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ADAPTIVE ENERGY-ABSORBING META-STRUCTURES FOR MULTI-DIRECTIONAL IMPACT PROTECTION IN LIGHTWEIGHT MECHANICAL SYSTEMS

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Abstract

In the case of lightweight mechanical systems, like those in transport, robotics or protective items, it is necessary to dissipate the impact energy from any direction with as little mass as possible. A route to this is mechanical meta-structures – in this case, the material's response is not only governed by its composition but its geometry. A total of 21 elemental researches on lattice structures, plate structures, shell structures, auxetic structures, buckling-based structures, multistable and 4D printed structures were collected and summarized from the literature. The sources were divided into seven categories as per the time of publication and evaluated using five criteria: specific energy absorption, multi-directional isotropy, reusability, tunability and manufacturability. The relative density of three representative architectures were compared for relative densities, 0.05, 0.10 and 0.20, using scaling relations for stiffness, plateau strength and densification strain. The highest normalized energy absorption was given to the plate-based architectures, while the highest scores in isotropy and reusability were for the multistable and phase transforming architectures respectively. Multistable architectures were the only ones that got the maximum tunability marks. The reversible nature of the field is shown for micro-lattices with densities of less than 1mg/cm³ and recoverable strains of over 50 per cent. The composite index showed that multistable architectures ranked the highest (3.6) followed by plate-based architectures (3.4). The synthesis indicates that hybrid solutions, comprising isotropic plate-based load paths and multistable or programmable components, seem to be the most promising way towards adaptive multi-directional impact protection.

Index Terms—Mechanical Metamaterials, Energy Absorption, Impact Protection, Lattice Structures, Auxetic Structures, Multistability, Buckling, Four-Dimensional Printing, Lightweight Systems.

I. INTRODUCTION

In lightweight mechanical systems, such as vehicle crash structures, drone frames, orthotic devices, and protective packaging, there is always a balance between mass and how much energy can be absorbed.Traditional materials like foams and honeycombs can be permanently deformed and absorb energy through plastic collapse, but they can't be recycled and only work well in one main direction of force.Besides the material's own properties, mechanical

metamaterials offer another way to control how stiff something is, its Poisson's ratio, compressibility, and how it deforms by changing the shape [1].Energy-absorbing metamaterial structures are designed to have a long energy-absorbing phase with high densification strain, and newer versions can even recover their shape.This review will look at how these properties can be extended to work in many directions and made adaptable.These structures are important in real-world use because they can be made safe in a crash without being too heavy due to thick walls.

Adaptivity means the structure changes shape when it experiences a load or an external stimulus.The flexible mechanical metamaterials can change their properties through elastic instabilities like buckling, snapping, and folding, some of which can be reversed or switched without changing the material itself [2].As shown in Figure 1, the research in this area has evolved over time, with one study published in 2011, followed by a sharp increase between 2014 and 2019, and another in 2020.This timeline shows the rapid development of additive manufacturing from ideas to real products.The key question being explored is how to combine load-bearing design, instability-driven reconfiguration, and programmed shape changes to create impact protection that is multi-directional, light, and reusable.The need for multi-directional performance can be challenging, as it requires the structure to reconfigure without losing effectiveness when subjected to angled, combined, or reversed forces.

