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Responsive materials: A novel design for enhanced machine-augmented composites

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The concept of novel responsive materials with a displacement conversion capability was further developed through the design of new machine-augmented composites (MACs). Embedded converter machines and MACs with improved geometry were designed and fabricated by multi-material 3D printing. This technique proved to be very effective in fabricating these novel composites with tuneable elastic moduli of the matrix and the embedded machines and excellent bonding between them. Substantial improvement in the displacement conversion efficiency of the new MACs over the existing ones was demonstrated. Also, the new design trebled the energy absorption of the MACs. Applications in energy absorbers as well as mechanical sensors and actuators are thus envisaged. A further type of MACs with conversion ability, *viz.* conversion of compressive displacements to torsional ones, was also proposed.

The last decade has seen significant advances in new composite materials, and arguably a most exciting one has been the use of inner architecture as an additional degree of freedom in design of composite or hybrid materials¹. Among these developments, the concept of machine-augmented composites (MACs) pioneered by Hawkins and co-workers²⁻⁴ deserves special attention, as it opens up principally new avenues for the use of advanced composites. The idea of a MAC is elegant in its simplicity: instead of using fibres or particles, as done with conventional composites, miniature 'machines' are embedded in a matrix². These machines can be equipped with the facility to respond to external loads in a desired fashion, thus providing the composite with responsiveness that can be utilized at the macroscale. This approach can be seen as an extension of the concept of 'architectured materials' to a new class of composites in which 'second phase inclusions' – the embedded machines of special geometry – become an active element of the material. The machines proposed by Hawkins and co-workers possess the ability to convert an applied compressive load into a lateral shear force (and vice versa) by using a simple compliant mechanism. By the same token, conversion of normal displacements into tangential ones can be effected, cf. Fig. 1. This kind of response makes MACs very attractive for a range of applications. Thus, they can be used in shock and sound absorbers, body armour and protective gear. Further possible applications include sports equipment, e.g. hockey and baseball catcher's masks and golf clubs⁵⁻¹⁰.

Here we demonstrate that the conversion performance of MACs, which is characterised by the ratio of the horizontal shear displacement to the input vertical displacement, can be enhanced substantially. This can be achieved in two ways: (i) through improved design and (ii) by optimising the choice of the materials employed for the matrix and the embedded machines. A third aspect central to this work concerns the manufacturing technique employed to realise the optimised MAC design. Additive manufacturing (particularly 3D printing) offers itself as a viable cost- and time-effective alternative to the two-step techniques of MACs fabrication used by the Hawkins group^{11,12}. Recent advances in 3D printing allow fabrication of composites with high levels of complexity of inner architecture and micrometre-scale resolution¹³. In addition, they make it possible to employ a broad variety of combinations of matrix and machine materials¹³⁻¹⁸. We made use of these advantages of 3D printing in producing the new MACs. Below we present the design, fabrication, and properties of novel MACs with enhanced conversion performance. The machines suggested by Hawkins et al.², dubbed 'Z-machines' due to their resemblance to the letter 'Z', cf. Fig. 1a, were used as an experimental test bed to evaluate the proposed 3D printing technique and validate the finite element modelling (FEM) procedures used. In this way, the concept proposed by Hawkins and the manufacturability of the machines by multi-material 3D printing were verified. These verification exercises



Figure 1 | Schematic representation of individual machines and MACs. (a), Stand-alone Z-machine. (b), Assembly of Z-machines to a machineaugmented composite (Z-MAC). (c), Stand-alone J-machine. (d), Assembly of J-machines to a machine-augmented composite (J-MAC).

are presented in Supplementary Information, Sections 1, 4, and 5. All individual machines and MACs were built with a Stratasys[®] Connex500 multimaterial 3D printer. The desired levels of the machine to matrix stiffness ratio were obtained by blending the stiffest one (VeroWhite[®]), which simulates conventional thermoplastics, and the softest one, which is a rubber-like material (TangoPlus[®] or TangoBlackPlus[®]). Details of the printing process used are given in the Supplementary Information, Section 1.

To achieve the aim of this work, FEM simulations were performed using the commercial package ABAQUS¹⁹ for optimisation of both the conversion machine design and the choice of the materials making up a MAC. The outcome is a modified machine, referred to as Jmachine for its "J-shaped" geometry, as well as a J-machine augmented composite (J-MAC). A favourable combination of the elastic properties of the embedded machines and the matrix enabling superior performance was established by FEM analysis and realised using new recipes for the polymers employed. These recipes were specially formulated for the novel MACs, which were then fabricated by stateof-the-art multi-material 3D printing. The displacement conversion efficiency of the MACs studied experimentally confirmed the results obtained by numerical simulations. In what follows, the concept of MACs based on embedded J-machines will be presented and it will be shown that J-MACs possess better displacement conversion efficiency and energy absorption than their Z-machine based progenitors. In addition, we will briefly introduce a new type of MACs, also based on embedded J-machines, which convert displacements under compression into a rotational mode.

