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Highly efficient and reusable energy-absorbing metamaterials exploiting soft rate-dependent frictional interfaces

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Abstract

Energy-absorbing materials with both high absorption efficiency and good reusability are ideal candidates of impact protection products. Despite the prosperous needs, the current designs are either efficient but one-time-use, or reusable but low capacity. Here, we show that metamaterials with unprecedentedly high energy-absorbing efficiency and good reusability can be designed, reaching an energy-absorbing capacity of >2000 kJ/kg per lifetime. The extraordinary performance is achieved by exploiting rate-dependent frictional dissipation between soft elastomer and hard constituents in a porous structure. Particularly, the compliant elastomer in the metamaterials ensures a large real contact area, while the stiff porous supporting frame offers high and robust compressive pre-stress for the sliding interfaces, both of which are essential for vast frictional dissipation. Owing to the rate-dependent friction of elastomer interface, the metamaterials also exhibit a self-adapting feature such that more energy can be absorbed when subjected to higher impact rates. We believe this design opens an avenue to develop high-performance reusable energy-absorbing metamaterials that enable completely novel designs of machines or structures.

1 Introduction

Energy-absorbing materials and structures¹, such as foams in helmets and car bumpers, play an important role in keeping humans and objects safe from unexpected impacts^{2–4}. This protective functionality demands two iconic features of their force-displacement relations: hysteresis and limited peak force⁵. They ensure impact energy is dissipated without imposing high stress onto the protected targets. Hence, an ideal force-displacement curve of an energy-absorbing material is rectangular-shaped and has a long and flat force

plateau. Achieving such curves is crucial for creating exceptional energy-absorbing materials, and has attracted great research interest in exploring original design strategies^{6,7}.

The most well-known energy-absorbing mechanism is damaging constituent materials, such as ductile metals^{8,9}, brittle foams^{10–14} and ceramics^{15,16}. Besides, in order to maintain a long yielding force plateau, curved shapes¹⁷ or auxetic materials¹⁸ are introduced to prevent structures from immediately losing their load-carrying capabilities due to localization. The mechanisms of damage and plastic flow can dissipate a huge amount of energy, benefited from bond breakage or dislocations motion at the molecule level. Taking commercial aluminum foams as an example^{19,20}, their energy-absorbing capacities are as high as 30 kJ/kg or 30 MJ/m³. The excellent performance has endowed them with broad applications in engineering, such as protecting cargo²¹ and preventing collapse of rocks in mining²². However, they are usually for one-time usage, after which the constituents are permanently damaged. This shortcoming can be partially overcome by incorporating damage-tolerant micro-lattices^{23–27} or phase-transforming constituents^{28–30} that allow the materials to undergo cyclic loadings, although the performance decreases along cycles.

To completely remove the one-time-usage limitation, a promising way is designing the microstructures of metamaterials, which provide a vast space to gain outstanding mechanical properties that are otherwise hard to achieve^{31–34}. By introducing non-damage energy dissipation mechanisms into microstructures, researchers have developed reusable energy-absorbing metamaterials. A well-investigated mechanism is mechanical instability of micro-cells, such as buckling of flexible beams^{35–39} and shells⁴⁰, and nonlinear forces between magnets^{41–43}. The assembled structures, obtained by connecting a series of these micro-cells, often produce hysteric saw-tooth force-displacement curves^{44,45}. The metamaterials constructed in this way are reusable since the deformation is elastic. Nevertheless, their energy-absorbing capabilities are typically several orders of magnitude lower than those of the non-reusable ones, which significantly

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limits their potential applications. For example, one kind of micro-beam based metamaterial⁴⁶ only has an energy-absorption capacity around 0.15 kJ/kg or 0.015 MJ/m³.

The relatively low performance of reusable energy-absorbing metamaterials is mainly caused by two reasons: the constituent materials can only sustain limited forces, and only a small portion of the microstructures contribute to energy dissipation. A strategy to improve the capacity is increasing the peak forces of the saw-teeth^{47–49} through increasing the maximum stresses and using stiffer materials. However, this method endangers both the constituent materials and protected targets. Researchers recently attempted other non-damage energy dissipation mechanisms, such as visco-elasticity⁵⁰ and dry friction^{51–53} between sliding particles, to build energy-absorbing metamaterials. Nevertheless, their designs are still in infancy and the obtained energy-absorption capacities are as low as other reusable ones. Therefore, it is still an open problem to simultaneously achieve high-reusability and high-capacity metamaterials for energy absorption (Fig. 1a).