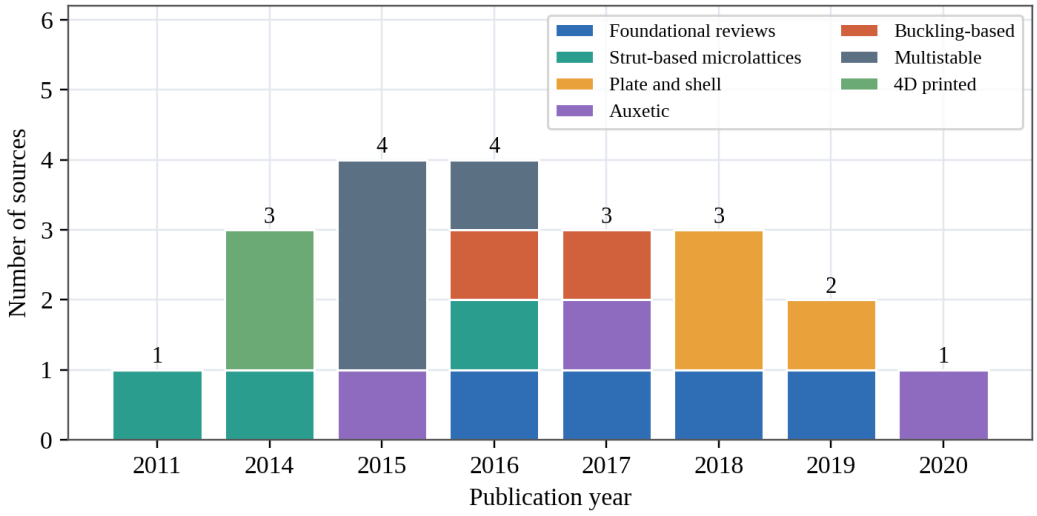


Fig. 1. Chronology of the 21 reviewed sources by year of publication and structural group.

II. REVIEW METHODOLOGY AND PERFORMANCE METRICS

A systematic approach was followed in the synthesis process, detailed in the flowchart of Fig. 2. There were no records which were judged to be irrelevant to energy absorption, multi-directional response or adaptive reconfiguration that were discarded from the 21 records provided. The classification was performed based on the previous researched work [3] that classifies the stiffness, rigidity and compressibility, extended to seven groups: foundational reviews, strut-based microlattices, plate and shell architectures, auxetic and Poisson-ratio

tunable, buckling-based lattices, multistable and phase transforming materials, 4D printed systems. There are four foundational reviews and four multistable studies, with each of the other groups having three records (14.3 percent). During a data-extraction phase, the energy-absorption descriptors were noted, including the topology, constituent material, fabrication route, loading mode, and reported and/or derivable energy-absorption descriptors. Scoring was not based on the number of publications, so that there was no bias against influential, but isolated studies.

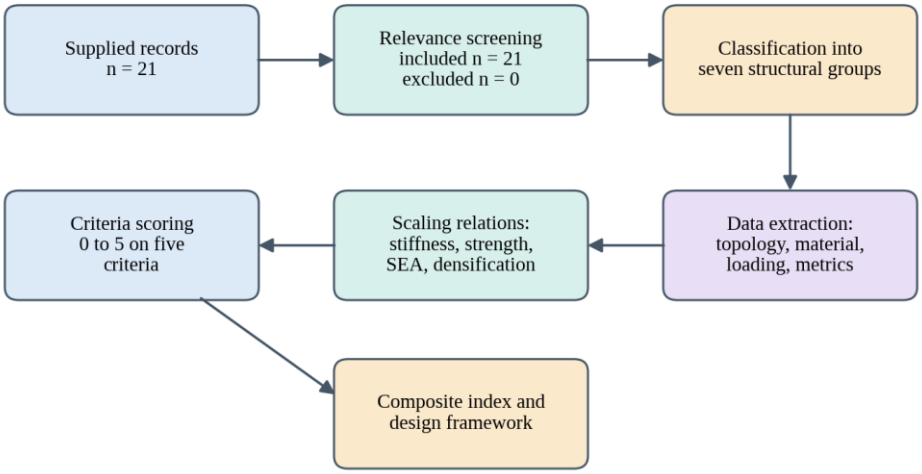


Fig. 2. Workflow of the systematic review from record screening to composite assessment.

TABLE I. DISTRIBUTION OF THE REVIEWED SOURCES BY STRUCTURAL GROUP

Structural group	Records	Share (%)	Years	Mean year
Foundational reviews	4	19.0	2016–2019	2017.5
Strut-based microlattices	3	14.3	2011–2016	2013.7
Plate and shell architectures	3	14.3	2018–2019	2018.3
Auxetic and Poisson-ratio-tunable	3	14.3	2015–2020	2017.3
Buckling-based lattices	2	9.5	2016–2017	2016.5
Multistable and phase-transforming	4	19.0	2015–2016	2015.2
Four-dimensional printed systems	2	9.5	2014	2014.0
Total	21	100.0	2011–2020	2016.2

Note. Shares are rounded to one decimal place; years refer to the year of publication.

