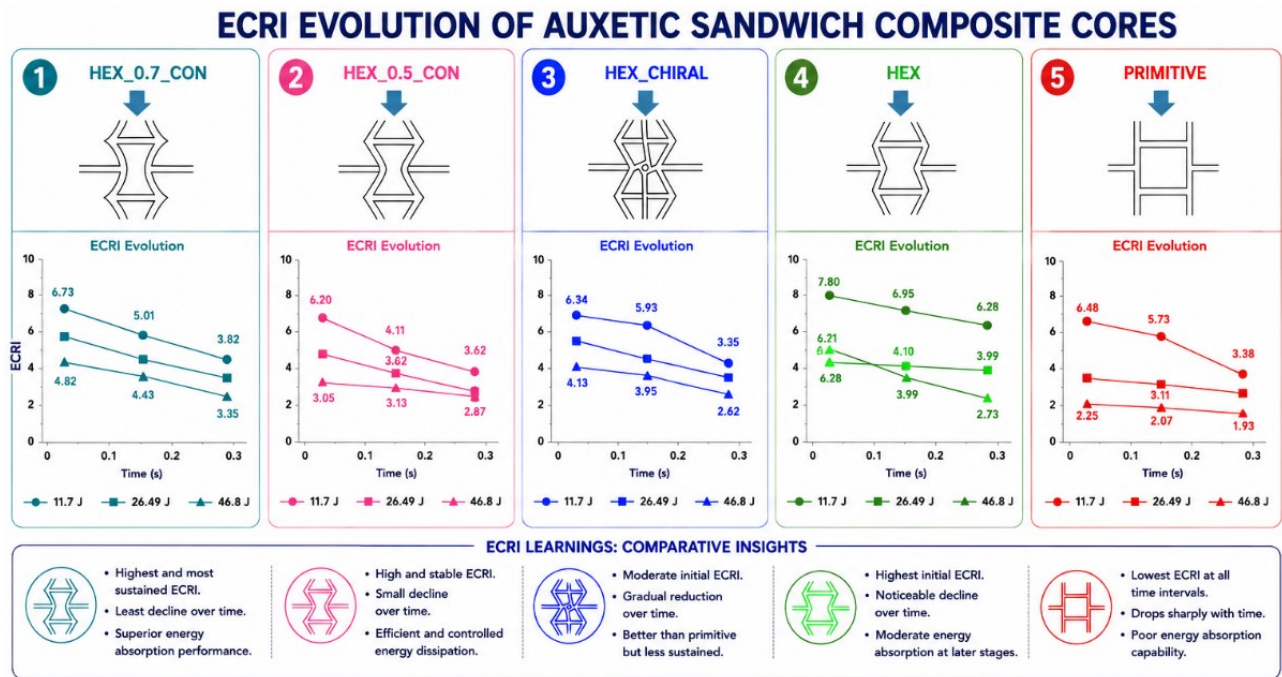


Figure 12: ECRI evolution of Auxetic sandwich cores

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