Composites Science and Technology 230 (2022) 109792

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Functional flexibility: The potential of morphing composites

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ARTICLE INFO

Keywords:
A. Smart materials
A. Flexible composites
B. Shape memory behaviour
B. Thermomechanical properties
C. Anisotropy

ABSTRACT

From plants tracking the sun to the aerodynamics of bird wings, shape change is key to the performance of natural structures. After years of reliance on mechanical joints, human engineering now focuses on improving aerodynamic efficiency through smooth, full form changes in material geometry, achieved using technologies such as morphing composites. Promising improved power generation and efficiency in wind turbines and safer more sustainable aircraft and cars, these materials can achieve both large geometric changes with low energy requirements by cycling between several stable physical states and more gradual changes in geometry by exploiting coefficient of thermal expansion mismatch and structural anisotropy, shape memory polymers and 4D printing. The merits and limitations of these various shape change systems are the subject of extensive and ongoing academic research and both commercial and defence industry trials to improve the viability of these technologies for widespread adoption. Shape change capabilities are often associated with problems in material cost, mass, mechanical properties, manufacturability, and energy requirements. Nonetheless, the considerable and rapid advances in this technology, already resulting in successful trials in advanced civilian and military aircraft and high-performance cars, indicate that future research and development of this materials platform could revolutionise many of our most critical power generation, defence and transport systems.

1. Introduction

Dynamic and controllable shape change is a very desirable but also exceptionally challenging property to achieve with engineering materials [1,2]. Highly influential in aerodynamics, shape changes have been perfected in nature over aeons by evolution and are demonstrated in the soar, dive and landing abilities of birds, which rely on small changes in wing feather position to adjust sweep and curvature [2–5]. Engineers have long attempted to approximate this efficiency through the invention of flight control surfaces, such as flaps and ailerons on aeroplane wings, but their designs are typically limited by reliance on motors and mechanical joints, such as hinges, and do not achieve the streamlined full form change efficiencies of flying beasts [6].

The pervasive allure of considerable aerodynamic performance increases and associated improvements in fuel efficiency, cost and environmental sustainability has prompted the development of a range of morphing materials and structures for use in everything from aircraft components [7–15] to car accessories [1,16–19] and wind turbine blades [1,8,20–25]. Material approaches typically focussed on combinations of metals and fibre reinforced polymer composites [26,27], shape memory alloys (SMA) [13,28,29] and polymers (SMP) [30,31] are typically used to enable shape changes in morphing materials. Bi-stability, or the ability to switch between multiple stable energy states, can also be used as a structural approach to create morphing structures.

Impressive advances have been made across a range of morphing technologies, including significant and energy conservative discrete shape changes between multiple stable physical states [26,28,29] and

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https://doi.org/10.1016/j.compscitech.2022.109792
Received 10 July 2022; Received in revised form 10 September 2022; Accepted 14 October 2022
Available online 18 October 2022

more controllable but energy intensive continuous shape changes using coefficient of thermal expansion (CTE) mismatches [32–34] or structural anisotropies in corrugated (compliant) structures, prestressing or slip [35–37]. However, identifying morphing technologies suitable for use in aerospace, automotive and power generation structures remains a challenge, with any advantages offered by a particular design, such as a wide morphing range and control, often offset by limitations, such as material cost, mass, mechanical property profile requirements or the energy required to induce shape change [1,2].

This article discusses the diverse range of emerging morphing composite material technologies pushing the boundaries of innovation in aerodynamics. Beginning with inspiration from nature we discuss the extension of dynamic shape change behaviour to active aerodynamic control surfaces in the aerospace, automotive and power generation sectors. Discrete shape changes in multistable composites are then contrasted with continuous shape changes achieved through CTE mismatch and structural anisotropy. Flexible matrices are also investigated before the unique manufacturing opportunities provided by SMPs and 4D printing are addressed and the study is concluded with design concepts for morphing structural aerospace components.

2. Back to basics: drawing inspiration from nature

From plants to animals, the natural world is rife with amazing active, self-shaping and stimuli-responsive materials and structures, which achieve large structural changes under ambient conditions [38]. Many of these materials fulfill biological functions, such as the hygroscopic actuation of pinecone scales as they open and close for seed dispersal [39]. This reversible movement results from structural orientation differences of cellulose microfibrils within the cone's cell walls, which more actively resist extension along their axis of alignment and are angled relative to the body to achieve controlled deformation [40]. Moisture driven changes in orientated cellulose microfibrils, polysaccharide matrices, aromatics and structural proteins are responsible for everything from the unfurling of plants [41,42] (Fig. 1) to tracking the sun [43] and ballistic seed dispersal, utilising the coiling and fracture of packed cellulose helices [44].

In animals, muscles produce macroscale contractions ranging from 20 to 40% through hierarchical structures of filaments stabilised by proteins arranged into muscle cells, which are themselves grouped and triggered by the release of calcium ions [45,46]. Tendons connect muscles to bones and can also store energy through their elastic nature, returning up to 93% of strain energy under 20 MPa [47,48]. These viscoelastic tissues comprising collagen are also hierarchical structures with liquid crystalline order ranging from the tropocollagen molecule, containing three intertwined helices crosslinked into fibres, to the fibrils and fascicles that are wound to form the tendon [49]. Even feathers and hair demonstrate reversible shape memory behaviour, with the moisture dependent deformation of keratin allowing hair to be styled by applying heat and crystalline regions, chemical and hydrogen bonds acting as netpoints to hold the molecular shape [50].

Such an enviably wide spectrum of advanced dynamic functionalities achieved through a small range of natural constituents and triggered through mild stimuli is the result of billions of years of evolution. Drawing inspiration from these natural morphing composites can accelerate the development of synthetic active materials [51–53], which to date typically rely on synthetic molecules and extreme environmental stimuli to achieve even modest shape changes. Interested readers in this area are directed to the review by Li and Wang [54] or that by Le Duigou et al. [55] on plant inspired adaptive structures and morphing materials (Fig. 2).