There were two ways of normalizing performance that were used. Specific energy absorption (SEA) is an energy absorption per unit mass up to the densification strain of the additively manufactured metallic lattice, which is reported as the primary figure of merit for lattices under static and dynamic loading [4]. Quantity is the area under the stress/strain curve divided by the effective density, ρ, of the structure as in Eq. 1 (where σ is the compressive stress and ε the nominal strain) and εd is the densification strain. The ratio of the average crushing force Fmean

to the maximum crushing force Fpeak is called crush force efficiency (CFE), as shown in Equation 2.This ratio tells us how flat the crushing force curve is and how much acceleration is passed on.Table II connects the sources to the structural class, the main failure mechanism, and the main contribution.It's important to remember that values of specific energy absorption (SEA) are only useful if they're given at the same density and strain rate; this was taken care of during the extraction process.

$$\text{SEA} = \frac{1}{\rho}\int_0^{\varepsilon_d} \sigma(\varepsilon)d\varepsilon \quad (1)$$

$$\text{CFE} = \frac{F_{\text{mean}}}{F_{\text{peak}}} \quad (2)$$

TABLE II. LITERATURE MAPPED TO STRUCTURAL CLASS, MECHANISM, AND CONTRIBUTION

Ref.	Class	Governing mechanism	Principal contribution
1	Foundational	Architecture-governed properties	Defines mechanical meta-materials and property categories
2	Foundational	Elastic instabilities	Reviews flexible metamaterials with reconfigurable response
3	Foundational	Stiffness, rigidity, compressibility	Classifies extreme-property metamaterials
4	Strut microlattice	Stretching and bending of printed struts	High SEA under static and dynamic loading
5	Strut microlattice	Hollow-tube microlattice	Ultralight architecture with recovery from large compression
6	Strut microlattice	Stretching-dominated cells	Near-constant stiffness-to-weight ratio over wide density range
7	Plate and shell	Strut, skeletal, and sheet topologies	Topology-property relationships in printed metallic cellular materials
8	Plate and shell	Closed-cell plate elements	Near-optimal isotropic stiffness at low density
9	Plate and shell	Smooth shells, cubic symmetry	Anisotropic elasticity, yield strength, and SEA
10	Foundational	Selective laser melting of lattices	Properties, performance, applications, and challenges
11	Auxetic	Re-entrant deformation	Compressive behaviour of printed auxetics, tested and modelled
12	Auxetic	Re-entrant origami	Negative Poisson's ratio combined with bistability
13	Auxetic	Mechanically tuned geometry	Tunable Poisson's ratio for vibration control
14	Buckling-based	Tailored beam buckling	Reusable lightweight shock absorbers
15	Buckling-based	Buckling elements	Characteristics of buckling-based metamaterials

Ref.	Class	Governing mechanism	Principal contribution
16	Multistable	Bistable elements	Trapping of elastic strain energy
17	Multistable	Snap-through under tension	Snapping metamaterials with recoverable deformation
18	Multistable	Discrete stable configurations	Shape-reconfigurable architected materials
19	Multistable	Phase-transforming cells	Recoverable energy dissipation with hysteresis
20	Four-dimensional printed	Multi-material shape change	Time introduced as a design dimension
21	Four-dimensional printed	Active origami	Autonomous folding of printed sheets

Note. Reference numbers correspond to the numbered reference list.

III. LATTICE AND SHELL ARCHITECTURES FOR ENERGY ABSORPTION

A. Strut-Based Microlattices

Scientists found that metals can be used to make very porous yet strong microlattices.Hollow Ni-P tubes with a wall thickness of about 100 nm were made, achieving very low densities as low as 0.9 mg/cm³, and these structures could recover over 50% of the strain [5] [6].The results from projection microstereolithography microlattices showed that these structures were stretch-dominated.The stiffness-to-weight ratio stayed almost the same across three orders of magnitude in density, with a linear relationship between stiffness and relative density.