Here, we survey the frictional mechanism in depth, and realize a kind of high-performance reusable energy-absorbing metamaterials. They have rectangular-shaped load-displacement curves and their energy-absorbing capacities are comparable to the non-reusable ones, reaching 0.1 – 10 kJ/kg or 0.1 – 13 MJ/m³. Our basic idea is maximizing friction forces. Roughly speaking, friction forces between two parts increase with their interface's real contact area at micro-scale rather than the nominal contact area at macro-scale. Real contact area of two hard materials is much smaller than nominal contact area, while that of a soft material and a hard material is almost the same as nominal contact area. Hence, we inserted stiff rods/ropes into smaller diameter holes of a soft porous elastomer to achieve large real contact area. Meanwhile, another stiff porous frame is interwoven with the elastomer to significantly enlarge the prestress between the sliding parts (Fig. 1b, c). The obtained load-displacement curve has a long plateau, whose height and length can be easily tuned by tailoring the geometry (Fig. 1d, e). Moreover, the energy-absorbing capacity shows no sign of notable decreasing after 200 loading-unloading cycles in experiments, indicating the outstanding reusability. An additional benefit of this design is passively adaptive energy-absorbing ability under different impact velocities, which is sourced from the rate-dependent friction coefficient between the elastomer and stiff rods/ropes and further magnified by geometric and material nonlinearity. This property is further utilized to create self-recoverable metamaterials. All these features shape the reported metamaterials as ideal candidates for energy absorption.

Fig. 1: Design of the proposed energy-absorbing metamaterials with both high capacity and high reusability. **a** A typical energy-absorbing material shows a trade-off between reusability and energy-absorbing capacity. **b-c** The proposed metamaterial is composed of stiff rods/ropes and a porous reinforced elastomer, which can slide between each other. The porous reinforced elastomer has a stiff frame interwoven with a soft silicone elastomer, inspired by tendon-bone interface shown in upper right corner of **(b)**. **d** The metamaterial can be subjected to compression or tension. Here, H_0 is the total height, including the supporting platform, and A is the cross-sectional area of the reinforced elastomer. **e** The measured force balances the friction forces between the rods/ropes and reinforced elastomer. The force F is expected to first sharply increase with the displacement u in the static friction region, and then reaches a plateau in the dynamic friction region, which shows an ideal rectangular shape for energy absorption.

2 Results

Interwoven structure of the proposed metamaterials. Figure 1b sketches the overall design of the proposed metamaterials. We interwove a soft porous silicone elas-

Fig. 2: Experimental verification of high capacity and reusability of the proposed energy-absorbing metamaterials.

a Three different structures, stacked up by cell i, ii and iii, to understand how the prestress of elastomer and stiffness of the supporting frame affect the energy-absorbing performance. The upper schematics display the structure of each cell. Cell i contains only an elastomer, ii and iii involve stiff frames with sharp and smooth corners, respectively, to reinforce the elastomer. Each cell has a height 5 mm and flat-to-flat distance 10 mm. The diameter of the rods 2.0 mm is slightly larger than that of the holes 1.8 mm to create pressure between the elastomer and the rods. The lower images show the corresponding manufactured seven-column samples. **b** Measured load-displacement curves for structures in (a) with a compression loading rate $v = 500 \text{ mm/min}$. All the curves show nearly flat force plateaus F_p when the displacement is high. The two metamaterials with interwoven structures exhibit higher F_p , 3 times as many as that of the one with only an elastomer. Inset: images showing the elastomer without a supporting frame is more compliant and undergoes a larger deformation. **c-d** Stress-strain curves of structure ii and iii under 200 loading-unloading cycles in reusability test. After all cycles, the capacity of the former decreases by about 14% , while that of the latter varies only about 4%.