Z-machines enabling conversion of loads or displacements from one direction to another are a particular case of *compliant mechanisms*²⁰. Examples of such conversion via compliant mechanisms can be found in animal kingdom. Inspired by the mechanics of hopping of kangaroos Ref. 21, 22 and frogs Ref. 23 and the high efficiency of translation of their vertical jumps into horizontal locomotion, we explored the idea of a converter machine with a curvature at the foot. The working hypothesis was that such design may resolve the buckling problem encountered with Z-machines with a wall inclination angle close to 90° and offer better displacement conversion. Therefore a converter machine with continuously changing curvature of walls was considered. A machine based on this kind of compliant mechanism (Fig. 1c) was designed and its displacement conversion efficiency,

 η = output shear displacement/input compression displacement,(1)

was tested both by FEM simulations and experimentally.

Because of the resemblance of the wall of the machine to the letter "J", we dubbed it a 'J-machine'. The profile of the J-machine wall (Fig. 1c and d) is described by the following equation:

$$\mathbf{y} = \mathbf{y}_{\infty} + (\mathbf{y}_0 - \mathbf{y}_{\infty})\mathbf{e}^{-\alpha \mathbf{x}} \tag{2}$$

where α , y_{∞} and y_0 are parameters that determine the geometry of the wall profile, particularly the curvature of the foot. Employing equation (2) for different values of these shape parameters in an interval 0 < x < 20 (in mm), the displacement conversion performance η of the machine was investigated. Fig. 2 shows J-machines with different shape parameters α and y_{∞} in the J-profile equation and their effect on the displacement conversion efficiency η of J-machines. It can be seen that as the value of y_{∞} (that defines the length of the "J" foot) increases, the output shear displacement decreases. A parametric study showed that the best efficiency of displacement conversion of a J-machine is achieved for $y_{\infty} = 1$ mm and $\alpha = 0.8$. The values of η for the Z75machine (Z-machine with the wall inclination angle of 75°) and the best-performing J-machine were found to be 1.32 and 2.31, respectively, which demonstrates superior properties of J-design. Based on these results, Z- and J-MACs with embedded Z- and J-machines were 3D printed for experimental characterisation (Fig. 1b and d).

In addition to a better displacement conversion efficiency of a J-machine with the optimized geometry parameters over that of a Z75-machine, the continual change of wall orientation from horizontal at the bottom flange to vertical at the top one also ensured a more uniform stress distribution and reduction of stress concentration at the wall foot/flange joint as compared to a sharp edge at the foot of a Z-machine, as demonstrated by FEM simulations in Fig. 3.



Figure 2 | Individual J-machines and their conversion efficiency. (a), CAD-generated J-machines with different shape parameters according to equation (2) with $y_0 = 0$ (all y_{∞} -values in mm). (b), Effect of the magnitude of the shape parameters α and y_{∞} on displacement conversion efficiency η of J-machines for an input vertical displacement of 2 mm. The conversion efficiency for the Z-machine with the wall inclination angle of 75° (labelled Z75) is shown for comparison.

A great variety of different types of materials may be used for the machines and the matrix. The criteria for material selection depend on the application at hand and the capability of the multi-material 3D printer to handle the materials. One of the requirements on a compliant machine is that the movement of the walls within a MAC be not obstructed by the support matrix. Therefore, the matrix

material needs to be more compliant than the machine material. The foremost role of the matrix is to stabilize the walls of the embedded machines, but it can also provide other properties, such as a more uniform load distribution upon impact. Also, these compliant mechanism-based machines transmit a force or displacement by virtue of their structural deformation. Thus, the machine material



Figure 3 | Distributions of the von Mises equivalent stress (in MPa) in Z- and J-MACs for the same output displacement of the middle bar (about 5.62 mm).



Figure 4 | Experimental (left column) and FEM (right column) images of J-MAC for three different input vertical displacements. (a,b), d = 0 mm. (c,d), d = 3 mm. (e,f), d = 6 mm.

should have a low Young's modulus, *E*, in order to undergo large deformations. At the same time, it is required to have a high yield strength σ_{y} , in order to elastically recover its initial shape upon unloading. Therefore, one of the challenges in designing MACs is to allow the embedded machines to have large deflections for good conversion performance, the resulting stress remaining below σ_{y} . Among other classes of materials, polymers have a relatively high σ_{y}/E ratio. Combined with this property, their low density and moderate manufacturing and processing cost make polymers, particularly elastomers, the materials of choice for MACs. Further material selection criteria relating to fatigue and creep properties may also need to be considered.

The results of the displacement conversion tests on J-MACs are presented in Fig. 4. Movement of the bar placed between two J-MACs with growing vertical displacement d is obvious. For a better comparison, pictures of FEM-simulated and physical tests on J-MACs are presented in Supplementary Information in Fig. S9.

A comparison of the best-performing implementations of Z- and J-MACs, Fig. 5a, shows that a J-MAC exhibits greater displacement conversion efficiency than a Z-MAC over a major part of the input vertical displacement range. We note an excellent agreement between experiments and FEM results. Minor differences for input displacements exceeding 5 mm can be attributed to separation of the ends of the MACs from the bar due to the rotation of the matrix. This was not considered in the simplified FEM boundary conditions used. Since the MACs were made from elastomeric materials, their deformation was completely reversible and repeatable. The behaviour of a J-MAC during loading and unloading is captured in the video clips presented in Supplementary Video_J-MAC.