$$\frac{E}{E_s} = C\left(\frac{\rho}{\rho_s}\right)^n \quad (3)$$

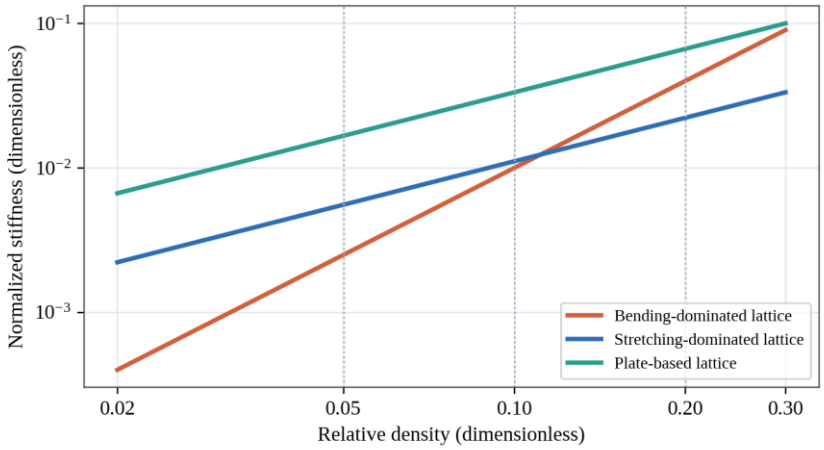


Fig. 3. Normalized stiffness as a function of relative density for three architecture classes.

B. Plate, Shell, and Sheet Architectures

Apart from strut based topologies, a systematic comparison of the topology of strut, skeletal and sheet based metallic cellular materials fabricated using additive manufacturing also showed that the mechanical response of the cellular materials have also been topology dependent at the same relative density [7]. The stress is evenly distributed in the geometries based on TPMS, which have no discontinuities (stresses) at the nodal junctions and continuous surfaces, and is higher at the same mass compared with the strut lattices that have discontinuities (stresses) at the nodal junctions. Such observations suggest a promising future for multi-directional loading with sheet based architectures, where a surface-based unit cell would not require a few aligned struts for loading. Continuous surfaces also provide a natural 'neighbour' connection between the cells which means that the loss of one connection is unlikely to cause a local 'failing'.

The plate-lattices were then found to be a family of lowdensity metamaterials, which have optimal isotropic stiffness, and were explained as the result of closed-cell elements of plate, which transmit the load in all directions, and are very close to the Hashin-Shtrikman upper limits at low density [8, 9]. The degree of directional dependence was demonstrated to be tunable by changing the shape of the shells and the metamaterials were analyzed in terms of anisotropic elasticity, yield strength and specific energy absorption. One of the traditional methods to measure the degree of directional dependence of a cubic-symmetry structure is by calculating the Zener anisotropy ratio, as in Eq. (4), with the value of 'isotropic' equal to 1. Multi-directional protection is directly related to isotropy, that is, if A does not equal one, then different amounts of energy would be absorbed by different directions of the impulse. Plate and Shell designs overcome this disadvantage of Strut Lattice, which is the strong loading directionality of the strength.

$$A = \frac{2C_{44}}{C_{11} - C_{12}} \qquad (4)$$

C. Comparative Scaling Analysis

While SLM is the most common manufacturing method for metallic lattices, manufacturing defects such as strut waviness, surface roughness and internal porosity limit the properties obtained in the fabricated lattice to values different from the nominal ones [10]. Idealized scaling relations were assessed to work out the scaling relations independent of such imperfections and the densification strain was approximated by the following Eq.5: r is a relative density. The values of stiffness, plateau strength and normalized SEA are calculated for 3 architecture classes and are presented in Table III and plotted versus the density range in Fig. 4 is the normalized SEA. The lattices that were bent and those that were stretched had stiffness curves which crossed at a relative density of 0.11. It is found that at a relative density of 0.10, the normalized SEAs and stiffnesses of the class-based lattice and the stretching-dominated lattice are both 0.430, and those of the bending-dominated lattice are 0.082 and 0.010, respectively, which indicate that the class-based lattice has higher stiffness and SEA than the bending-dominated lattice by 3.3 times and 5.3 times, respectively. The ranking is based on the

qualitative results of the experimental studies, but the absolute values may vary depending on the prefactors used.