tomers structure (gray) with a stiff porous polylactic acid (PLA) frame (yellow) to obtain a reinforced elastomer that has a better load-bearing capability. This interwoven structure was inspired by human's tendon-bone interface^{54,55}, where soft tendon tissue interconnects with hard bone tissue to achieve a robust anchor (upper right part of Fig. 1b). The porous stiff frame was designed to have a number of hollow columns in a hexagonal packing, since a hexagonal packing has a better compression strength than a square or triangular one⁵⁶ due to higher connectivity. Meanwhile, its surface was modified from a minimal surface to guarantee smoothness everywhere⁵⁷, and avoid unnecessary stress concentrations. The PLA frame was 3D printed, while the porous silicone elastomer was cast using a mold composed of several parts (see Methods and Supplementary Fig. 1). More details on the structural geometry is given in Supplementary Fig. 2.

Steel or carbon fiber rods were inserted to the cylindrical

holes in the reinforced elastomer. The diameter of the rods is slightly larger than that of the holes, which creates pressure between the elastomer and the rods along the frictional surfaces. When the rods are pushed downward (Fig. 1d), a compression force F balances the friction forces. When F is low, there is no relative displacement between the rods and the elastomer due to static friction, and F linearly increases with the deformation of the elastomer. When F is high, relative sliding between the rods and the elastomer occurs, and F remains at a plateau corresponding to the dynamic friction force (Supplementary Movie 1). For the convenience of quantifying the energy-absorbing capacity, strain of the proposed metamaterials was defined as displacement u divided by the initial height H_0 (Fig. 1d), and stress as force F divided by the cross-sectional area A . Then, the stress-strain curve is expected as Fig. 1e, and the area of the stress-strain loop is the absorbed energy per unit volume. In addition, replacing the rods with

ropes (right part of Fig. 1d) should yield similar frictional behavior against tensile loads.

Prestress of the elastomer and high stiffness of the supporting frame contribute together to high energy-absorbing capacity and reusability. As shown in Fig. 2a, we fabricated three different structures to reveal how the soft elastomer and stiff frame contribute to the energy-absorbing performance. All the structures have seven columns, arranged as Fig. 1c, and each column is stacked up by six regular hexagonal cells of height 5 mm and flat-to-flat distance 10 mm. All the cells have four straight holes of diameter 1.8 mm. The differences among the cells of the three structures are: cell i is composed of the elastomer only; cell ii adopts a stiff porous frame, in which cylindrical bridges with sharp corners are used to connect adjacent cells, to reinforce the elastomer; and cell iii has a smooth stiff frame.

Inserting 2mm-diameter steel rods into the 1.8mm-diameter holes introduces prestress between the rods and the elastomer. Pushing rods downward, Fig. 2b shows the obtained load-displacement curves, measured under displacement control by a single-axis MTS Testing Machine with a loading rate $v = 500$ mm/min. Each of these curves possesses a linearly increasing region, followed by a long plateau with plateau force F_p , just as expected. As a result, both structures ii and iii show a higher slope of the force-displacement curve in the linear region and a higher plateau force than those of structure i due to the reinforcement of the stiff frames. Besides, the plateau force F_p of structure ii is slightly larger than that of structure iii, since the supporting frame of cell ii is stiffer. More quantitative, the energy-absorbing capacities of structure ii and iii are around 1.0 MJ/m^3 , which is about three times as large as that of structure i and comparable to non-reusable energy-absorbing materials, such as aluminum foams.

Further, we checked the reusability of structure ii and iii through cyclic loading. After 200 stress-strain cycles at a loading rate of 500 mm/min, the energy-absorbing capacity of structure ii decreases by about 14% (Fig. 2c), which might be caused by the stress concentration in the elastomer and potential debonding between the soft elastomer and stiff frame due to sharper corners. However, energy-absorbing capacity of structure iii does not change notably (Fig. 2d). Overall speaking, structure iii has better comprehensive performance on energy-absorbing capacity and reusability, so that it was adopted here to design our metamaterials.