3. New opportunities for aerodynamic efficiency: active control surfaces

Geometry plays a critical role in aerodynamics, with both lift and drag heavily influenced by an object's shape. It is consequently hardly surprising that the primary applications of morphing composites are in the aerospace, automotive and power generation industries. Wing design and use of composite materials in modern aircraft are aimed at achieving optimal aerodynamics and minimising structural weight to improve fuel efficiency but are compromised in off-design flight conditions [1,14]. In addition to reducing fuel consumption and structural weight, wing morphing aims to more consistently maintain optimal aerodynamic performance by adapting the wing shape as flight conditions change to reduce drag and acoustic noise, improve high-lift performance, power requirements and control, and provide versatility across multiple mission profiles for defence applications [6,57–61]. Flight safety aspects, such as stall characteristics and gust load alleviation, may also be improved [6]. These improvements are achieved by utilising modifications to the sweep angle, span and chord length to modify effective surface area and aspect ratio during flight (planform morphing), changes to aerofoil camber and thickness to optimise aerodynamic characteristics within a wide flight envelope (aerofoil

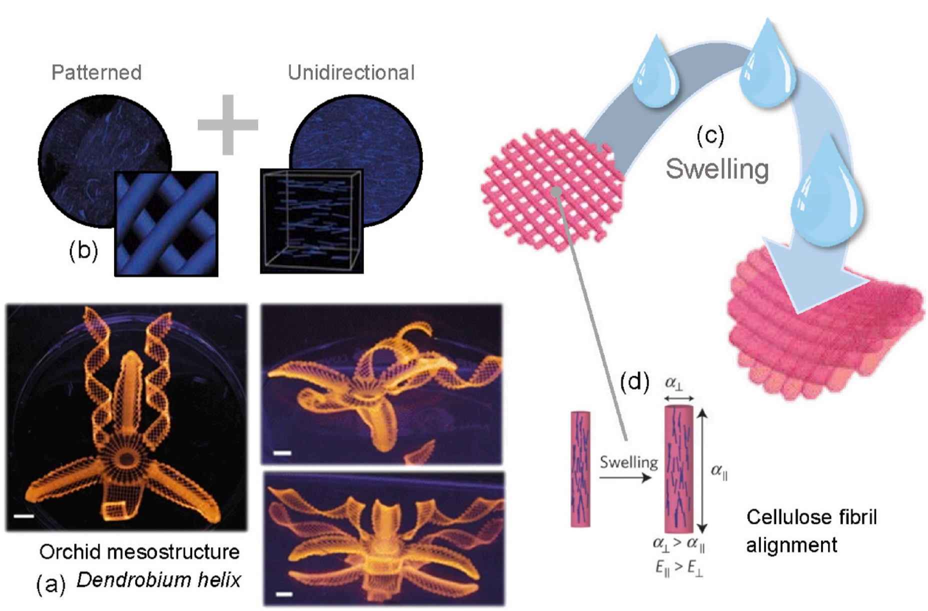

Fig. 1. 4D printed cellulose hydrogel composite mimicking the *Dendrobium helix* orchid flower curvature and shape. Moisture and time (fourth dimension) dependent opening of the printed orchid mesostructure (a) is facilitated through localised anisotropy in cellulose fibril orientation, either unidirectional or patterned, within the printed hydrogel (b), which results in shape changes when immersed in water or exposed to a moist environment (c). In this case, the shape change is due to anisotropic swelling parallel ($\alpha_{\parallel}$) and perpendicular ($\alpha_{\perp}$) to the printed fibre direction caused by differences in fibre elastic moduli in ($E_{\parallel}$) and perpendicular to ($E_{\perp}$) the printing direction. Scale bars in panel (a): 200 μm. Adapted from Oliver, Seddon and Trask [38] (open access) based on original work reported in Gladman, Matsumoto, Nuzzo, Mahadevan and Lewis [42]. A video showing printing and shape change can be found in: https://www.youtube.com/watch?v=7Q_Fu1KlVac .

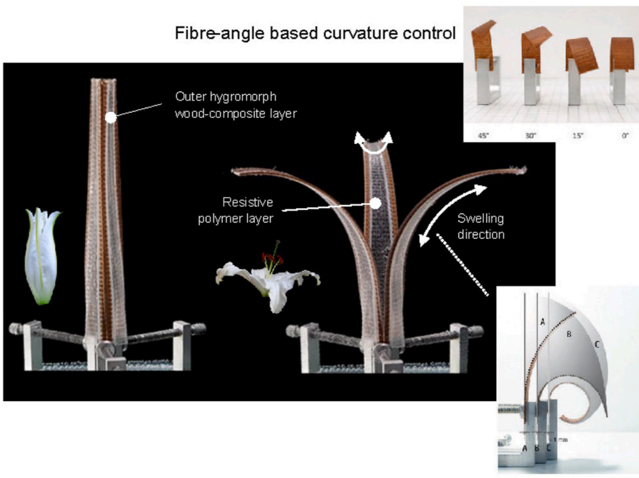

Fig. 2. Passive-hydraulic actuated curvature in the lilium 'Casa Blanca' drives the flower opening mechanism, a principle that is translated into a 4D printed composite structure comprising wood composite (outer hygromorph layer) printed on a polymer structure (resistive layer). Opening of the structure is driven by anisotropic swelling, which is restricted to the outer wood composite layer by the presence of the resistive middle layer. This causes a strain gradient resulting in the double curvature of the structure. This illustrates that simple moisture actuated natural plant opening mechanisms can be replicated using 3D printing. Reproduced from Le Duigou et al. [55] (open access) based on original work reported by Poppinga, Correa, Bruchmann, Menges and Speck [56].

morphing) (Fig. 3) or transformations to wing di- and anhedral angles in addition to twisting and spanwise bending to shift the wing positions out of the original plane (out-of-plane morphing). Notable modern morphing aircraft development programs have included the Active Aeroelastic Wing (AAW), which was implemented at full scale on a F/A-18 fighter jet [59], the Defense Advanced Research Projects Agency's (DARPA) Morphing Aircraft Structures (MAS) program, which aimed to generate multi mission capabilities in defence aircraft [62], the Adaptive Compliant Trailing Edge (ACTE) flap [57,63] and Variable Camber Continuous Trailing Edge Flap (VCCTEF) [58,64] for commercial aircraft. Currently active research programs include Airgreen 2 from the Clean Sky 2 program examining morphing winglets and adaptive wingtips to improve aerodynamic performance by 10–15% and cut emissions by up to 6% and the Shape Adaptive Blades for Rotorcraft Efficiency (SABRE) program, which is investigating adaptive blade technology in helicopters [2].