Figure 5 | Characterization of conversion performance and energy absorption of Z- and J-MACs. (a), Conversion response of a best-performing J-MAC (for $y_{\infty} = 1 \text{ mm}$ and $\alpha = 0.8$) and a Z-MAC with embedded Z75-machines. The displacement conversion efficiency at a vertical displacement of 6 mm is indicated in the lower right corner of the diagram. (b), The effect of the quotient of the elastic moduli of the machines and the matrix, ξ , on the conversion behaviour of the best-performing J-MACs. The inset photos show 3D-printed J-MACs with elastomer couples corresponding to $\xi = 15$ and $\xi = 60$ at d = 6 mm. (c), Experimental loading/unloading curves for Z75- and J-MACs with $\xi = 60$. The calculated values of the absorbed energy, *W*, are indicated.



Figure 6 | Compression-rotation converter device. (a), 3D design of a single J-machine-based device. (b), 3D design of a stack of two devices in a mirror arrangement. Rotation of the plates in the middle of the assembly with progressive vertical displacement is made visible by a shift to the right of the long black marker: (c), d = 0 mm. (d), d = 2 mm. (e), d = 4 mm.

We also investigated the effect of the ratio ξ of the elastic moduli of the machines and the matrix. The conversion performance of J-MACs for two different values of ξ (*viz.* ξ = 15 and ξ = 60), and the lower and upper boundaries of this ratio (i.e. $\xi = 1$ and $\xi = \infty$), are shown in Fig. 5b. The photographs of 3D-printed J-MACs with different ξ -values are displayed in Fig. S1 in Supplementary Information. It is seen that the displacement conversion ability η of J-MACs is directly influenced by the value of ξ and is larger for larger ξ -values. The maximum efficiency corresponds to the limit case when no matrix is present ($\xi = \infty$). In the limit when the matrix has the same Young's modulus as the machines, $\xi = 1$, the MAC performs as a 'normal' elastic material (albeit with cavities between the walls of the 'degenerated machines') and does not possess any conversion ability. There is no 'optimal' ξ , the best performance corresponding to infinite ξ , but the value of $\xi = 60$ realised in our MACs corresponds to a conversion performance reasonably close to that for $\xi = \infty$. It is remarkable that the conversion efficiency of MACs is a function of machine geometry and the magnitude of the *ratio* of the elastic moduli, ξ , and is independent of the absolute values of the elastic moduli. Hence, our results suggest a wide range of potential applications for MACs: from soft materials such as living matter in bioengineering to hard materials, including metals and ceramics, for structural and other engineering applications. Photographs taken during three different stages of loading for J-MAC with $\xi = 15$ are presented in Fig. S10.

An interesting aspect of the properties profile of MACs is their energy absorption capacity. We performed cyclic loading and unloading of MACs and calculated the energy absorbed per cycle. The results are shown in Fig. 5c, where the area of the hysteresis loop represents a measure of the strain energy absorbed by a MAC. It can be seen that a J-MAC with $\xi = 60$ studied has an energy absorption capability three times higher than the Z75-MAC with the same ξ value. It can thus be concluded that J-MACs outperform Z-MACs in their damping properties and offer themselves as potent damping materials.

To gain an insight into further possibilities of using J-machines as actuators, we developed a novel mechanism with the capability of compression-rotation conversion, which is illustrated in Fig. 6. In short, when a compressive load or displacement is applied at the top face of the machine shown in Fig. 6a and b, rotation is actuated due to conversion of vertical displacement to shear displacement of the J-machines placed at the circumference of a circular plate. This mechanism can be actuated, for example, by pressure of a gaseous or liquid medium. It can be calibrated to be used for sensing pressure and unlocking of valves to release overpressure.

In summary, this study presented a novel design for machineaugmented composites, dubbed J-MACs, with superior displacement conversion and energy absorption capability. A new method of MAC fabrication employing high-definition multi-material 3D printing technologies was used. This made it possible to precisely tailor the materials of the embedded machines and the matrix and obtain excellent quality of interfacial bonding. Furthermore, the possibility to produce MACs converting displacement under compression into torsional deformation was demonstrated.

Obviously, machine design for enhanced performance is not limited to the variants presented. For example, MACs for another conversion mode, *viz.* load conversion, will be studied elsewhere. Owing to their excellent properties, J-MACs can be used in mechanical sensors and actuators, shock and sound absorbers, protective gear, footwear with embedded locomotion functions and for other applications. Recent developments in nano- and micro-scale fabrication open up exciting avenues for design of novel responsive structures utilizing the J-MAC design at different size scales and for a broad range of materials.

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Author contributions

Y.E. and Y.B. designed the study, J.W. selected the appropriate resin formulations and performed the 3D printing, while E.B. and A.M. did the FEM simulations and conducted the experiments. E.B. also wrote a first draft of the manuscript. All authors contributed equally to analysing and interpreting the results and putting the paper in a final form.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/ scientificreports

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