Load-displacement performance of a single column. Next, we would like to understand how physical parameters affect energy-absorbing capacity, which is mainly featured by F_p of a single column. Obviously, F_p can be modified by tailoring the parameters, e.g., the height h of the elastomer, or the diameter d of the steel rods (Fig. 3a). Theoretically, frictional dynamics says

$$F_p = \mu N, \quad (1)$$

where μ is the coefficient of dynamic friction between the elastomer and the rods, and N is the total normal contact force acted on the rods. Intuitively, increasing the column height h enlarges the contact area, and increasing the diameter difference between rods and holes $d - d_h$ enlarges the prestress. As a result, N , and therefore F_p , should be proportional to both h and $d - d_h$, which was validated by varying a single geometric parameter in controlled experiments (Fig. 3b-c). To simplify the experiments, only four steel rods were inserted into the central column for each seven-column module (right in Fig. 3a); thus the obtained plateau values F_p are about 1/7 of that in Fig. 2b. Moreover, we observed F_p increases notably with the loading rate v (Fig. 3d), which indicates that energy-absorbing capability gets higher for a higher impact velocity. This attractive feature will be quantified and understood in the next few paragraphs.

Mechanisms of rate-dependent energy-absorbing behavior. The plateau force $F_p = \mu N$ relies on the loading rate v , indicating that at least one of μ and N changes with v . Further quantitative studies reveal they both are, and only in that case can the velocity curve in Fig. 3d be understood. More specifically, we attribute the metamaterials' rate-dependent energy-absorbing behavior to the synergy of two iconic characteristics of elastomers: rate-dependent frictional coefficient, and nonlinear hyperelastic property in large deformation.

Frictional coefficient μ , especially for elastomers⁵⁸, can be rate-dependent⁵⁹⁻⁶¹; therefore, we first conducted friction experiments on a Tribometer (Rtec MFT-V) to quantify μ between our silicone elastomer and steel (see details in Supplementary Fig. 3). In the tribometer experiments, a steel sphere was pressed by a downward force F_z onto an elastomer disc, placed on a rigid flat plate (inset of Fig. 3e). The plate was rotated to control the sliding speed, meanwhile, F_z was maintained to be an almost constant. Considering that μ relies on normal contact stress⁶² and elastomer thickness, we prepared two elastomer discs of thicknesses $t = 0.4$ and 1.3 mm, since the thickness of the elastomer surrounding a single rod varies along the rod; and applied normal force $F_z = 1.1$ and 3.0 N respectively, ensuring the nominal normal contact stress acted on the steel sphere approaches the average normal stress applied to the rods, which is about 0.5 MPa according to the finite element method (FEM) simulations (for details see Supplementary Fig. 4), in which the constitutive behavior of silicone elastomer is assumed to follow the third order Ogden hyperelastic model⁶³ (see Methods and Supplementary Fig. 5). Taking the ratio of the lateral force to the normal force at different loading rates v , the frictional coefficient μ versus v can be obtained. Averaging the measured data of the two elastomer samples yields μ - v curve in Fig. 3e. When v rises from 57 to 471 mm/min, μ increases by 30%, while $F_p = \mu N$ increases by 60%, greater than μ .

Therefore, besides μ , the normal contact force N at the

Fig. 3: Dependence of F_p on geometric parameters and loading rate v . **a** Geometry of a single column of the reinforced elastomer (left), stacked up by multiple cells of type iii in Fig. 2a. The image (right) shows the experimental setup to quantify the performance of a single column under certain loading rate v , in which the scalar bar represents 2 cm. **b-d** Dependence of F_p on h , $d - d_h$ and v . The former two show linear relations, while the last one is nonlinear. For every data point, three samples were fabricated, and each sample was tested for four times; the error bars represent the ranges of the results obtained. **e** Measured $\mu - v$ curve between elastomer discs, with thickness 0.4 and 1.3 mm, and a steel sphere by the experimental setup shown in the inset, where the scalar bar represents 2 cm. The error bars represent the ranges of the results measured with different elastomer thickness. **f** FEM model of a single column, whose supporting frame is set to be invisible for clarity. The rods are forced to move downward by displacement u , the vertical reaction force F is computed, and the normal force N is obtained by integrating the normal stress σ_n along the rods. **g** $N - F$ curve calculated from the FEM model in (f). **h** Comparison of the experimentally measured $F_p - v$ curve (black solid) and the numerically calculated $F_p - v$ curve from the FEM model in (f-g). **i-j** A self-recoverable energy-absorbing metamaterial, and its load-displacement curves under different loading rates. The right images show the configurations of the metamaterial corresponding to the different loading states indicated on the curve at a loading rate $v = 500$ mm/min.