Additional aerospace applications of morphing technologies include use in unmanned aerial vehicles (UAV) [65] and deployable structures, such as solar arrays and boom structures, which occupy a small volume during launch but can be deployed over a large area when in orbit [11,12,15,66,67]. Use of morphing composites in aerospace applications is described in the following reviews [2–6,68–70] and is a very active research topic. For instance, Thalès Alenia Space has investigated the concept of a space telescope containing 2 mirrors that can be deployed in orbit (Fig. 4). In the deployed configuration, these two mirrors are separated by a distance of 2 m. Deployment is assisted by the autonomous unwinding of 6 hybrid tapes, which release the elastic deformation energy that was stored in them as they were wound. Optimising deployment rate to obtain a controlled and reliable process is critical and has led to the development and use of composite tapes with a viscoelastic layer, rather than stainless steel.

Aerodynamics are also important in the automotive industry, where drag increases parabolically with vehicle speed. Car body morphing is of considerable interest to automotive manufacturers enabling a reduction in drag of 10% improving fuel economy by 2% [71]. Morphing composites can be applied to drag reducing features, such as boat-tail extensions [72], vortex generators [17], morphing fender skirts [18,29], active radiator grills [73] and underbody covers [74], deployable side mirrors [75], air dams [76] and rear diffusers [73] to improve aerodynamic efficiency. Cars incorporating these technologies include the Porsche 911 Turbo S, Ferrari 458 Speciale, and BMW and Mercedes Benz prototypes [1]. Morphing panels can also be used to improve aerodynamic performance at speed and retracted to enhance exterior styling, thermal efficiency, and crashworthiness at low speed [77]. The utilisation of morphing composites in the automotive industry was described by Daynes and Weaver [78].

Other applications of morphing composites include wind turbine blades, the aeroelastic properties of which can be customised to achieve maximum power and durability. Adjustable stiffness lightweight blades can be used to generate power up to the critical aerodynamic load, before morphing into idle shapes to alleviate stress and enhance durability [1,8,20–25]. Morphing composites are also used in soft robotics to achieve locomotion and dextrous activities like gripping and moving objects [79–81]. These applications were reviewed by Chillara and Dapino [1].

As detailed in Ref. [82] morphing structures developed for aeronautical applications must fulfil many constraints, which relate to (i) the applied static load at cruise conditions (due to aerodynamic forces), (ii) dynamic vibration (around 5 Hz in civil aviation), (iii) operating temperature (ranging from −55 °C to 10 °C during cruise conditions) and (iv) not drastically increase the mass of the structure. As such, composite materials intended for use in morphing structures, must exhibit (i) an

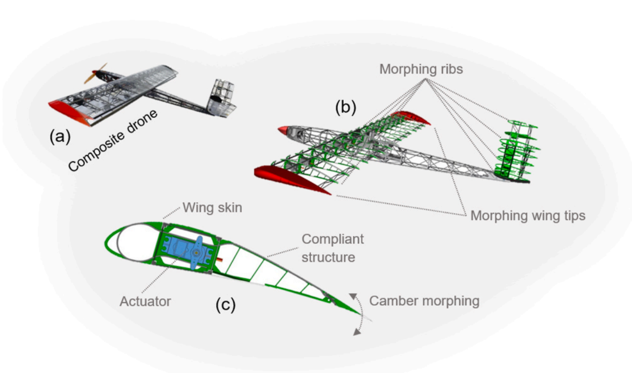

Fig. 3. Camber morphing drone (a) utilising morphing ribs (green) and wing tips (red) (b) with a compliant composite structure and electromechanical actuator (c). Adapted from Fasel, Keidel, Baumann, Cavolina, Eichenhofer and Ermanni [14]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

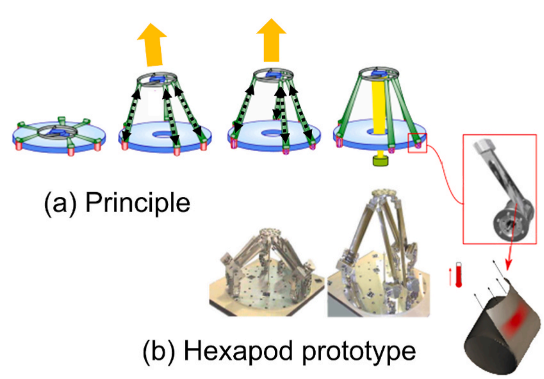

Fig. 4. (a) Deployment principle for a hexapod included in a deployable space telescope developed by Thalès Alenia Space, (b) photos of a 1/4 scale prototype in collapsed and deployed configurations. Temperature actuated expansion of the hybrid composite struts results in vertical lift of the lens, as indicated in the figure using arrows. Adapted from Guinot [70] (open access).

elastic domain, to ensure reversibility of the process at relevant operating temperatures and environmental conditions, (ii) appropriate mechanical properties (rigidity and strength) to sustain applied loads and (iii) the ability to switch from one stable configuration to another at a controllable transition rate (damping properties of the material) to enable flight control.

4. Discrete shape changes: energy efficient but with limited profile options

Both discrete and continuous shape changes can be achieved using morphing composites but have varying energy requirements and degrees of control. Discrete shape changes are most readily achieved by moving between multiple stable physical states in what are known as bistable or multistable composites. Most multistable composites are created by utilising residual stresses induced by unsymmetrical layups and thermal actuation [33,78,83–92] (Fig. 5). The ratio of the CTEs in the longitudinal and transverse fibre directions of unidirectional composite plies [87] means that residual stresses are generated in plies of a multidirectional laminate when cured at a high temperature and brought back to room temperature due to CTE mismatch between the plies [32–34]. A similar result can be achieved using mechanical [16,29,32,88,89] and viscoelastic fibre prestressing [93], whereby the energy stored in the prestressed fibres and their matrix imparts a residual stress on the composite after curing. Residual stresses are present in all states and must be considered along with design loads during the component design phase. These stresses can affect component durability and service life and designers must therefore consider these factors when considering the suitability of bi- or multistable composites for morphing structures.