$$\varepsilon_d \approx 1 - 1.4r \tag{5}$$

TABLE III. COMPUTED SCALING METRICS AT REPRESENTATIVE RELATIVE DENSITIES

Architecture class	Relative density	Normalized stiffness	Normalized plateau strength	Densification strain	Normalized SEA
Bending-dominated lattice	0.05	0.0025	0.0034	0.93	0.062
Bending-dominated lattice	0.10	0.0100	0.0095	0.86	0.082
Bending-dominated lattice	0.20	0.0400	0.0268	0.72	0.097
Stretching-dominated lattice	0.05	0.0056	0.0150	0.93	0.279
Stretching-dominated lattice	0.10	0.0111	0.0300	0.86	0.258
Stretching-dominated lattice	0.20	0.0222	0.0600	0.72	0.216
Plate-based lattice	0.05	0.0167	0.0250	0.93	0.465
Plate-based lattice	0.10	0.0333	0.0500	0.86	0.430
Plate-based lattice	0.20	0.0667	0.1000	0.72	0.360

Note. Prefactors assumed for illustration: C = 1, 1/9, 1/3 with n = 2, 1, 1; plateau coefficients 0.3, 0.3, 0.5 with exponents 1.5, 1, 1. Normalized SEA = plateau strength × densification strain ÷ relative density.

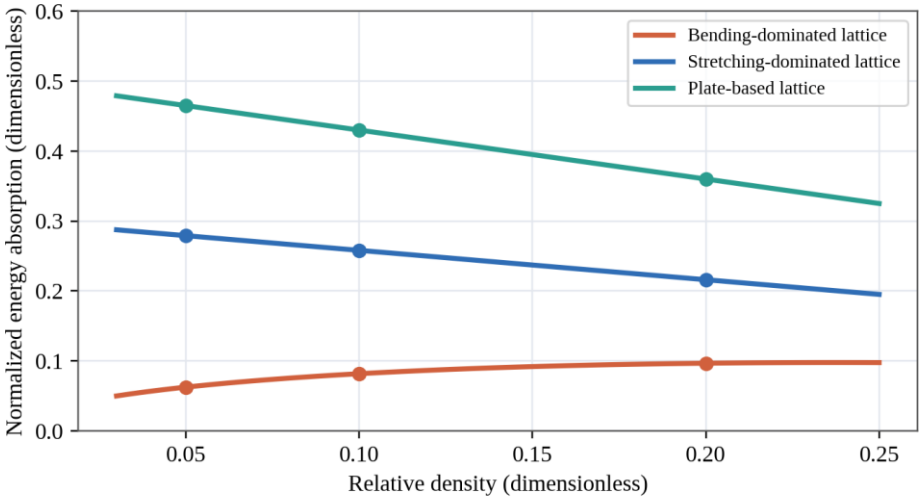


Fig. 4. Normalized specific energy absorption as a function of relative density.

IV. AUXETIC AND POISSON-RATIO-TUNABLE ARCHITECTURES

Auxetic (contraction) structures are those that get smaller when squeezed to the side, and could be used for energy absorption by having them concentrate the material under the compression point. Experimental and numerical tests of auxetic 3-D printed structures were performed to show their capability of capturing the mode of deformation and the plateau stress, and to compare the compressive behavior of re-entrant and related structures [11]. It is believed that such coupling between lateral contraction and densification postpones the start of rapid stress escalation, thus increasing the effective stroke. However, the auxetic effect is typically used in one direction only, and may only assist in more than one direction if the unit cell is designed to have three-dimensional symmetry. The late-stage response, therefore, relies on cell collapse: numerical modelling is therefore indispensable to design.