1 steady sliding stage must also increase with v . We found
2 this is implicitly caused by the combination of the geomet-
3 ric and material nonlinearity of the elastomer. When the
4 soft elastomer around the holes is subjected to frictional
5 shear forces F from the rods, its large deformation pat-
6 tern tends to shrink the holes, which in turn enlarges N .
7 This was validated via a FEM model of a column of the
8 metamaterial, as shown in Fig. 3f (for details see Meth-
9 ods and Supplementary Fig. 4). Rods and the elastomer
10 were assumed to bond together. In quasi-static numer-
11 ical simulations, each rod has a diameter of 1.8 mm in

the stress-free state, and then was expanded to 2.0 mm to
introduce prestress, after which the rods were forced to
move downward by displacement u . Integrating normal
stress over the interface Ω gives the normal force N . The
obtained $N - F$ curve, black solid line in Fig. 3g, confirms
that N increases with F .

Combing the measured $\mu - v$ curve and the calculated
 $N - F$ curve, we can quantitatively explain the rate-
dependent behavior $F_p - v$ of the metamaterial. Under
a given loading rate v , to reach the impending sliding
condition, the normal and downward forces should sat-

isfy $F - \mu(v)N = 0$. On the other hand, F and N are intrinsically related due to the geometric and material non-linearity, as predicted by the FEM model. As shown in Fig. 3g, under a given loading rate v , the linear relation $F = \mu(v)N$ can intersect with the nonlinear $F - N$ curve obtained by the FEM to determine the critical force $F_p(v)$ when impending sliding occurs. Several predicted values of F_p at different v are depicted by blue diamonds in Fig. 3h; they agree well with the measured force data.

Self-recoverable energy-absorbing metamaterials. The rate-dependent behavior of the friction force was utilized here to build a self-recoverable energy-absorbing metamaterial. As shown in Fig. 3i, we integrated each column of the previous metamaterial with an off-the-shelf coil spring, whose stiffness is 4.85 N/mm. Pushing the rods downward, the springs are compressed; and retreating the loading plate, the spring forces return the rods back against friction forces. It is expected that the return rate decreases as the spring forces decrease. Therefore, when the return rate of the rods is less than the unloading rate of the testing machine v , the loading plate detaches from the rods and the compression force F drops to zero immediately (Fig. 3j and Supplementary Movie 2). After detaching, the rods can be further pushed back by the springs since the resistant friction forces decrease at lower rates (inset in Fig. 3j); this helps to extend the working stroke of the metamaterial.

The measured stress-strain curves at different rates in Fig. 3j confirm that a larger loading rate yields a larger hysteresis loop. At a loading rate of 500 mm/min, the energy-absorbing capacity is about 0.3 MJ/m³, which is about 20 times of that of the self-recoverable energy-absorbing metamaterials previously reported⁴⁶.

Improving energy-absorbing capacity by light-weight constituent materials. Although the above metamaterials can absorb a large amount of energy, they are heavy since the rods are made of steel. Making use of the high frictional coefficients between silicone elastomers and other materials⁶⁴, we replace the steel rods with other light-weight cores, such as carbon fiber rods and Kevlar ropes, to improve the energy-absorbing capacity per unit mass of the metamaterials. Consider a seven-column module (Fig. 4a) with the height of its elastomer h , mass density of the elastomer $\rho_r = 6.6$ g/cm, length of the cores L , and mass density of the cores $\rho_c = 1.3$ and 0.56 g/cm for carbon fiber rods and Kevlar ropes, respectively. If the magnitude of the friction force per unit length is f , the dissipated energy per unit mass E_m is:

$$E_m = \frac{fh(L-h)}{\rho_r h + \rho_c L} = \frac{fL}{\rho_r} \frac{\alpha(1-\alpha)}{\alpha + \rho_c/\rho_r} \quad (2)$$

where $\alpha \triangleq h/L$ is the ratio of the elastomer height to the core length. For a given core, E_m monotonically increases with L . When L is fixed, we define a dimensionless quantity $\bar{E}_m \triangleq E_m \rho_r / (fL) = \alpha(1-\alpha)/(\alpha + \rho_c/\rho_r)$,