The presence of residual stress in the composite structure can result in multistability between several minimum energy states [32,88] with morphing achieved by switching between them [87]. Bistability has also been demonstrated in laminates comprising a stress-free isotropic spring steel core layer sandwiched between two asymmetric, mechanically-prestressed, fibre-reinforced elastomeric layers [94].

Fibre direction control can also be used to achieve various out-of-plane deformations in the laminates of unsymmetrical layups [33,88,95]. Asymmetrical laminates with varying fibre direction in a single ply, can be multistable due to CTE mismatch [96–101] and are produced by generating a continuous curvilinear fibre path in the fibre tow [33,102] or differing discrete orientations of fibres in the ply [96–100].

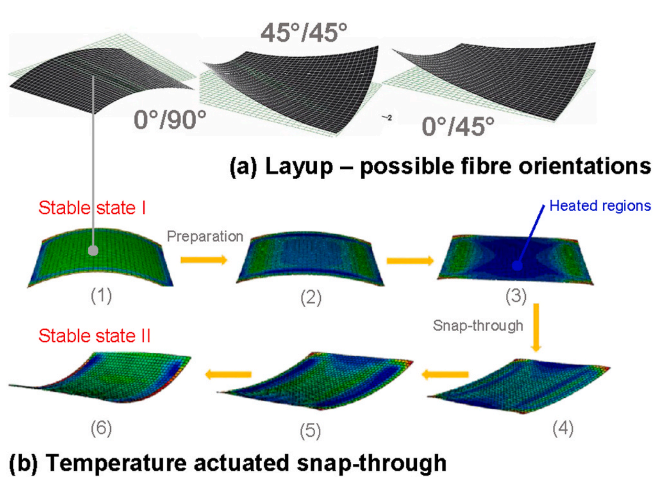

Fig. 5. Finite element (FE) models of bi-stable structures. (a) Bi-stable composite structures can be prepared to exhibit various curvatures based on their layup i.e., 0°/90°, 45°/45° and 0°/45°. (b) An example bi-stable composite with layup $0_3/90_3$ switches by temperature-activated snap-through (heated regions shown in blue) from stable state I (convex) to stable state II (concave). Reproduced from Portela, Camanho, Weaver and Bond [95] and Zhang, Chen, Lu, Wu, Wu, Jiang and Chai [103]. Experimental realisations of these FE models can be found in the references provided. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Shifts from one low energy state to another are achieved via an external energy source in an actuation known as snap-through [83]. External systems, such as piezoelectric microfibre composites [8,9,104,105] or heat-driven SMAs [13,28,29,83,88] and shape memory alloy-polymer (SMA/SMP) hybrids [106] can be bonded to the composite surface [78,84,85,88,90,91,107] to deliver the force required for snap-through to occur. Thermal actuation through local heating [27,86,88,103,108,109], hygrothermal actuation through modification of the local relative humidity [55,82,110], aerodynamic actuation through local lift or drag forces [32,111], pneumatic actuation [26], electrochemical actuation through lithium-ion insertion [112] or magnetic actuation using the force generated by magnetic fields and plies or matrices embedded with magnetic particles [81,88,101,113,114] can also be used to achieve this shift in state. In a domino effect, multistable composites can then in turn be used as actuators to induce shape changes in larger morphing structures, such as aerofoils [13,97–100].

The ability of multistable composites to hold several equilibrium states without any continuous external energy input and to undergo large deformations between stable structural forms with minimal energy input makes them very energy efficient [88,95,107,114,115]. However, their inability to hold shapes between those dictated by their discrete low energy states limits the application of these composites for flight control surfaces on aircraft wings, which require continuous and controllable shape changes. Unintentional transitions between energy states will result in unexpected flight response that could lead to catastrophic accidents. Actuator selection can also be challenging, with reproducible and reversible snap-through sometimes difficult to achieve and some actuators, such as piezo-ceramic macro-fiber composites (MFC), affecting the structural properties of such composites [34]. Experimental work often focuses on developing and analysing modes of snap-through. Material properties of composite constituents are sometimes assessed but practical studies often concentrate on characterising shape change potential rather than mechanical properties of morphing structures when in various energy states. This makes any real assessment of their viability for real-world applications challenging.

Literature relating to bistable and multistable morphing composites is often simulation based, relying on different methods to investigate shifts in energy state and associated deformation behaviour. When modelling the global response of a laminate, as detailed in Refs. [78,90], it is necessary to consider thermal strain (to accurately represent residual stress), hygroscopic strain (resulting from relative humidity changes, which tends to ease residual stress) and mechanical strain (resulting from mechanical loads). The simulated global response capturing snap-through can be calculated using fast computational analytical approaches [69,70,82,116] based on classic laminate theory (suitable for optimisation of the process) or finite element (FE) simulations [90] based on a classic Riks method [117] available in most commercial FE software. If viscoelastic/plastic layers are introduced into a composite structure to control snap through rate, as previously detailed for spatial applications, viscoelastic behaviour and kinetic energy [69] must also be considered. This increases the complexity of the simulation. Additionally, if piezoelectric (PZL) actuators are included, it becomes necessary to model the actuators and their interaction with the composite material [82,118].

Ultimately, simulations allow for the design of innovative bi-stable composites, currently used as deployable structures in aerospace applications for which environmental conditions are constant and only two deployable configurations necessary. That said, the low load-bearing capacity of some stable states and temperature dependency of material properties (which must be considered in flight conditions) can complicate and restrict the use of these materials in structural aeronautical applications. A lack of accurate mathematical models for complex non-linear small and large amplitude dynamics, as relevant to environment- and configuration-based constraints imposed by aeronautical industries, hinders research and development efforts [2]. The application of load to a composite structure also changes the snap-through transition value (i.e., transition temperature for heating processes, transition relative humidity for hygroscopic processes, or transition voltage for PZL actuators). Applied loads (which can be numerous for aeronautical applications) must be known and accounted for during the design of morphing composite structures. To the best of our knowledge this has yet to be achieved.