Reports have been published of origami-based re-entrant metamaterials being negative Poisson's ratio materials or bistable (that is, the same structure would switch between two stable states) [12,13]. A tunable lattice metamaterial for vibration control applications with a change in geometry through pre-compression to change the dynamic behavior was demonstrated. The Poisson's ratio (εlat/εax) is defined as in Eq. 6. A negative value will indicate the auxetic property and tuning or switching values will provide an instant means to switch between the energy absorbing response to the load. The bistability and tunable Poisson's ratio can thus be linked to the multistable ideas presented in the following section and to auxetic geometry. This switching could be employed to make a structure stiffer before encountering an impact and softer after the impact to minimise the peak impact transmitted force.

$$\nu = -\frac{\varepsilon_{\text{lat}}}{\varepsilon_{\text{ax}}} \qquad (6)$$

V. INSTABILITY-DRIVEN ADAPTIVE MECHANISMS

A. Buckling-Based Lattices

The post-buckling plateau gives a force limiting response which is repeatable in energy absorption, as there is no material failure involved in elastic buckling. A set of tailored buckling microlattices, which involved carefully arranging the cross-sections of the beams to buckle one-by-one, were shown to be recoverable lightweight shock absorbers after being compressed [14, 15]. Further analysis of mechanical metamaterials gave insights into the geometry, slenderness and arrangement of elements to control the critical load, hysteretic response, and dissipated energy. The disadvantage of many buckling designs is that the buckling beams are aligned along a design axis giving a directionality. For such multi-directional action, therefore, either orthogonal arrays of buckling elements, or isotropic arrays of curved members must be used. The volume between the loading and unloading curve represents the amount of energy lost per cycle, and is the definition of the amount of energy that can be recovered, the reusable absorption capacity.

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B. Multistable and Phase-Transforming Materials

Multistable architectures are an extension on this idea, that includes additional bistable components that store elastic strain energy in a "metastable" state. Experiments conducted on elastomeric architected materials showed that strain energy could be stored during loading, and could be stored until it was desired to be released; that the number of stored energy per cell depends on the energy barrier between the stable states [16]. The double-well potential in Eq. (7) is a convenient idealisation of a bistable element, the strain energy being represented by U, the displacement coordinate by x, the half-distance between the stable states by a, and the height of the barrier by U0. The potential and energy absorbed during a forward transition is shown in Fig. 5. The barrier has to be surmounted when the compression occurs, and during compression mechanical work is transformed into stored elastic energy and dissipated without permanent damage. The energy absorbed per transition scales with U0, which is a design parameter which may be tuned by the slenderness and geometry of the beam.

$$U(x) = U_0 \left[\left(\frac{x}{a} \right)^2 - 1 \right]^2 \qquad (7)$$

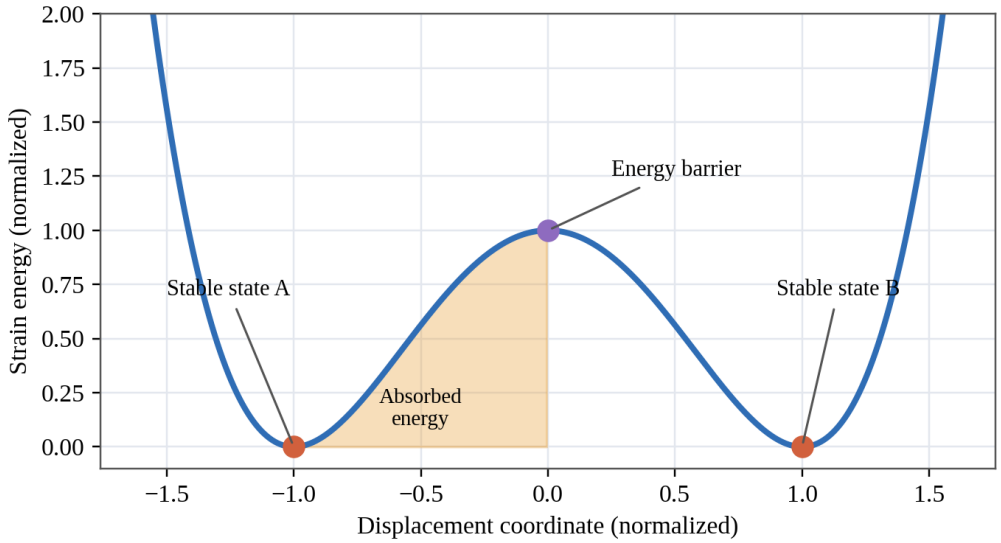


Fig. 5. Double-well strain energy landscape of a bistable element with the energy absorbed during forward transition.