Fig. 4: Improving absorbed energy per unit mass. a Parameters of the metamaterials for calculating absorbed energy per unit mass. **b** $\bar{E}_m$ - α curves for metamaterials with different cores, where E_m is absorbed energy per unit mass. The hollow circles represent the maximal values of $\bar{E}_m$, and the solid stars correspond to the parameters in the metamaterials shown in (c) and (e). **c-d** Metamaterials with carbon fiber rods as the cores and the corresponding load-displacement curve. **e-f** Metamaterials with Kevlar ropes as the cores and the corresponding load-displacement curve. The insets in (d) and (f) illustrate the dependence of the force plateau F_p on the loading rate v .

which only depends on two dimensionless quantities α and ρ_c/ρ_r . While $\bar{E}_m$ monotonically decreases with ρ_c/ρ_r , it non-monotonically increases and then decreases as α increases, reaching the maximal value at an optimal α (Fig. 4b).

Two samples were made to demonstrate the practical performance of the design. The first sample (Fig. 4c) used 2mm-diameter carbon fiber rods as cores. The length of the rods is 10 cm and the height of the elastomer is 3 cm, so that the length ratio is $\alpha = 0.3$. The corresponding dimensionless energy-absorbing quantity $\bar{E}_m$ approaches the maximal value (see the red dashed line in Fig. 4b). This metamaterial only weights 33 g, but can dissipate energy as large as 80 ~ 140 J, depending on the loading rate (Fig. 4d). In other words, the energy-absorbing capacity

Fig. 5: Energy-absorbing capacity versus reusability of previous and current energy-absorbing materials. The cycle numbers are the maximum tested loops, and the dotted lines with arrows represent variation of energy-absorbing capacity with recycle number. Here, all points are calculated by experimental data from references^{12–14,19,20,25–29,36,37,46,47,51–53}.

reaches $2.6 \sim 4.2$ kJ/kg, comparable to the non-reusable ones.

The second sample adopted Kevlar ropes as cores (Fig. 4e). In detail, we used a needle to thread two strands of 1.2mm-diameter Kevlar ropes into a 1.8mm-diameter elastomer hole. Since the ropes are more compliant, the prestress in this sample is lower than the first one. We enlarged L to 850 cm (limited by the working stroke of our MTS machine) and h to 10 cm to improve E_m . The obtained length ratio is $\alpha = 0.12$, and the corresponding $\bar{E}_m$ is about 90% of the maximal value (see the blue dashed-dotted line in Fig. 4b). The metamaterial weights 121 g, but can dissipate energy as large as $820 \sim 1190$ J, depending on the loading rate (Fig. 4e). In other words, the energy-absorbing capacity is $7 \sim 10$ kJ/kg, which is even better than the first sample.

3 Discussion

We summarize energy-absorbing materials' performance in the literature into Fig. 5 and Supplementary Fig. 6. Plot of capacity versus reusability (Fig. 5) convinces that the previous materials have trade-off between capacity and reusability, while the current proposed ones (solid red circles) own both high capacity and high reusability. In a single cycle, our metamaterials' energy-absorbing capacity is the best one among the reusable category, reaching 10 kJ/kg/cycle, which is comparable to the non-reusable category. Meanwhile, this value remains almost unchanged in 200 tested cycles, while the capacity of traditional reusable designs with relatively large capacity decreases notably in less than 10 cycles (dotted lines in Fig. 5). If the energy-absorbing

capacity per cycle is multiplied by the number of repeated cycles to calculate the total energy-absorbing capacity in the entire life of a material, then a conservative estimate of our design is $10 \times 2000 = 2000$ kJ/kg per life, since the metamaterials are still intact and reusable after the tested cycles; and this value is at least 40 times as many as the others (Supplementary Fig. 6).