5. Continuous shape-changes in thermal bimorph composites

Morphing composites exhibiting continuous shape change exhibit a greater degree of shape control but typically have much higher energy requirements. One of the simplest and most effective continuous morphing capabilities can be achieved by exploiting CTE mismatch in unsymmetrical composites [119–124]. Metals generally have a higher CTE than fibre reinforced polymer composites and materials combining these two can be bent using temperature variations in a manner resembling a bimetallic strip. These so termed thermal bimorphs have been demonstrated in carbon (CFRP low CTE heater, CTE $\approx 0.9 \times 10^{-6}$ K^{-1}), and Kevlar (KFRP low CTE insulator, CTE $\approx 1.5 \times 10^{-6}$ K^{-1}) fibre reinforced composites interfaced with metal plates (CTE $\approx 23.6 \times 10^{-6}$ K^{-1}) [119,120], which change shape with changing temperature due to their layered structure. The curvature of a three-layer structure (r^{-1}) can be modelled based on the elastic modulus (E), CTE (α) and thickness (t) of the layers placed at a certain distance from the neutral axis to the surface of the layer (a) and temperature difference (ΔT) (Equation (2)) [119]:

$$\frac{1}{r}=\frac{2(E_1\alpha_1t_1+E_2\alpha_2t_2+E_3\alpha_3t_3)\Delta T}{E_1t_1(t_1+2a)+E_2t_2(t_2+2(a+t_1))+E_3t_3(t_3+2(a+t_1+t_2)))} \tag{2}$$

This principle has been further adapted to utilise the CTE mismatch or temperature difference between the layers of fibre reinforced polymers to create controlled behaviour composite materials (CBCM), with similar results achieved using combinations of CFRP (CTE $\approx -0.41 \times 10^{-6}$ K^{-1}) and glass fibre reinforced polymer (CTE $\approx 4.9 \times 10^{-6}$ K^{-1}) [121,123]. The effect can also be realised on a smaller scale in the form of Janus fibres, which incorporate a 3D printed passive layer with a glass transition (T_g) and melting temperature (T_m) exceeding those of the actuating material, for instance polylactide (PLA) and polycaprolactone (PCL), respectively, to produce thermally induced shape change at < 50 °C [125]. The Timoshenko equation [126] used for bimetallic strips can also be used to model these bi-polymer (Janus) structures using the radius of curvature (R), thickness (h), linear coefficient of thermal expansion (α), the thickness ($m = \frac{h_1}{h_2}$) and modulus ratio ($n = \frac{E_1}{E_2}$) (Equation (3)) [125]:

$$\frac{R}{h}=\frac{3(1+m)^2+(1+mn)\left(m^2+\frac{1}{mn}\right)}{6(\alpha_1-\alpha_2)(1+m)^2} \tag{3}$$

where the subscripts 1 and 2 refer to the combined materials (metals, composites or polymers). A widely applicable effect, thermal morphing has also been more recently demonstrated using CTE mismatch between metal matrix composites and pure metals to achieve bimorph composites that are capable of operating at temperatures up to 600 °C [122]. With continuous shape change capabilities independent of their mechanical properties, these materials can be tuned by controlling the interlaminar bond strength and layer structure. However, the requirement for a continuous thermal energy input and slow rate of shape change in response to heating limits the viability and applications of these materials. This snap-through rate issue has resulted in a switch from stainless steel to hybrid composite tapes with a viscoelastic layer utilised to obtain a robust deployment method. The focus of research pertaining to thermal bimorphs is the ability to control the curvature of materials and structures in addition to the potential to exert a force induced by the curvature change, which can be used as an actuator. This morphing concept has been successfully demonstrated [119–125] for a variety of material combinations, however, is limited to operating temperatures below T_g of the matrix in cases where the low CTE constituent is a polymer composite.

6. Corrugated composites and structural anisotropy for morphing skins

Morphing skins must be capable of large recoverable strain without failure while maintaining adequate load bearing capacity and controlled stiffness to provide a valid structural contribution and minimise weight penalties arising from the need to reinforce material with insufficient stiffness [35]. In case of a morphing wing structure, a flexible skin is needed which has conflicting requirements: low in-plane stiffness allowing for shape change and high out-of-plane bending stiffness to support loads [127] (Fig. 6). Such structures are most commonly achieved by generating curved fibre paths in composite plies [33,127–133] or by creating a corrugated (compliant) composite structure [78, 127–137], which can then be actuated through incorporation of SMP within the composite [37]. Anisotropy is more simply achieved through modification of composite geometry rather than material properties. Corrugations exhibit high stiffness in their longitudinal (non-morphing) direction, due to the increased moment of inertia, and low stiffness in their transverse (morphing) direction and are a useful geometric form for generating anisotropy. Stiffness parameters in the non-morphing direction can be three orders of magnitude higher than that in the morphing direction [35]. While the high bending stiffness in the non-morphing direction negates the need for reinforcement, the low bending stiffness in the morphing direction means that excessive deformation under aerodynamic pressure could potentially lead to undesirable effects on flow over the aerodynamic surface [35]. Further increases in the stiffness of the transverse (morphing – low stiffness) direction can be achieved through the use of CFRP reinforcement without adversely affecting the stiffness longitudinal to the corrugation [138], while modification of the corrugation shape also provides opportunities for controlled axial and bending stiffness [36,138–140]. Tensile elongation at failure in the morphing direction considerably increases with the ratio of the corrugation amplitude (h_c) to the period (w_c) [35,138,141]. Local bending or 'bubbling' of wing skin between support points [142] can be an issue but can be addressed by bonding two corrugated composites together and inserting a foam core in the closed cell obtained [134,143–145]. Proper selection of the corrugated laminate geometry and spacing of skin supports in the morphing

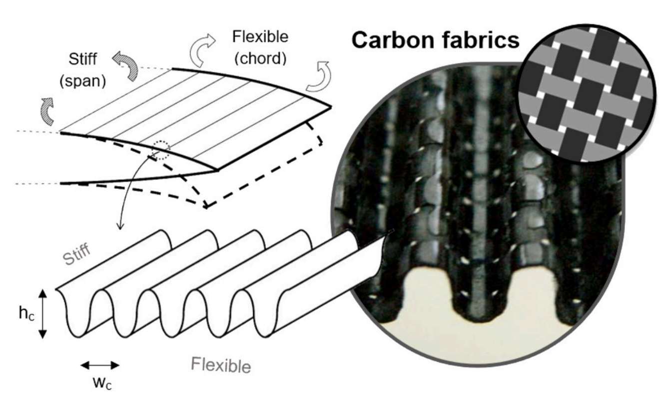

Fig. 6. Carbon fabrics utilised to generate corrugated composites to be used in flexible wing structures. A combination of high stiffness and flexibility is simultaneously achieved perpendicular (span) and parallel (chord) to the corrugation (defined by a respective height, h_c, and width, w_c), respectively. Adapted from Yokozeki, Takeda, Ogasawara and Ishikawa [138].

direction can prevent excessive bending deformation [35].