Mechanical metamaterials made of bistable elements that undergo multiple snap-through deformations and then recover to one of the other states, have been demonstrated to have a serrated response of the force with snap behavior under tension [17]. The discovery is important as many of the energy-absorbing architectures are better designed to work in compression, while impact events in the real world often have both tensile and shear components. Reversible energy absorption is then possible under a wider range of loading modes thanks to tension-

activated snapping. Orthogonal and 3D patterns may be used for the elements to provide direction independent force limitation if the sequential unloading of energy barriers is designed to be. This is not a common feature in the collection of elements reviewed. Dynamic testing is required for this behavior, as it is sensitive to loading rate, and the behavior needs to be quantified.

Multistable shape reconfigurable architected materials were shown that could reconfigure between discrete stiffness and energy absorption properties as desired [18, 19]. Phase Transforming Cellular Materials, where the structural elements were switching between stable states like martensite, showed high energy dissipation and also a definite hysteresis loop, which enabled them to achieve both energy dissipation and full shape recovery. In the comparison shown in Table IV, the adaptive mechanisms discussed above are compared with respect to trigger, how the energy is handled, reversibility and direction sensitivity. Buckling and elastic-storage are elastic-dissipation while auxetic and multistable are full-reversibility/dissipation. Hence, the choice of a mechanism should be based on the predominant loading mode and number of re-use cycles required.

TABLE IV. COMPARISON OF ADAPTIVE ENERGY-HANDLING MECHANISMS

Mechanism	Primary trigger	Energy-handling route	Reversibility	Directional sensitivity
Auxetic densification	Axial compression	Geometric densification and collapse	Partial	High
Elastic buckling	Compression above critical load	Post-buckling plateau with elastic storage	Full	Moderate to high
Bistable snapping	Compression or tension above barrier	Barrier crossing and trapped elastic energy	Full	Moderate
Phase transformation	Compression across transition	Hysteretic transition between stable states	Full	Moderate
Four-dimensional programmed	Thermal or other stimulus	Stimulus-driven reconfiguration	Material dependent	Low to moderate

Note. Entries represent the qualitative assessment derived from the reviewed sources.

VI. INTEGRATED ASSESSMENT, CHALLENGES, AND OUTLOOK

A. Integrated Assessment

Multi-material printed structures are 4D printed structures, which have been added as an additional design dimension as they change shape after printing in response to a stimulus [20]. The scores (sk) for each of the five criteria were scored from 0 to 5 based on the evidence extracted and the unweighted composite index was computed as follows (Eq. 8) using the scores (sk) for the five criteria and the number of criteria (K = 5). The score is shown in Table V and Fig. 6 shows the profiles. The highest index (3.6) was achieved with the multistable architectures, followed by plate and shell architectures (3.4) and auxetic architectures (3.2). The

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most isotopic score was achieved by the plate and shell group (5), and the strut lattices' score was the lowest (2.6), because they were the easiest to manufacture of the load-bearing groups. This is because there was no preference in a generic application to any one criterion in the corpus.

$$\Psi = \frac{1}{K}\sum_{k=1}^{K} s_k \qquad (8)$$

TABLE V. CRITERIA SCORES AND COMPOSITE INDEX OF STRUCTURAL GROUPS

Structural group	SEA	Isotropy	Reusability	Tunability	Manufacturability	Index
Strut lattices	3	2	2	2	4	2.6
Plate and shell	4	5	2	3	3	3.4
Auxetic	3	2	3	4	4	3.2
Buckling-based	3	2	5	3	2	3.0
Multistable	3	2	5	5	3	3.6
Four-dimensional printed	2	3	3	5	2	3.0

Note. Scores range from 0 (lowest) to 5 (highest); the index is the unweighted mean.