We attribute the extraordinary performance of the proposed metamaterials into two strategies of our design. Firstly, we utilized friction between soft elastomer and hard constituents rather than between hard particles, which is the strategy of the previous frictional metamaterials. Involving elastomer helps to achieve tightly contacted frictional interfaces that have a large amount of real contact area. Secondly, the interwoven structure strongly anchors the soft elastomer on the stiff supporting frame, which empowers the reinforced elastomer with robust load-bearing capability and applies larger prestress at the frictional interface. These interfaces notably improve the capacity of energy-absorbing metamaterials based on friction as shown in Fig. 5. In addition, the rate-dependent frictional behavior of elastomer interfaces enables the reported metamaterials passive adaptability to fit impacts with different velocities. We believe our design strategy opens a new technical path to obtain high-performance reusable energy-absorbing metamaterials.

Methods

Fabrication of the reinforced elastomer. The reinforced elastomer samples were manufactured by combing fused deposition modeling (FDM) 3D printing technology (Hori Z300 3D Printer) and mold-casting process. Materials adopted were commercial 3D printing PLA filaments (eSUN poly lactic acid), bright-finished 304 stainless steel rods of different diameters and a commercially available silicone elastomer (Dongguan ShinBon New Material Co., Ltd., China). The elastomer consists of two liquid constituent parts. They were mixed in a ratio of 1:1, then poured into 3D printed molds assembled with PLA frame and 1.8mm-diameter steel rods, and finally cured for 6 hours at room temperature. These steel rods were then removed after curing, and the corresponding holes left in the elastomer were subsequently inserted with thicker rods/ropes.

Measurements of the stress-strain curve of the silicone elastomer. To quantify the mechanical properties of the elastomer, uniaxial tension and compression tests were conducted using the single-axis MTS testing machine (E44.104). Due to the large deformation and low stiffness of the elastomer, video extensometry, instead of conventional clip-on extensometry, was used to measure the tensile strain. Specifically, a ruler was placed vertically on one side of the tension specimen, and the coordinates of the markers on the specimen were video recorded (see

Supplementary Fig. 5).

Experimental tests of the proposed metamaterials. To characterize the energy absorption capacities of the metamaterials, uniaxial compression or uniaxial tension tests were performed. The force-displacement curves of the samples were measured under displacement control by a MTS testing machine. The loading rates were from 1 mm/min to 500 mm/min, which is the maximal loading speed of the machine. In the experiments, assisting frames made of PLA were fabricated by 3D printing.

FEM simulations. In the present studies, several FEM models have been built in commercial software Abaqus/Standard 2014 to estimate the stress distribution in the silicone elastomer under loading. The elastomer was considered as incompressible, and its hyperelastic behavior was formulated by the third order Ogden material model with strain energy density

$$W(\lambda_1, \lambda_2, \lambda_3) = \sum_{i=1}^3 \frac{2\mu_i}{\alpha_i^2} (\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \quad (3)$$

where λ_1 , λ_2 , and λ_3 are principle stretches, and material parameters were adopted as $\mu_1 = 0.322$ MPa, $\alpha_1 = 3.248$, $\mu_2 = 7.949 \times 10^{-5}$ MPa, $\alpha_2 = 13.706$, $\mu_3 = 6.667 \times 10^{-2}$ MPa, $\alpha_3 = -3.490$. These parameters were determined by fitting against experimental data of uniaxial tensile and compression tests (for details see Supplementary Fig. 5).

In addition, Young's Modulus $E = 3$ GPa, Poisson's ratio $\nu = 0.33$, and $E = 206$ GPa, $\nu = 0.3$ were taken for the PLA frame and steel rod, respectively. Eight-node linear elements with hybrid formulation and reduced integration (C3D8RH) were adopted for the silicone elastomer due to its incompressibility, and eight-node linear elements with reduced integration (C3D8R) were adopted for the PLA and steel rod. All geometric parameters of the model were consistent with those of the experimental samples.

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Author contributions

Z.H.Z and J.Y.L. designed the research. Z.H.Z, L.H.J. and Q.Y.L. supervised the research. J.Y.L. made all of the metamaterial samples, and conducted related experiments and numerical simulations. J.Y.L and Z.C. measured frictional coefficient between elastomer and steel. All authors

discussed the results and revised the manuscript at all stage.

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