Other anisotropic structures include composites with a curvilinear fibre path, which are designed to have a higher load bearing capacity than quasi-isotropic composites and can be produced through fibre tow placement and tow steering [33,131,132]. Curvilinear fibre paths also result in anisotropic flexural properties, with flexibility ratios (change in in-plane area of the wing skin to the maximum value of out-of-plane deformation) up to 700% achievable between in-plane and out-of-plane directions [127].

Materials being explored for applications as flexible skin have very different flexibility in morphing and non-morphing directions and it is therefore possible to produce the required shape change in the low stiffness direction by applying lower loads than for standard planar composites. However, in this case load must be permanently applied to maintain a shape other than the original shape post manufacturing. This is possible using e.g., fishbone active cambers (FishBAC, www.youtube.com/watch?v=y-owNyXaClo) [146] for the activation of flexible (wing) skins [140,145,147] that carry the aerodynamic pressures acting over the surface and transfer loads to the underlying structure.

Compliant structures have been trialled in aerofoils, in the Mission Adaptive Compliant Wing (MACW), intended for use on High Altitude Long Endurance (HALE) aircraft, incorporating a compliant trailing edge flap to control aerofoil camber shape. Tests indicated that the dynamic shape control improved the laminar (low-drag) bucket capability (minimum drag coefficient over a range of lift coefficients) and improved flight range by >15% [148]. Unfortunately, aerofoils utilising corrugated composites as skins experience high drag [78,149], a problem that becomes more severe as the ratio of the corrugation height to the chord of the aerodynamic profile increases [149,150]. However, this drag increase can be mitigated by filling or covering the corrugations with a flexible elastomeric material to provide a smooth surface and form a flexible sandwich structure [68,78,138].

7. Flexible matrix composites as foams and aerodynamic skins

Fibre reinforced polymer (FRP) composites designed with flexible matrices, such as elastomers, typically have a Poisson's ratio of zero and can subsequently exhibit 1D morphing capabilities [146,151]. This is illustrated by fibre direction dependent differences in the stiffness of unidirectional fibre reinforced elastomers [152]. In the fibre dominated direction, fibre stiffness results in high modulus and minimal deformation [153], while in the matrix dominated direction, elastomers, such as polyurethane [153–155] or silicone [154], allow considerably more deformation. These properties make these materials potentially useful as flexible skins for morphing honeycomb cores [152,155–157] or bio-inspired ornithopters [158].

Flexible matrices, such as polydimethylsiloxane (PDMS), have also been used as skins for SMA wires interwoven with glass or nylon fibre mats, which can then be thermally stimulated [159,160] (Fig. 7). The same effect can be achieved in plain elastomer matrices [161,162], using magnetic fillers [163], and in 3D printed plies with SMAs used as smart actuator interleaves [164]. SMAs have also been embedded or used as interleaves in conventional composites to induce morphing behaviour [165–169]. The programmable nature of SMAs means that multiple different shapes can be achieved [161], while their reliance on thermal energy for shape change opens potential for expansion of function to repair of the elastomeric matrix and other (self-)healing capabilities [170].

Fluid-filled flexible matrix composites (F^2MC), on the other hand, comprise a tubular composite layout that varies in stiffness based on the fluid pressure in their cavities. This facilitates the production of materials, such as flexible foam composites incorporating a silicone matrix, various low melting point materials in their pores, such as Field's metal, and a Joule heater [171]. The resulting composites exhibit varying stiffnesses when transitioning through the melting temperature of the filler and a shape memory effect resulting from the thermal energy stored in the foam.

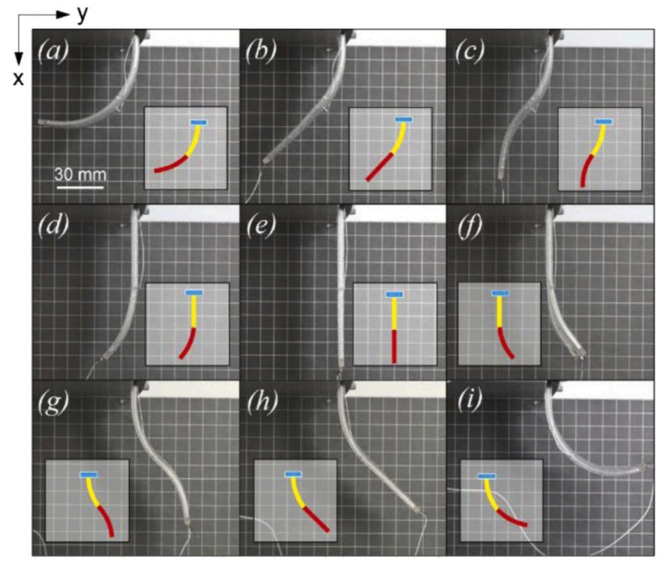

Fig. 7. Morphing composite actuator comprising fusible alloy, Ni-Cr and SMA wires in a smart soft composite structure to achieve local changes between a high- and low-stiffness state. Reproduced from Wang, Rodrigue and Ahn [162].

8. Unique opportunities for manufacturing: shape memory polymers and 4D printing

Shape memory polymers (SMP) can react to external stimuli to achieve reversible shape changes of up to 400% [30,172] and can be reinforced with particles to form nanocomposites or used as a matrix phase in morphing FRP composites. With a T_g typically exceeding their operating temperature, these polymers are programmed using heat and mechanical treatments above their T_g before being cooled to achieve a fixed temporary shape that is free of external loads. The material then returns to its original permanent shape at temperatures $> T_g$ [173,174]. With a lower density than SMAs, SMPs are practical and comparatively easily produced [175] but must typically be used in conjunction with load bearing fillers, such as mats, fibres, nano- or macroparticles.