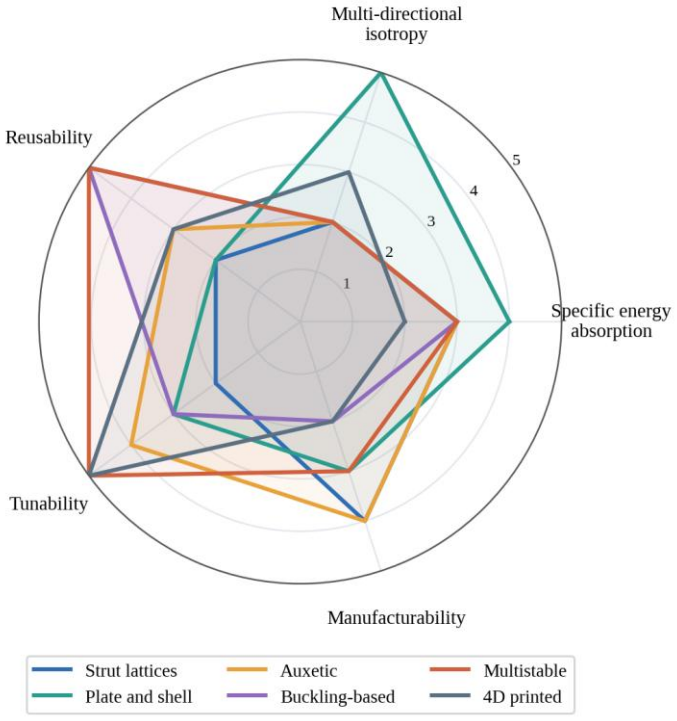


Fig. 6. Criteria profiles of the six structural groups on a radial scale from 0 to 5.

B. Challenges and Outlook

However, a first demonstration of printed multi-material Sheets with embedded Active Material that can automatically reconfigure in desired 3D shapes revealed that 4D printing can be employed to manufacture such printed material such that the reconfiguration needed for a direction adaptive protection can be programmed during the printing process [21]. However, there are a number of drawbacks to translation. There are many different fabrication routes, and they have different feature sizes, materials available, and sensitivity to defects as outlined in the table below. Studies reviewed did not consider all three of the following: rate dependence (fatigue as a function of repeated cycling); scalability (from micrometre scale specimens to engineering size components). The combination of multistable and programmable elements with isotropic plate-based load path is therefore expected to be a priority in future research and will be addressed with emphasis on dynamic multi-axial load path. Direct comparisons between SEA, CFE and recovery across studies would be possible with comparable scales.

TABLE VI. FABRICATION ROUTES AND PRINCIPAL LIMITATIONS

Fabrication route	Typical material	Feature scale	Principal limitation
Templated electroplating	Nickel-phosphorus on polymer template	Wall thickness near 100 nm	Restricted to thin-walled hollow members
Projection microstereolithography	Photopolymers, coated metals or ceramics	Micrometre scale	Limited build volume
Direct laser writing	Photopolymers	Sub-micrometre to micrometre	Very small build volume and slow throughput
Selective laser melting	Metallic powders	Sub-millimetre struts	Waviness, roughness, and internal porosity
Multi-material polymer printing	Elastomers and active polymers	Millimetre to sub-millimetre	Limited resolution and rate-dependent response

Note. Feature scales indicate orders of magnitude.

VII. CONCLUSION

By integrating three design levels – namely an isotropic load-bearing topology, an instability-based energy-handling mechanism and a programmable reconfiguration path for the lightweight system – a multi-directional adaptive impact protection has been demonstrated in a synthesis of 21 studies. The computed scaling relations indicated that the stiffness of the lattice was 3.0 times that of lattices that were dominated by stretching, while the stiffness of the multistable and phase-transforming lattices was the highest composite value of 3.6, with better reusability and tunability. Areas for improvement are identified as rate dependent dynamic validation, multi-axial testing, fatigue assessment and scale-up of fabrication. The most promising direction of future investigation is the hybrid designs, in which the use of the bistable elements is combined in the plate-based or shell-based designs, and the use of stimulus responsive members. In order to facilitate quantitative benchmarking in future syntheses,

reporting of the density and loading rate of the SEA and CFE are recommended to be comparable.

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