Carbon nanoparticles, such as nanofibres [176], nanotubes (CNT) [172,177–181], black (CB) [182–185] and other fillers [186–190] are popular reinforcements for SMP nanocomposites to enhance their mechanical [178,180,183] and shape recovery properties, although they can also result in decreased T_g and thermal stability [31]. In the case of CNTs, CBs and metallic particles, such as Ni, composite thermal stability is, however, improved [181] in addition to the electrical conductivity [177,178,180–182,184,186,187], which enables Joule heating. Inductive heating can also be achieved through electromagnetic activation of the magnetic fillers [189,190] and provides SMP nanocomposites with the energy required to induce and accelerate shape recovery [191], which can be thermally, electrically, optically, chemically or magnetically activated [183,188].

SMPs can also be used as a matrix phase in composites to produce load bearing fibre reinforced shape memory polymer composites (SMPC) [192–195]. These composites have been used in structures, such as wings [192], booms and hinges [66,186,193,196] and can achieve small radius bends resulting from the physical properties of the SMPs [197]. Load bearing morphable structures can also be produced by combining SMP interleaves and stiff plies or layers to achieve rigid shape changes [198–202]. Metal [199,202] or conventional CFRP [201] layers can further be used to improve composite mechanical properties with two-way actuation also possible using combinations of SMPs and SMAs, with SMPs imparting shape flexibility and SMAs shape recovery on SMPCs [203–206]. SMPCs have already been tested in microgravity

[207,208] and are currently being tested on the Materials International Space Station Experiment (MISSE) Flight Facility outside the International Space Station [30]. Future space applications could include self-deploying structures, such as solar sails, arrays and shields, large aperture antennas and space debris capture systems [30,186,209].

Recent developments in additive manufacturing have enabled the production of 3D printed composites that are capable of controlled deformation over time, a technology known as 4D printing (time being the fourth dimension) [179,210–215]. 4D printed composites, or printed active composites (PAC), typically comprise SMPs, liquid crystal elastomers or hydrogels [214] and provide morphing capabilities in bending, elongation, twist or corrugation [173] through material anisotropy, such as thermal mismatch between a flexible SMP matrix and printed fibre [42,135,211]. Several deformed states are able to be achieved using various 3D printed SMP fibres [136]. An alternative approach is the use of flexible matrices that incorporate additives to induce morphing. Bio-inspired 4D composites use cellulose fibres embedded in a soft acrylamide matrix, which is capable of anisotropic expansion through absorption of moisture (water) into the fibres [42]. High stability, fast response speeds and large equilibrium deformations can also be achieved in swellable elastomeric materials using the reversible liquid-vapour change of embedded low boiling point liquid chambers and functional liquid metal fillers [216]. However, PACs tend to have a considerably lower stiffness than conventional composites, potentially limiting their applications to non-structural applications, such as soft robotics [217] and biomedical devices [42], such as reactive containers that release pharmaceuticals under the correct environmental conditions or stimuli in targeted drug delivery [218], fabrication of custom stents, the size of which is minimised to enable easy insertion but then expands to the desired geometry at body temperature [210, 219,220] and splints that can change in geometry to accommodate human growth [221–223]. Mechanical and shape recovery properties can be improved through melt blending [224–227] or hybridisation of SMP and elastomers, use of microfillers, such as carbon fibres [228,229], and nanofillers, such as CNTs [230–232] and graphite oxide [233], silicon carbide [234] into silicone or other elastomeric matrices [230,235]. Avoiding support structures, especially for internal structures that are not easily accessible, simultaneously printing different material groups in addition to the limited range of economically printable materials and slow print times are other issues that limit the adoption of these technologies for applications other than aerospace and transportation [173].

9. Design concepts for structural aerospace components: controllable stiffness

Structural aerospace applications require high stiffness, a property that can be difficult to achieve in morphing composites, which are by definition flexible. Structural composites with morphing capabilities can be achieved by controlling material properties, such as flexural modulus, or geometric properties, such as area moment of inertia. One way to achieve this is by introducing slip between the plies of the composite, resulting in a decreased area moment of inertia in the cross-section. This slip also prevents transfer of shear stress between the plies and can be either passive, whereby composite plies that undergo relative slip in ambient conditions are coupled together though an external stimulus, or active, whereby interply slip must be induced.

Passive slip can be readily achieved in composites exhibiting electrostatic bonding between plies [236–240], which are coated with materials, such as polyvinylidene fluoride (PVDF) or polytetrafluoroethylene (Teflon, PTFE). These coatings produce electrostatic attraction under applied electric potential and subsequently impart normal stresses (σ) between the plies, which can then be translated into shear stresses between layers (τ) by the friction between the plies (Equations (4) and (5)). Ply slip can subsequently be controlled by the dielectric constant of the material (ε_r), its thickness (d), the applied electric potential (V) and coefficient of friction (μ).

$$\sigma = \frac{\varepsilon_r \varepsilon_0 V^2}{2d^2} \tag{4}$$

$$\tau = \mu\sigma \tag{5}$$

Conversely, structural morphing composites utilising active slip typically incorporate thermoplastic (TP) layers as interleaves between composite plies to induce slip when the service temperature exceeds T_g of the interleaf during the phase change from stiff to flexible [145,199, 236–246] (Fig. 8). Balsa wood plies interleaved with a hot glue (TP) layer and aluminium plies interleaved with TP polymers embedded with a nichrome wire heating element and electric heating blankets, respectively, are simple examples that can illustrate the potential of structural morphing composites with controllable stiffness [246,247]. More recently, extensive studies investigating CFPR plies as interleaves with polystyrene (PS) or poly(styrene-co-maleic anhydride) (SMP) TPs identified possible flexural modulus reductions of up to 98% resulting from ply slip [243–245,248,249].

Flexible TP layers impede load transfer that would typically occur between composite layers and discontinuous load bearing plies, reducing composite flexural stiffness. This has been demonstrated in steel segments connected with thermoplastic polyurethane (PU), which varies in stiffness based on temperature [202,250,251] and composites, which utilise the softening of TP layers binding individual reinforcement fibres to the matrix to generate flexibility [252]. Reversible strain has also been observed in segmented composites.

Controllable stiffness has been demonstrated in thermoplastic interleaved thermosetting composites. It was shown that the bending stiffness of the composites can be tuned by controlling the layup structure i.e., by blocking plies (Eq. (6)). By increasing the service temperature to a temperature above T_g of the thermoplastic interleaves (but below T_g of the matrix) during bending the plies are decoupled causing a considerable loss in bending stiffness. Nevertheless, the bending stiffness at elevated temperatures is also controlled by the composite ply thickness (Eq. (7)). Composite stiffness changes are reversible, with stiffness restored upon removal of the stimulus. This has been demonstrated in CFRP, where energy stored in the plies (or fibres) resulting from deformation at low modulus conditions can be used to reverse shape changes in a shape memory effect but without the need for any shape memory materials [248]. This can be used to create deployable structures, such as box shapes, however, unexpected out-of-plane fibre waviness should be considered and can be investigated using structural analysis i.e., microscopy.

$$E_f^{RT} = \frac{12E_c}{h^3}\sum_{i=1}^{N}\left(\frac{t_i^3}{12} + t_i z_i^2\right) \tag{6}$$

$$\textit{Composite layers only } E_f^{HT} = \frac{E_c}{h^3}\sum_{i=1}^{N}\left(t_i^3\right) \tag{7}$$

Composite layers only

Active interply slip is favoured for prolonged use in structural applications due to the higher stiffness of the unstimulated state, which has conservative energy requirements compared to the continuous energy supply required to maintain stiffness in composites with passive interply slip. However, at a given thickness the mechanical properties of active interply slip composites, such as flexural modulus and failure stress, tend to be compromised by the presence of the TP interleaves with the composites exhibiting lower mechanical properties than traditional CFRPs and other materials of constant stiffness. Investigations have been limited to coupon sized specimens. Additionally, the load bearing capacity of composites with controllable stiffness is very low in their low stiffness state. This means that they cannot be used as standalone structural reinforcement and are better suited to applications with minimal structural load, such as reduced gravity conditions in space design.

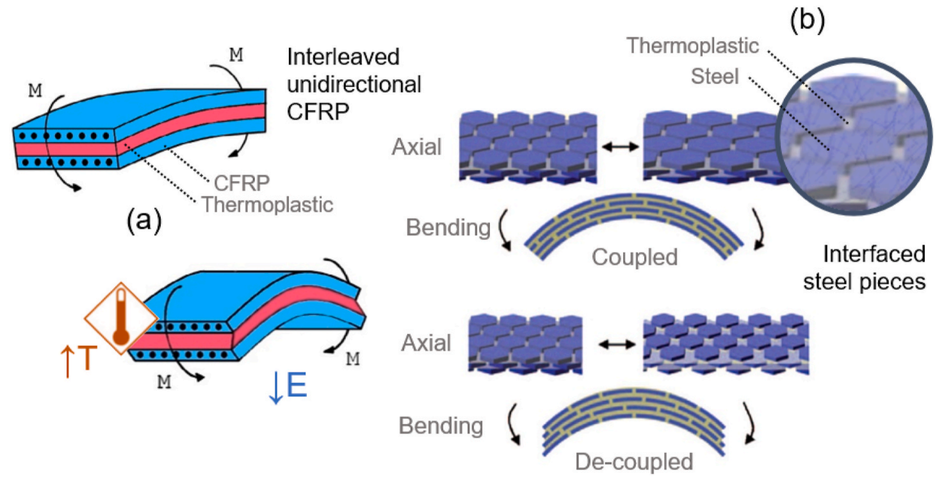

Fig. 8. (a) Flexural stiffness control in a thermoplastic interleaved unidirectional CFRP composite laminate structure and (b) segmented reinforcement controllable stiffness composite comprising steel pieces interfaced with thermoplastic. Adapted from Maples, Wakefield, Robinson and Bismarck [243] and Kuder, Arrieta, Raither and Ermanni [175].

10. Conclusion and outlook

Inspired by a wide range of biological morphing composites in nature, humans continue their endeavour to reproduce smooth, full form shape changes that could considerably improve aerodynamic efficiency in the aerospace, automotive and power generation sectors. From morphing flaps, winglets, and wingtips to drag reducing features, deployable structures and expanding stents and splints, many dynamic composite technologies hold considerable promise to improve machine sustainability and safety across a range of applications. Morphing composite capabilities to date range from low-energy yet large structural changes achieved by multistable composites, although this can be modified using interleaving, to controlled and continuous shape change technologies utilising coefficient of thermal expansion mismatch and structural anisotropy, shape memory polymers and 4D printing. However, despite the enormous potential of these technologies and their relative success in defence, commercial aviation and automotive industry trials, these emerging materials platforms still experience issues with high material costs and mass, undesirable mechanical properties including low strength in the low-stiffness state, complicated manufacturing processes, and high energy requirements to induce shape change. Undoubtedly technologies that will shape the future, considerable further research and development is still required to realise the full potential of these emerging materials and bring them into active service, a process that can perhaps be accelerated to some extent through biomimicry.

Morphing composites hold particular promise in applications where minimal service loads are present, or where structures at least experience minimal loads during morphing. If loads acting on a bi- or multi-stable structure are too high, it may be impossible to change from one stable state to another, and if considerable loads act on a controllable stiffness structure very large deformations may occur. That said, morphing composites are useful for single deployment in biomedical and robotic devices, 4D printing holds promise to programme materials, such as those used in vents to be able to respond to the environment, to augment architecture, and controllable stiffness and bistable morphing in space applications for deployable structures. Controllable stiffness composites could also be useful for applications where the intrinsic stiffness of composites could result in safety hazards e.g., car exterior components could cushion impacts by reducing their stiffness when activated by a sensor [253].

Author statement

All authors wrote the manuscript. MPJ and FL designed the figures. All authors contributed to manuscript review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

G.M. acknowledges funding from the HyFiSyn project, which was funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 765881.

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